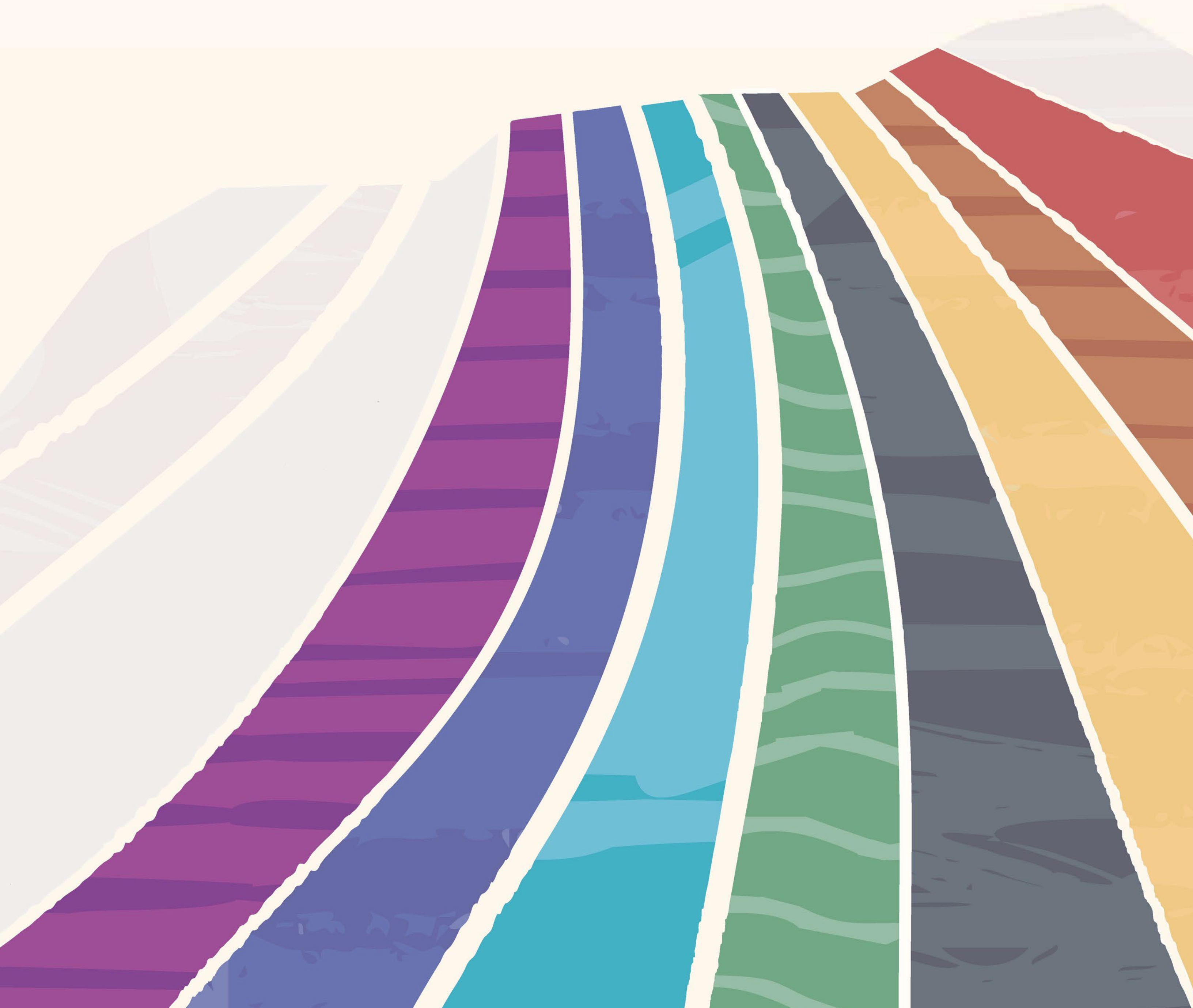
Austrian Panel on Climate Change | APCC | 2025

# Second Austrian Assessment Report on Climate Change | AAR2

## Full Report



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Bundespräsident
Alexander Van der Bellen

200 Wissenschaftler:innen. 100 externe Gutachter:innen. 3 Jahre intensive Arbeit. Zahllose Daten und Analysen. Das Ergebnis davon halten wir nun in Händen: den Zweiten Österreichischen Sachstandsbericht zum Klimawandel. Es ist ein Blick in den Spiegel, ein Realitycheck, der uns zeigt, wie sich die Klimakrise in den letzten Jahren beschleunigt hat – global und hier in Österreich. Hitzewellen, Dürren und Hochwässer sind Realität geworden, und das mit gravierenden Folgen für Gesundheit, Wohlstand und Wirtschaft.

Eine gute Nachricht gibt es, und zwar dass die heimischen Treibhausgas-Emissionen auf einem historischen Tiefstand sind. Großartig! Aber wie so oft bei guten Nachrichten hat auch diese einen Haken, nämlich sind wir – fast schon typisch gemütlich Österreichisch – ein bisschen spät dran, was unsere Emissionsreduktion betrifft. Wollen wir bis 2040 klimaneutral sein, müssen wir nicht nur vieles ändern, sondern vieles rasch ändern. In der Energieversorgung, Mobilität, Ernährung und mehr. Das ist natürlich nicht einfach. Und es kostet! Aber der Bericht macht klar: Nichts zu tun kostet uns noch viel mehr. Und damit meine ich gar nicht Geld, sondern etwas viel Wertvolleres: unsere Zukunft. Klimaschutz lohnt sich allemal – ökologisch, sozial und wirtschaftlich. Entscheidend ist, dass wir ihn nicht isoliert von allem rundherum betrachten, sondern Biodiversität, Energieunabhängigkeit und vor allem auch soziale Gerechtigkeit einbeziehen. Denn die Klimakrise trifft sozial Schwächere am stärksten.

Dieser Sachstandsbericht ist aber nicht nur ein Weckruf, der uns zeigt, wo wir stehen. Sondern zugleich auch eine Anregung, die uns den Weg in eine nachhaltige Zukunft zeigt. Die Klimakrise ist real, die allermeisten Menschen wissen das. Sie fordern mehr Mut, mehr Taten – und ich schließe mich da an. Ich bin sicher, dieser Bericht ist dazu ein geeigneter Anstoß.

A. Van der Bellen

Bundesministerium
Land- und Forstwirtschaft,
Klima- und Umweltschutz,
Regionen und Wasserwirtschaft

Bundesminister Mag. Norbert Totschnig, MSc

Mit dem Zweiten Österreichischen Sachstandsbericht zum Klimawandel liegt nach nun dreijähriger interdisziplinärer Forschungsarbeit eine der fundiertesten und umfassendsten Analysen der Klimawandelfolgen sowie der möglichen Handlungsoptionen für Österreich vor. Dafür möchte ich mich bei den rund 200 beteiligten Expertinnen und Experten herzlich bedanken.

Die Ergebnisse zeigen die Herausforderungen in aller Deutlichkeit. In Österreich sind die Folgen des Klimawandels besonders spürbar. Unser Land erhitzt sich stärker als der globale Durchschnitt. Die Folgen zeigen sich längst in allen Lebens- und Wirtschaftsbereichen – von Land- und Forstwirtschaft und Gesundheit bis hin zu Infrastruktur, Tourismus und Ökosystemen.

2024 war das wärmste Jahr der Messgeschichte mit belastenden Hitzeperioden und schweren Überflutungen. Mit fortschreitendem Klimawandel verstärken sich diese Extreme und deren Auswirkungen. Angesichts dessen braucht es ambitionierte Maßnahmen mit gezielten Investitionen und ein abgestimmtes Vorgehen beim Klimaschutz und der Anpassung an den Klimawandel – quer durch alle Sektoren. Wir müssen sicherstellen, dass unsere Energieversorgung, Mobilität, Wärmebereitstellung, Industrie sowie Land- und Forstwirtschaft zukunftsfähig ausgestaltet sind und dabei gleichzeitig unsere Wirtschaft und unser Standort gestärkt aus der Transformation hervorgehen.

Wenn wir es richtig angehen, können Investitionen in Klimaschutz und Anpassung positive Auswirkungen auf Beschäftigung, Einkommen und Wohlstand haben und die Abhängigkeit von Energieimporten sowie Folgekosten verringern. Das Ziel der Klimaneutralität ist im Regierungsprogramm verankert. Wir arbeiten auf Hochtouren an einem Klimagesetz, um damit den Rahmen für abgestimmtes Handeln zu setzen. Der Sachstandsbericht zeigt eindrücklich, dass wir rasch und entschlossen handeln müssen – als Gesellschaft, als Politik, als Einzelne. Gemeinsam können wir unsere Natur, Wirtschaft und unser Leben resilienter und nachhaltiger machen – darauf kommt es jetzt an. Ich bin davon überzeugt, dass wir unsere Klimaziele erreichen können, wenn wir gemeinsam an Lösungen arbeiten, die ökonomisch sinnvoll und umsetzbar sowie sozial tragfähig sind.

Norbert Totschnig

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## AAR2 PREFACE

Daniel Huppmann, Margreth Keiler, Keywan Riahi, Harald Rieder

The effects of climate change can already be observed in Austria – it is reshaping life and landscapes in Austria. Detectable changes include extended dry periods, increasing frequency of heatwaves and floods, and retreating glaciers, which are consistent with global trends in a warming world. These impacts, driven by anthropogenic greenhouse gas emissions, have become more frequent, intense, and widespread, with increasing risks for natural systems, the economy, public health, and infrastructure. The regional manifestation of these changes in alpine as well as lowland areas demands targeted responses from all parts of society.

At the same time, Austria has committed itself to ambitious climate goals at the national, European, and international level. These include the **Austrian target of climate neutrality by 2040**, the legally binding **European Climate Law** (greenhouse gas neutrality by 2050), and Austria's contribution to the **Paris Agreement** of limiting global warming to well below 2 °C. Emission reductions observed since 2022 indicate a shift of the long-term trend, but the country's per capita and consumption-based emissions remain high and significantly above the EU average.

### Aim and scope

The Second Austrian Assessment Report on Climate Change (AAR2) provides a **systematic and comprehensive assessment of the scientific literature on climate change for Austria** across all relevant scientific domains. It builds upon the First Austrian Assessment Report on Climate Change published in 2014 and a series of subsequent Special Reports published by the Austrian Panel on Climate Change (APCC) under the auspices of the Climate Change Centre Austria (CCCA).

The objective of the AAR2 is to inform an evidence-based societal transformation by assessing the physical, ecological, economic, and social implications of climate change in Austria. More than 200 scientists collaborated to produce this report. It offers a **science-based foundation for policymakers and public dialogue** on the portfolio of options for emissions reduction and adaptation. The assessment does not advocate for specific policy instruments but highlights the **risks, opportunities, barriers, trade-offs and synergies** of alternative climate-friendly transformation pathways. This includes interactions with sustainable development and societal well-being, notably the **Sustainable Development Goals (SDGs)**.

### Structure of the report

The AAR2 combines insights from various scientific perspectives including natural sciences, engineering, social sciences, economics, law, and public health. This integration is essential for assessing the multi-faceted challenges related to climate change. It reflects Austria's diverse institutional, ecological, and socio-economic contexts and strengthens the report's systemic and interdisciplinary perspective.

The report consists of **eight chapters**.

Chapter 1 provides an overview of **past, current, and projected changes in Austria's climate system**. Key climate indicators are analyzed across the atmosphere, cryosphere, hydrosphere, biosphere, and lithosphere. A Cross-Chapter Box on Risk introduces the IPCC risk framework and identifying key climate-related risks and their evolution with rising global warming levels (GWLs).

Chapter 2 assesses the **impacts of climate change on land use, ecosystem services, and human health** with a focus on climate-sensitive sectors such as agriculture and forestry. The chapter explores both domestic and international supply chains and identifies co-benefits from nature-based solutions. Mitigation in land systems focuses on sustainable consumption and ecosystem-based carbon sinks.

Chapter 3 focuses on the systems that structure **Austria's built environment, including settlements, spatial planning, buildings, and transport**. It examines how urban form, infrastructure, and mobility systems influence emissions, energy demand, and climate risks. Mitigation strategies include compact development, electrification of heating and transport, and promotion of low-carbon mobility. Adaptation priorities include resilient infrastructure, urban heat mitigation, and inclusive spatial planning.

Chapter 4 focuses on the **provision of goods and services in a climate-resilient economy** with emphasis on material provisioning, energy systems, and labor. The chapter includes a Cross-Chapter Box on the Avoid–Shift–Improve (ASI) framework. Mitigation in provisioning systems relies on decarbonization of energy and industry, circular economy principles, and sufficiency-oriented approaches. Adaptation focuses on reducing systemic vulnerability through diversification of supply chains, strengthening infrastructure resilience, and building institutional capacity.

Chapter 5 investigates the **demand-side transformations necessary to achieve net zero through human decisions and behavior**, with particular emphasis on how household consumption, social norms, and lifestyles contribute to greenhouse gas emissions and climate vulnerability. It also assesses inequality, collective action, and the enabling role of institutions, education, and civil society.

Chapter 6 reviews the **legal, political, economic, and societal frameworks for climate governance** in Austria. The analysis covers policy instruments, just transition mechanisms and financing needs as well as governance challenges and capacity gaps.

Chapter 7 focuses on the Alps as an area of particular relevance for Austria. The Alps are examined on three levels: As a natural or near-natural environment, as a provider of services, goods and livelihoods, and as a home to communities. The chapter highlights climate-related impacts and adaptation needs with an integrated environmental and socio-economic perspective.

Chapter 8 synthesizes knowledge on **transformation pathways toward climate neutrality**. It presents integrated scenario assessments of emissions, energy demand, carbon budgets, and adaptation to examine the feasibility of different pathways from a biophysical, economic, and socio-cultural perspective.

## Assessment approach and methodological frameworks

The assessment follows the procedures and methods established by the Intergovernmental Panel on Climate Change (IPCC). Key findings are formulated with **a level of confidence** as assessed by the author team and using the **calibrated language of the IPCC** to indicate the strength of the scientific evidence and level of agreement in the literature. In situations where available evidence and region-specific published literature was limited or insufficient for a reliable assessment, the authors assessed evidence from other regions if the insights were transferable and relevant for Austria.

The IPCC's further procedures and methods were adapted for the AAR2, and the various approaches and methodological frameworks applied in the AAR2 are discussed in cross-chapter and chapter boxes throughout the report.

This assessment evaluates climate-related **risks** related to climate change following the IPCC risk concept, which considers the interaction of **hazard, exposure, and vulnerability** {Cross-Chapter Box 1}. This enables a differentiated understanding of how and why risks emerge and escalate. The report identifies the most relevant key risks for Austria and discusses options to increase climate resilience, acknowledging limits of adaptation.

The risks related to climate change depend directly on the speed of global temperature increase and the implied changes on climatic conditions in Austria. Rather than describing the climatic conditions in a particular set of years (2030, 2040, 2050), the report evaluates impacts from climate change when certain thresholds of global temperatures are crossed (1.5°C, 2°C, 3°C, 4°C), the so-called **Global Warming Levels** (GWL). This approach reflects the physical basis of climate change and aligns with international policy targets. It enables the identification of climate tipping points, changes in the level of risk, and the effectiveness of adaptive responses at different warming levels. GWLs also allow integration across sectors and scales and ensure policy relevance under conditions of timing uncertainty {Box 1.1}.

The report explores both demand-side and supply-side options to reduce greenhouse gas emissions, including changes to the provisioning systems. It is generally preferable to prioritize (1) the avoidance of climate-harmful activities, (2) the shift toward sustainable alternatives, and (3) the improvement of efficiency in existing systems. This is known as the **Avoid-Shift-Improve (ASI) framework** {Cross-Chapter Box 4}. Wherever possible, this report presents an assessment of options that follows the avoid-shift-improve rationale.

Not all sectors will be able to reach carbon-neutrality within the timeframes currently discussed by policymakers. As a complementary measure to ambitious mitigation, **Carbon Dioxide Removal** (CDR) can help balance residual emissions in hard-to-abate sectors. The portfolio comprises nature-based solutions (e.g., increasing natural sinks through afforestation) and technical approaches, but CDR is constrained by costs, land-use conflicts, and limited social acceptance {Cross-Chapter Box 6}.

The transformation of the Austrian society towards climate resilience will require substantial changes to the economy, reducing emissions and resource use while ensuring sufficient resources for **well-being** of every person living in Austria. Two related concepts to reduce resource-intensity of goods and services are the notion of a **circular economy** (maximize re-use of resources, minimize waste) {Cross-Chapter Box 5} and a **sharing economy** (moving from ownership of goods to use-as-a-service) {Section 5.5}. In addition, there is an ongoing debate whether continued economic growth is a prerequisite to support the transition or whether a deliberate focus on reducing material consumption is a more effective strategy to ensuring adequate living conditions for every person living in Austria {Cross-Chapter Box 7}.

Further overarching topics across the AAR2 are **health and climate change** {Cross-Chapter Box 2}, the **needs orientation in provisioning systems** {Cross-Chapter Box 3}, and **green finance**, i.e. the redirection of investments to facilitate transformations while ensuring growth and competitiveness and societal well-being {Cross-Chapter Box 8}.

The report draws on a range of **quantitative analysis and model-based scenarios** to explore plausible futures for Austria under different emissions trajectories. This allows to understand the feasibility, costs, and trade-offs of various climate policy options in the energy system, industry, transportation, and land use. It illustrates the broad range of policy choices towards a climate-resilient society that are available to policymakers and society while navigating the transformation to climate neutrality.

## Acknowledgement

We express our deepest gratitude for the contribution and commitment of the entire author team. We appreciate the dedication and hard work of the Technical Support Unit and Chapter Scientists who supported the chapters and cross-chapter teams in the development of the report. We are grateful for the commitment and diligence of the Review Editors, which were critical in assisting the author teams and ensuring the integrity of the review process. We would also like to thank all the expert reviewers who submitted comments on the drafts to ensure that the final report meets the highest levels of scientific rigor and quality, and we are indebted to all the stakeholders that participated in multiple workshops to help developing a scientific assessment that is hopefully useful and usable for decisionmakers at all levels of society.

The Steering Committee of the Austrian Panel on Climate Change (APCC) and the Climate Change Centre Austria (CCCA) have been instrumental for guiding the AAR2 from the initial scoping phase to its publication over a period of more than five years. We acknowledge the funding and the support from the Climate and Energy Fund throughout the entire process that facilitated the development of the report. We thank the production team including translation, layout, graphic design, website development and public relations, which did an amazing job under tight deadlines. Last, but not least, we appreciate the support of all universities, institutes and research organizations that facilitated the contribution of the authors and thereby enabled this report as an accomplishment of the Austrian climate science community.

## A call to action

The report highlights that achieving climate neutrality by 2040 requires urgent action across all parts of society – supported by science-based planning and governance, effective climate policy, and broad engagement with civil society. The AAR2 aims to support this transformation by providing a shared knowledge base for public debate, institutional reform, and cross-sectoral cooperation. We hope that this assessment report provides relevant input for effective climate action.

## SUMMARIES

The *Summary for Policymakers* (SPM) is available at the following links:
https://aar2.ccca.ac.at/summary (in English) and
https://aar2.ccca.ac.at/zusammenfassung (in German).

The *Technical Summary* (TS) is available at the following links
https://aar2.ccca.ac.at/technical-summary (in English) and
https://aar2.ccca.ac.at/wissenschaftliche-zusammenfassung (in German).

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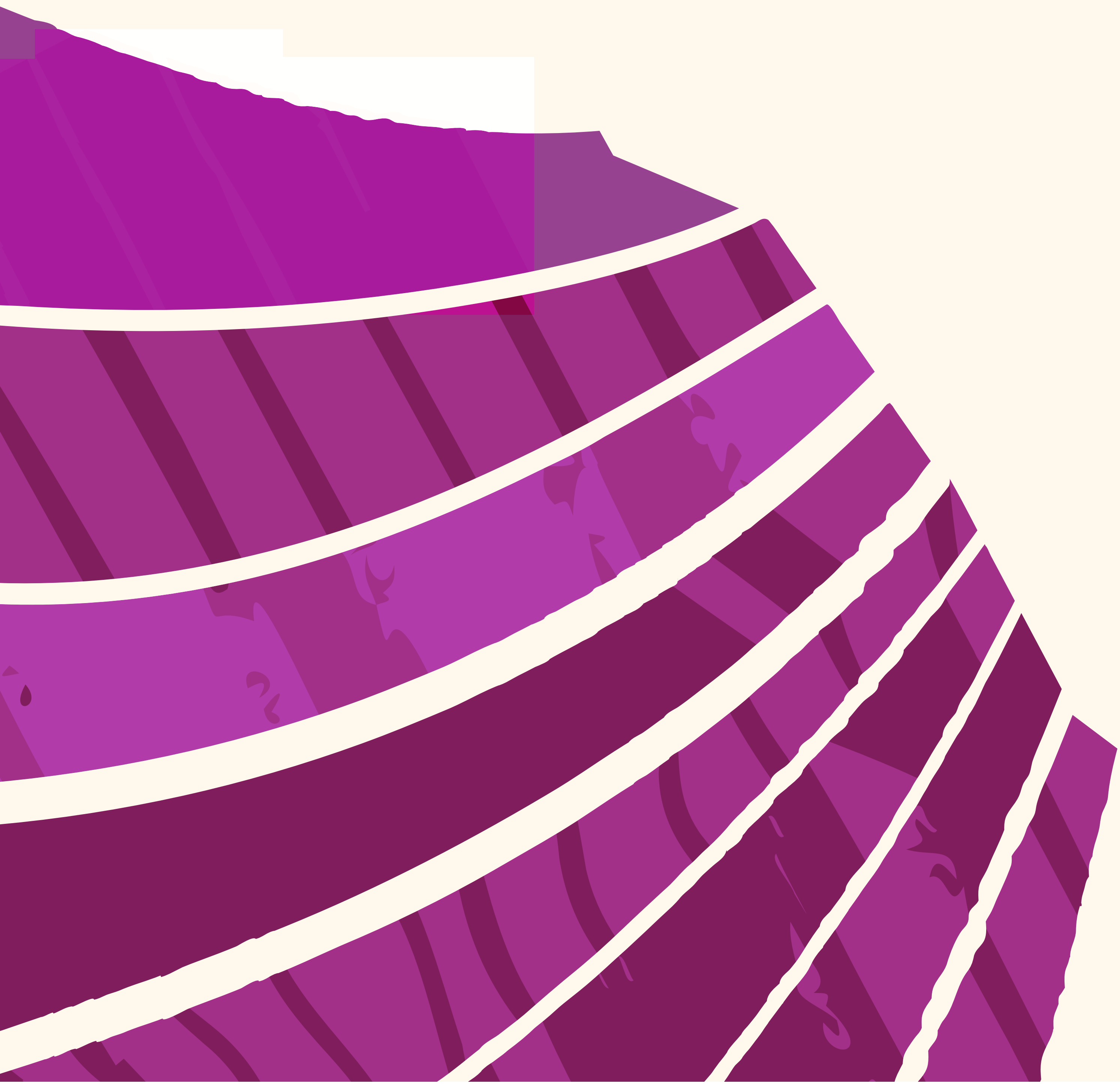
## Chapter 1

# Physical and ecological manifestation of climate change in Austria



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## Chapter 1
## Physical and ecological manifestation of climate change in Austria



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## EXECUTIVE SUMMARY

**Changes in Austria's thermal environment are detectable both for the mean and for the extremes, with a particularly pronounced acceleration of temperature increase since the 1980s (*high confidence*). The temperature increase is markedly stronger in Austria than in the global mean, mainly due to the regional thermodynamic and dynamical forcings in large parts of Europe (*high confidence*). {1.2.1}**

- In Austria, the annual mean surface air temperature until 2024 has increased by 3.1°C since pre-industrial times. Since the 1980s, this warming has been particularly strong (+0.5°C per decade) in Austria and other parts of Europe. {1.2.1}
- Temperature extremes during the day and at night, such as hot days or tropical nights, and the associated heat stress, have increased significantly in the summer half-year (April-September). This increase is particularly pronounced in urban areas. In Austrian federal province capitals, heat waves are now 50 % more frequent and 1–4 days longer than in previous decades (1991–2020 vs. 1961–1990). {1.2.1}
- The number of hot days in very hot years (with a statistical return period of 10 years) has increased on average by the factor of 3 in these periods. {1.2.1}

**All climate projections show a further increase of the global mean temperature at least until mid-century. The development thereafter strongly depends on the amount of anthropogenic greenhouse gas emissions. Assuming a continuation of current policies, anthropogenic greenhouse gas emissions are projected to lead to a median global warming of 2.7°C [2.2 to 3.4°C] by 2100. The temperature increase in Austria continues to be higher than the global mean. Heat extremes will become more severe. The frequency and duration of heat waves will increase and the temperature within individual heat waves will strongly increase (*high confidence*). {1.2.2}**

- Mean temperatures over Austria are clearly projected to increase for all seasons with increasing levels of global warming (*high confidence*). Compared to the past (climate period 1961–1990), annual mean temperatures are expected to increase by 2.0°C, 2.6°C, 3.6°C and 4.9°C at global warming level (GWL) 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C, respectively. {1.2.2}
- The number of hot days in a very hot year occurring once in 10 years in the past (climate period 1961–1990) will likely multiply 3.5 times at GWL 1.5°C, 4.3 times at GWL 2.0°C, 5.7 times at GWL 3.0°C, and even 8.1 times at GWL 4.0°C on average for Austria. In addition, the average temperature of heat waves will likely increase by 6.6°C at GWL 4.0°C compared to the climate period 1961–1990 (*robust evidence, low agreement*). {1.2.2}
- Projections of future temperature for Austria represent conservative estimates and need to be interpreted with caution given the cold bias (largely driven by deficiencies in aerosol forcing and atmospheric dynamical components) of the regional climate models backing the ÖKS15 ensemble. Current warming is already exceeding temperature projections at low GWLs. It is expected that Austrian mean air temperatures in the future exceed global mean temperatures by at least a factor of 1.3 (*high confidence*). {1.2.1, 1.2.2}

**The observed and future temperature changes in Austria are directly linked to changes in several other climatological variables and have far-reaching consequences (*robust evidence, medium agreement*). {1.2.1, 1.2.2}**

- Average evaporation in Austria has increased by about 110 mm/yr in total over 35 years (1978–2013) and will increase with further warming (*high confidence*). {1.4.1} Increased evaporation contributes significantly to low flows in rivers and streams, to the severity of droughts and to changes in the water level of Lake Neusiedl (*robust evidence, medium agreement*). {1.4}
- Since the 1960s, snow cover duration (SCD) has decreased by 5–10 days per decade in the entire Alpine region, including Austria. Until the year 2050, SCD in Austria will most likely continue to decrease by at least 5 days per decade on average (*high confidence*). {1.3.1}
- All glaciers in Austria are losing mass and have been shrinking at an accelerating rate in recent years. 40 % of glacier area in Austria were lost between 1969 and 2015. Actual deglaciation before the end of the century is virtually certain (*high confidence*). {1.3.2}
- The intensity of multi-day, daily and small-scale short-duration (hourly) heavy precipitation events has increased in the warm season (May-September), closely following the observed rise in temperature and associated increase in the water vapor content of the air (*robust evidence, medium agreement*). {1.2.1}
- Daily maximum precipitation with a 10-year return period will likely increase by 14.3 % at GWL 1.5°C, 17.2 % at GWL 2.0°C, 23.4 % at GWL 3.0°C and 30.3 % at GWL 4.0°C compared to the past (climate period 1961–1990) (*medium confidence*). {1.2.2}

**The impact of anthropogenic climate change on precipitation in Austria is much more complex than on temperature. It shows regional and seasonal variations and differs for climatological sums (e.g., seasonal or annual sums) and for individual precipitation events (*robust evidence, medium agreement*). {1.2, 1.4}**

- Seasonal mean precipitation in Austria is projected to increase in winter (*high confidence*) and decrease in summer (*robust evidence, medium agreement*). These changes are clearly evident under high emissions scenarios or GWL 3.0°C and higher. {1.2.2}
- There is a regional difference in long-term changes in seasonal precipitation over the last 200 years, especially in winter, of the order of 10–15 %, with an increase in western Austria and a decrease in south-eastern Austria (*high confidence*), probably due to decadal variability (*medium confidence*). {1.2.1}

**Observed floods (fluvial and pluvial) show an increase in part of the catchments (*medium confidence*).** For fluvial floods, the trend is more pronounced in smaller catchments (24 % show increasing trends) than in larger catchments. There is a clear seasonal shift from winter and spring floods to summer floods, so that summer is now also the dominant flood season in the eastern half of Austria. Climate projections indicate a potential increase and notable seasonal shift in flood occurrences in Austria, particularly an increased frequency of summer floods due to more intense and localized extreme precipitation events, especially in the Alps and smaller river basins (*robust evidence, medium agreement*). {1.4.1}

**Low-flow trends in Austria (both drying and wetting) have become more pronounced in recent years compared to the previous assessment (*high confidence*).** Low flow discharges have increased in alpine catchments (+23 % over 43 years (1977–2019)) and decreased in lowland catchments (-17 % over the same period). They are expected to continue to decrease in the lowlands of eastern and southern Austria. In alpine catchments, low flows will increase significantly due to decreasing frost. {1.4.1}

**The surface water temperature of all monitored lakes has increased during the last 20 to 40 years (*high confidence*).** The surface temperature of selected lakes in Austria has increased concurrently with increasing air temperature by an average of between 2.0°C (last 40 years) and 1.5°C (last 15 years). Since lake surface water temperature is closely correlated with changes in air temperature, lake surface water temperature is expected to increase in the future. Higher lake water temperatures lead to higher lake metabolism, which leads to higher respiration, and thus to higher emissions of greenhouse gases such as $CO_2$, and possibly $N_2O$ and $CH_4$. {1.4.2}

**The water loss in Lake Neusiedl in the years 2021 and 2022 is primarily the result of evaporation due to high temperatures (surface water temperatures exceeded 30°C at times in summer) and a decrease in precipitation (*medium confidence*).** Ongoing climate change will have a significant impact on the future of Lake Neusiedl and its surrounding ecosystems, with lower average water levels, especially in summer, and as yet unknown effects on the species community. {1.4.2}

**Currently and in future projections, there is a west-east gradient with generally higher groundwater recharge in the western part of Austria than in the eastern or south-eastern part (*high confidence*).** Seasonal changes in groundwater recharge are expected in the future, but they depend strongly on climate scenarios (*limited evidence, medium agreement*). Available groundwater resources may decrease by up to 23 % by 2050, and regionally by as much as 30 % (*medium confidence*). {1.4.3}

**Changes in water and temperature regimes will significantly increase soil erosion (*high confidence*).** This occurs due to increased frequency of convective events and expected extreme precipitation, if no countermeasures are taken. {1.5}

**High temperatures combined with sufficient water supply will lead to increased loss of soil organic carbon (*high confidence*).** Mineralization of soil organic carbon will be enhanced by higher temperatures at sites with sufficient precipitation (e.g., at higher sea level). {1.5}

**Land use and climate change are the most important drivers of wetland degradation (*high confidence*).** Many wetlands will lose important ecosystem functions such as carbon storage, resulting in positive feedbacks with climate change (*high confidence*). Other commonly affected ecosystem functions include water retention (*medium evidence, high agreement*) and the support of biodiversity (*medium evidence, high agreement*). {1.6.1}

**Limited water supply will be the most important direct impact factor in Austrian forests (*high confidence*).** Disturbance regimes (storms, snow, insects, fungi) will intensify and strongly affect the provision of ecosystem services (*high confidence*). Forest management decisions will strongly determine the pathways and speed of adaptation in species composition (*medium confidence*). {1.6.2}

**Climate change drives species ranges upslope in elevation and promotes the replacement of cold-adapted species by warm-adapted species in many taxonomic groups (*high confidence*) and a decline in some habitats such as alpine grasslands (*limited evidence, high agreement*).** Under strong further warming, major population declines, and increased vulnerability are expected especially for cold-adapted species of higher altitudes (*high confidence*), including many endemic taxa, whose eventual extinction would reduce Austria's unique contribution to the global species pool (*high confidence*). {1.6.4}

**Climate change mitigation via land-based carbon dioxide removal and energy decarbonization could have significant negative impacts on biodiversity (*medium evidence, high agreement*).** However, carefully designed, e.g. via appropriate spatial planning or tree species selection for afforestation these measures can also generate double benefit for the intertwined climate and biodiversity crises. {1.6.4}

**Climate change will lead to responses in Earth's surface processes, and thus to a change in the causes and triggers of landslides (*medium confidence*).** Permafrost degradation, glacier retreat, and extreme precipitation conditions are the most obvious factors responsible for increasing landslide activity of various types, although data for the Austrian Alps need to be substantially improved. The frequency of shallow earth/debris slides and debris flows will increase in Austria. In the high mountains, affected by glacier retreat and permafrost degradation, a further increase in rock fall/avalanche and rock slide activity is expected. {1.7}

**Depending on the topographic situation, climate change will have a significant impact on different types of natural hazard processes in Austria (*medium confidence*).** Numerous cascading or compound processes have been identified for Austria in the past, some of which have resulted in major damage and high financial losses. These processes should be given special attention in the future. {1.8}

## 1.1. Chapter introduction

### 1.1.1 Setting the scene

The concept of Chapter 1 is to provide general information on the current situation as well as on historical and future developments of the climate system, its components and the direct impacts on the natural environment in Austria. Basic processes and drivers and their response to anthropogenic climate change are described. The chapter provides important reference data on past and future changes in climate indices, general trends and extremes for the subsequent chapters. The chapter is divided into subchapters according to the spheres involved in the processes.

- The introduction (Section 1.1) describes the physiographical and climatological characteristics of Austria.
- Section 1.2 focuses on the atmosphere and discusses processes relevant to weather and climate in Austria and their response to anthropogenic climate change in the past and the future.
- Section 1.3 covers the cryosphere, including regional/temporal occurrence, drivers and magnitude of past and future changes, and interactions and impacts on other natural systems.
- The subchapter 'Hydrosphere' (Section 1.4) summarizes the understanding and assessment of the impacts of climate change on runoff generation processes and the magnitude, seasonality and frequency of water fluxes in streams, groundwater and lakes, including extremes and water quality.
- The subchapter 'Pedosphere' (Section 1.5) discusses the types and characteristics of soils in Austria, identifies the most important representatives and assesses the effects and feedbacks of climate change and other global change drivers on soils via erosion and the dynamics of organic matter and water.
- The subchapter 'Biosphere' (Section 1.6) focuses on selected important habitats and land use categories (according to the IPCC) that will be strongly affected by climate change and also have important feedback effects on climate change. The effects of a changing climate on biodiversity are summarized across habitats and taxonomic groups.
- The subchapter 'Lithosphere' (Section 1.7) focuses on the description of the Earth's geological and geomorphological processes in Austria, with emphasis on exogenous processes, in particular landslides of various types relevant to the Alpine region of Austria. These processes are strongly controlled by climate.
- The last subchapter (Section 1.8) focuses on the cross-cutting issue of natural hazards, describing those occurring in Austria and their response to anthropogenic climate change. An overview of natural hazard processes and relevant hazard cascades in Austria is summarized in a table (Table 1.A.4).

### 1.1.2 Physiographic setting of Austria

Austria is a small country in Central Europe (see Figure 1.1). It has an area of 84,000 km$^2$ and a population of about 9 million (Statistik Austria, 2023) with an urbanization rate of ~60 % (World Bank, 2023). The population increased by 11.3 % between 2000 and 2020, with the proportion of very old people (80+) increasing from 3.5 % to 5.5 % (Federal Ministry of Social Affairs, Health, Care and Consumer Protection, 2021). Almost two-thirds of the country is mountainous. Austria's high mountain regions are dominated by the Eastern Alps, but the granite and gneiss plateau in the north of the country also reaches heights of 1,379 m a.s.l.

The Alps in Austria extend from the western edge of the country to the far east. At the Großglockner, they reach 3,798 m a.s.l., which is the highest point in the country. Throughout western Austria, peaks exceed 3,000 m a.s.l. While Austria's western regions are entirely in the Alps, east of Salzburg, the granite and gneiss plateau extends to Austria's borders with Germany and the Czech Republic, north of the foothills of the Alps. The east of the country is occupied by lowlands: The Carpathian foothills to the north and the Pannonian Plain farther south. In the southeast, the southeastern foothills of the Alps border Hungary and Slovenia. The lowest point of Austria is located east of Lake Neusiedl, near the border with Hungary, at 114 m a.s.l. Austria's topographic situation has a strong influence on the country's settlement structure, land use, vegetation and climate, including the occurrence and relevance of natural hazards.

Austria's topographic and climatological conditions result in very heterogeneous and diverse landscapes. On the highest mountain peaks, a relevant part of the precipitation currently falls as snow, even in summer, and at altitudes above 3,000 m a.s.l., there are glaciers and permafrost. Thus, several climate zones, from the snow-dominated nival to the wine-growing lowlands, extend over a few tens of kilometers (Rubel et al., 2017). Elevation-dependent air temperature

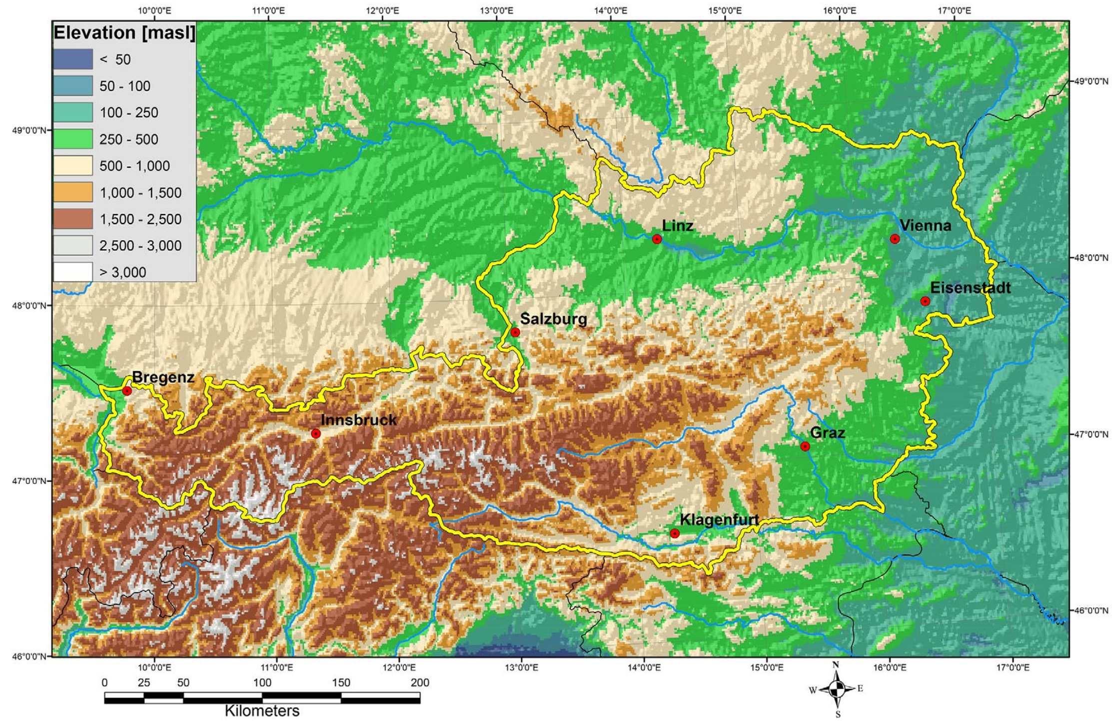



Figure 1.1 Topographic map showing the terrain in Austria (Data source: European Environment Agency, 2016).

variability is influenced by windward and leeward modulated precipitation, leading to small-scale variability of ecosystems. Climate gradients themselves are superimposed by land use pressure and history to shape ecosystem variability. Due to the short distances between different climatic and ecosystem zones, climate change-induced migration of biota can occur immediately, unless there are local (natural or anthropogenic) barriers to migration (Holzinger et al., 2008).

### 1.1.3 Climatological conditions

Due to Austria's location in the mid-latitudes (~48 °N), radiation and temperature show a pronounced seasonal cycle. In the warmest areas of Austria, the lowlands in the east and south, the annual mean temperature reaches 12°C and drops to -6°C on the highest mountain peaks. Extreme daily maximum temperatures reach 40°C in summer and -30°C in winter. These extremely low temperatures are not limited to the mountain peaks. Even in the northeastern lowlands, temperatures below -20°C occur during cold spells (Lhotka and Kyselý, 2015), when continental 'Siberian' air masses are advected to Central Europe.

The Austrian precipitation distribution is dominated by the advection of maritime air masses and the associated windward/downwind effects at mountain ridges. The main source of moisture is the Atlantic, but maritime air masses can also originate from the North, Baltic, Mediterranean or Black Sea, leading to very complex precipitation patterns. The driest area is in the northeast, with an average annual rainfall of nearly 500 mm. In the northern and southern 'Stau-regions' values up to 2500 mm occur (Stangl et al., 2021). Due to windward/downwind effects even nearby mountain valleys, such as the upper Inn valley, receive only 700 mm.

Convective precipitation is an important source of moisture in Austria during the summer half year. Especially areas in the transition zone between the lowlands and the foothills, such as the 'Steirische Randgebirge' or the Upper Austrian foothills, have a high probability of thunderstorms (Schulz et al., 2005) and associated high local short-term precipitation intensities.

Large-scale precipitation extremes are mainly associated with cut-off lows centered at the European Alps (Awan and Formayer, 2017), where warm and moist Mediterranean air is transported to the Alps over several days and precipitation totals of more than 200 mm can be reached.

The hydrological conditions show a similarly high diversity (Merz et al., 2008). Nival-dominated discharge patterns are common for alpine rivers, with low flows in winter and a pronounced discharge maximum during the snowmelt period. In foothill catchments in the east and south, snowmelt plays a minor role and low flows occur not in winter but in summer and fall. Steep terrain and localized heavy precipitation from thunderstorms often lead to pluvial floods and mass movements. Fluvial floods, especially those of the Danube, are caused by completely different processes, such as cut-off lows, but snowmelt and the elevation of the snow line during the precipitation event also contribute to these events.

The first Austrian Assessment Report (APCC, 2014) provides a detailed description of the Austrian climate. In the decade since this report was written, anthropogenic climate change has continued in Austria. Several hot and dry summers, such as during 2015 or 2018, highlighted the vulnerability of Austrian agriculture and especially forestry, as well as the importance of heat mitigation measures in urban areas. Local or temporary water shortages became a topic in the media, and other extreme events such as local flash floods, forest fires, or spring frost damage became more visible to the general public.

## 1.2. Atmosphere

This subchapter discusses the drivers and processes relevant for weather and climate in Austria and their response to anthropogenic climate change in the past and in the future. It describes the current situation and past and future changes based on climatological indicators. Climate change projections are discussed in the context of climate change signal, depending on emission scenarios and general skills and limitations of models at global and regional scale.

Regional climate variability and change result from both natural and anthropogenic forcings external to the climate system, internal climate variability, and feedbacks between them (Doblas-Reyes et al., 2021). Anthropogenic forcings include changes in greenhouse gas concentrations, aerosols, and land use. The strength of the regional response to external forcings is first determined by climate sensitivity, which is the overall temperature response to radiative forcings such as greenhouse gases. Our understanding of this key property of the climate system has improved considerably in recent years. The best estimate of equilibrium climate sensitivity is a 3°C increase in global mean surface temperature (with likely and very likely ranges of 2.5°C to 4°C and 2°C to 5°C, respectively) for a doubling of $CO_2$ concentrations (IPCC, 2021b). A key determinant of regional climate change is changes in atmospheric circulation, i.e., how large-scale to regional-scale winds and weather systems respond to overall temperature changes. Regional feedbacks between the land-surface and the atmosphere further modulate the strength of regional climate changes.

### 1.2.1. Past changes

The current IPCC report (AR6) assesses past global changes back to the deep past (65 million years before present) in Chapters 2 and 11 (observations, weather and climate extremes) (Gulev et al., 2021; Seneviratne et al., 2021). The historical investigations in this subchapter are limited to the period after 1850. This is consistent with the IPCC definition of the 'pre-industrial' period. The focus is on describing climatological changes within this period based on impact-relevant climatological indicators and their dependence on large-scale processes and drivers.

#### Observed changes in global climate drivers

Increases in greenhouse gas concentrations and trends in aerosol concentrations and properties due to anthropogenic activities lead to a net positive effective radiative forcing and an imbalance in the Earth's energy balance, resulting in a warming planet since the late 19th century and at an increasing rate since the 1970s. The change in effective radiative forcing due to natural factors since 1750 is negligible compared to anthropogenic forcings (Gulev et al., 2021).

#### Observed changes in large scale circulation, weather patterns and modes of variability

Since the late 19th century, major modes of climate variability relevant to the European climate, such as the North Atlantic Oscillation (NAO) or the Atlantic Multidecadal Variability (AMV) show no persistent trends but fluctuate in frequency and magnitude on interdecadal time scales. Due to the expansion of the tropical circulation, a poleward shift of extratropical jets and cyclone tracks has been observed since the 1980s, with marked seasonality in the trends. Since the 1970s, there has been a global weakening of surface winds, especially over land in the northern hemisphere (Gulev et al., 2021).

#### Observed changes in selected essential climatic variables in Austria and Europe

*Air temperature*

According to a recent analysis (Chimani et al., 2024), the mean annual air temperature in Austria has increased by 3.1°C since pre-industrial times, from 5.1°C (1850–1900) to 8.1°C in 2024 (Figure 1.2, Table 1.1). Primary drivers (con-

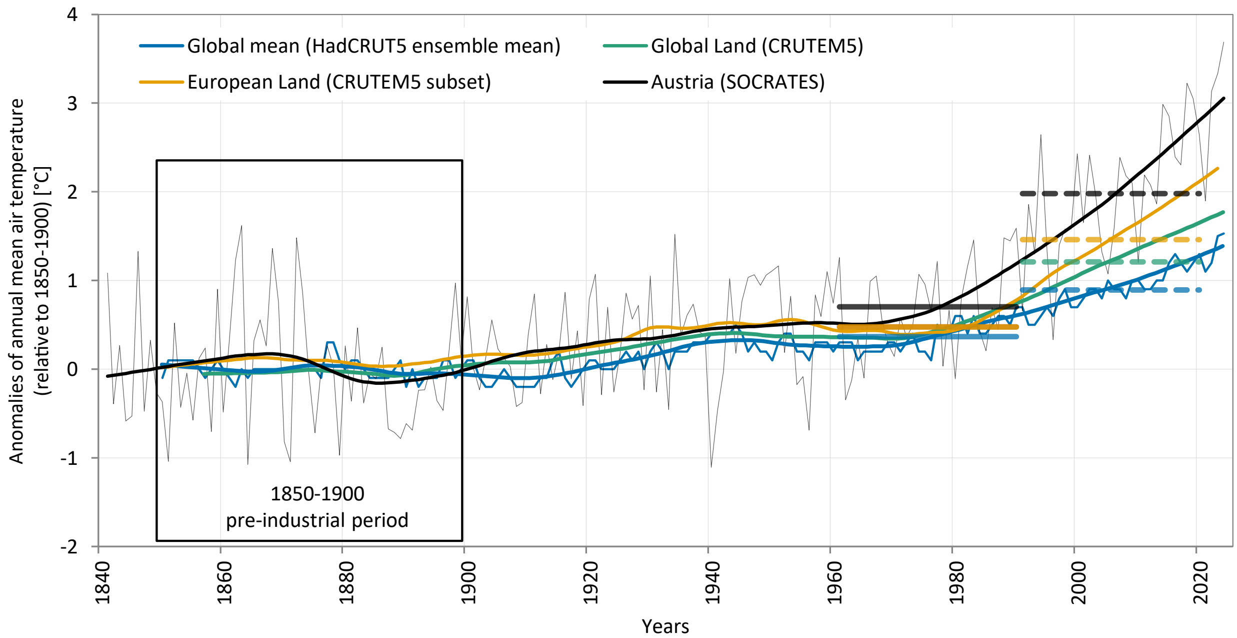



**Figure 1.2** Time series of annual mean air temperature deviations from the pre-industrial mean: Global mean, global land areas, European land areas (bounding box 25 °W – 40 °E, 34 °N – 72 °N) and Austria for the period 1841–2024 (2023 for European land areas). Note that Austrian data is based on 7 homogenized stations and that the global datasets only start in 1850. Thin lines show annual values (for clarity only shown for Austria and the global mean). Thick lines are smoothed with a 42-year LOESS filter. Horizontal lines show the mean values of the 30-year climate normals (1961–1990, solid; 1991–2020, dashed) (Data sources: Geosphere Austria; Auer et al., 2007; Morice et al., 2021; Chimani et al., 2024).

tribution of ~70 %) of this excessive warming compared to the global average are regional thermodynamic and dynamical forcings in large parts of Europe, as described below. Secondary drivers (contribution of ~30 %) are related to heat capacity (faster warming of air over land) and latent heat fluxes (evaporative cooling over oceans) as well as the different scales (IPCC, 2019a; Chimani et al., 2021).

As a primary driving component of the excessive warming, the regional thermodynamic forcing is dominated by increasing incoming near-surface solar radiation in large parts of Europe since the 1980s. This is due to a 50 % decrease of aerosol loads (Glantz et al., 2022; Philipona et al., 2023; Schumacher et al., 2024) and a decrease in cloudiness associated with the indirect aerosol effect and large-scale atmospheric circulation changes (Sfîcă et al., 2021). Schumacher et al. (2024) estimate the relative contributions of these two effects to be two thirds (aerosols) and one third (dynamic circulation effect), respectively. From a temporal perspective, the aerosol effect is mainly restricted to the period 1983–2002, while the cloudiness effect unfolds in the period 2001–2020 (Schilliger et al., 2024). A reduced cooling effect due to less aerosols unmasks the thermal greenhouse warming effect (increasing thermal longwave downward radiation) due to steadily increasing anthropogenic greenhouse gas concentrations in the atmosphere (Philipona et al., 2023) and readjusts the shortwave clear-sky transmissivity of the atmosphere to pre-1950s values (Wild et al., 2021) and beyond (the latter due to circulation changes). In addition to the strong reduction of aerosol loads, positive regional feedbacks, especially the soil moisture (Haslinger et al., 2021; Glantz et al., 2022) and snow/ice albedo (Kiem et al., 2024) feedbacks, amplify the regional thermodynamic effect, leading to the fact that Europe has warmed faster than any other World Meteorological Organization region since the 1980s (Schumacher et al., 2024); in Austria with an enormous rate of almost 0.5°C per decade. Moreover, a large part of the warming since pre-industrial times has occurred in the last four decades since 1980, and the five-year period 2019–2023 was already 2.7°C warmer than in pre-industrial times (Table 1.1). The observed warming of global land masses (CRUTEM data) exceeds global average warming by a factor of at least around 1.3. Since this discrepancy is mainly attributed to different heat capacities, it is expected to hold as lower limit for future temperature development.

Within Austria, the long-term variations of the annual air temperature show a large spatial concordance. There are no significant regional or altitudinal differences. In mountainous regions, the atmosphere warmed by the same amount as in the lowlands (Auer et al., 2007; Kuhn and Olefs, 2020). Air temperature variations in the free atmosphere at about

Table 1.1 Mean air temperature deviations from the pre-industrial average (1850–1900) for different regions during the 30-year average periods 1961–1990, 1991–2020 and the 2023 and 2024 values, respectively.
* defined by the bounding box 25 °W – 40 °E, 34 °N – 72 °N;
** derived from the 41-year smoothed value (LOESS filter).

| Climate normals (30-year average periods) | Global mean (HadCRUT5 ensemble mean) [°C] | Global land areas (CRUTEM) [°C] | European land areas (CRUTEM subset*) [°C] | Austria (SOCRATES) [°C] |
|---|---|---|---|---|
| 2024** | 1.4 | 1.8 | n/a | 3.1 |
| 2023** | 1.32 | 1.71 | 2.26 | 3.0 |
| 1991–2020 | 0.89 | 1.21 | 1.47 | 1.98 |
| 1961–1990 | 0.37 | 0.48 | 0.48 | 0.7 |

3,000 m a.s.l. derived from radiosonde data are very similar to the time series recorded at summit stations (Haimberger et al., 2012). This lack of observed elevation dependence based on Austrian station data contrasts with future temperature projections (see Section 1.2.2 and Chapter 7) and analyses of gridded datasets in the greater Alpine region (Pepin et al., 2022), which show stronger warming at mid to high elevations. As many mechanisms for elevation dependence operate simultaneously, some independently, most of them interconnected by feedbacks, this discrepancy may be due to model simplification (e.g., too coarse spatial resolution, parameterizations) or to the fact that relevant processes have not yet been triggered (Kuhn and Olefs, 2020; Pepin et al., 2022).

From a seasonal perspective and based on homogenized long-term observations, the warming in the lowlands during the period 1991–2020 vs. 1850–1900 is strongest in spring and winter (+2.1°C and +2.3°C, respectively), followed by summer (+2.0°C), and weakest in autumn (+1.4°C). The only significant warming difference between lowland and summit regions is observed in winter (+2.3°C vs. +1.7°C) (Kuhn and Olefs, 2020). This may be due to the reduction of aerosols at their highest concentration near ground sources, which contributes to stronger warming at low elevations (Philipona et al., 2009; Philipona, 2013).

Smaller-scale phenomena such as temperature inversions are associated with the accumulation of pools of cold air near the surface. An analysis of daily gridded observational data in the period 1961–2017 shows that inversions have become less frequent and less intense, especially in the months of October, December, and January in southern Austria and near the main Alpine ridge (Hiebl and Schöner, 2018).

The marked temperature increase since 1980 has led to pronounced changes in temperature dependent extreme values. For example, the number of summer days and hot days (daily maximum temperature ≥25°C and ≥30°C, respectively) in the Austrian lowlands increased significantly by 40 % and 66 %, respectively (see Table 1.2). The number of hot days in very hot years (occurring with a statistical return period of 10 years) has tripled between the periods 1961–1990 and 1991–2020 on average over Austria (GeoSphere Austria, 2020). In addition, heatwaves have increased in intensity, duration and frequency in the Austrian federal province capitals: In the period 1991–2020 compared to 1961–1990, heatwaves became 50 % more frequent and 1 to 4 days longer (GeoSphere Austria, 2023a). In urban areas, heat stress is intensified during the day and at night (urban heat island effect) (Oke et al., 2017). In Austrian province capitals, the number of hot days increased by 6 to 14 days (factor of 1.5 to 4.3) in the 30-year period 1991–2020 compared to 1961–1990. In the same period, tropical nights (daily minimum temperature ≥20°C) increased by up to 5 days.

As of 2024, a record number of 29 to 52 hot days in a single year is recorded in these cities (GeoSphere Austria, 2023b). In addition to these increasing mean and extreme temperature values, the available literature shows no significant long-term change in temperature variability on synoptic time scales in Austria since the end of the 19th century (Hiebl and Hofstätter, 2012).

In general, annual and multi-decadal variations are superimposed on the long-term anthropogenic warming trend. Due to atmosphere-ocean feedbacks and the relative importance of circulation changes during the cold season, winter temperatures in Austria show the largest variability of all seasons. After a short cooling phase (between 1995–2005 in the lowlands and 1989–2012 in the summit regions) induced by natural variability and associated atmospheric circulation changes (Saffioti et al., 2016), winter temperatures started to increase again (Olefs et al., 2021).

Finally, the observed temperature increase in Austria is confirmed by independently measured air pressure time series at different elevations (Kuhn and Olefs, 2020).

**Table 1.2** Selected prime climatic indicators for the national territory of Austria. Definitions of the indicators used in Chapter 1 are given in Table 1.A.1.

| Short name | altitudinal range (m a.s.l.) | | ≤500 m | | | | 501–1,000 m | | | | 1,001–1,500 m | | | | 1,501–2,000 m | | | | ≥2,001 m | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Indicator name | Unit | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) |
| *su25* | *summer days* | *d* | 45 | 64 | +19 | +42 | 25 | 39 | +14 | +56 | 7 | 15 | +8 | +114 | 1 | 2 | +1 | +100 | 0 | 0 | 0 | |
| *su30* | *hot days* | *d* | 6 | 16 | +10 | +167 | 2 | 6 | +4 | +200 | 0 | 1 | +1 | | 0 | 0 | 0 | | 0 | 0 | 0 | |
| *tr20* | *tropical nights* | *d* | 0 | 1 | +1 | | 0 | 0 | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | |
| *kys* | *heat episodes (kysely days)* | *d* | 4 | 14 | +10 | +250 | 0 | 4 | +4 | | 0 | 0 | 0 | | 0 | 0 | 0 | | 0 | 0 | 0 | |
| *cool* | *cooling degree days (20°C tresh)* | *°C* | 43 | 107 | +64 | +149 | 9 | 34 | +25 | +278 | 1 | 5 | +4 | +400 | 0 | 0 | 0 | | 0 | 0 | 0 | |
| *gsl* | *vegetation period (5°C)* | *d* | 224 | 235 | +11 | +5 | 196 | 208 | +12 | +6 | 166 | 180 | +14 | +8 | 123 | 142 | +19 | +15 | 52 | 75 | +23 | +44 |
| *fd0* | *freezing days* | *d* | 104 | 90 | -14 | -13 | 134 | 117 | -17 | -13 | 163 | 146 | -17 | -10 | 191 | 173 | -18 | -9 | 245 | 224 | -21 | -9 |
| *id0* | *ice days* | *d* | 29 | 22 | -7 | -24 | 41 | 32 | -9 | -22 | 56 | 44 | -12 | -21 | 82 | 67 | -15 | -18 | 149 | 128 | -21 | -14 |
| *id7* | *extreme ice days* | *d* | 17 | 11 | -6 | -35 | 27 | 18 | -9 | -33 | 40 | 30 | -10 | -25 | 61 | 48 | -13 | -21 | 115 | 95 | -20 | -17 |
| *hdd* | *heating degree days* | *°C* | 3662 | 3306 | -356 | -10 | 4384 | 3976 | -408 | -9 | 5232 | 4796 | -436 | -8 | 6196 | 5723 | -473 | -8 | 7647 | 7189 | -458 | -6 |
| *rr1* | *precipitation days (1 mm)* | *d* | 112 | 110 | -2 | -2 | 135 | 134 | -1 | -1 | 143 | 143 | 0 | +0 | 149 | 149 | 0 | +0 | 150 | 153 | +3 | +2 |
| *rr20* | *heavy precipitation days (20 mm)* | *d* | 6 | 7 | +1 | +17 | 10 | 12 | +2 | +20 | 15 | 16 | +1 | +7 | 17 | 18 | +1 | +6 | 17 | 18 | +1 | +6 |
| *sdii* | *precipitation intensity* | *mm* | 6.4 | 6.7 | +0 | +5 | 7.6 | 7.9 | +0 | +4 | 8.7 | 9 | +0 | +3 | 9.1 | 9.4 | +0 | +3 | 8.9 | 9.3 | +0 | +4 |

| Short name | altitudinal range (m a.s.l.) | | ≤500 m | | | | 501–1,000 m | | | | 1,001–1,500 m | | | | 1,501–2,000 m | | | | ≥2,001 m | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Indicator name | Unit | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) | 1961–1990 | 1991–2020 | diff. | diff. (%) |
| *rx5day* | *max. 5-day precipitation* | *mm* | 70 | 77 | +7 | +10 | 91 | 97 | +6 | +7 | 108 | 111 | +3 | +3 | 116 | 119 | +3 | +3 | 115 | 121 | +6 | +5 |
| *cdd* | *longest dry period* | *d* | 24 | 24 | 0 | +0 | 21 | 21 | 0 | +0 | 20 | 20 | 0 | +0 | 20 | 20 | 0 | +0 | 19 | 19 | 0 | 0 |
| *hd1525* | *dry hiking days* | *d* | 100 | 86 | -14 | -14 | 83 | 82 | -1 | -1 | 67 | 71 | 4 | +6 | 40 | 47 | 7 | +18 | 10 | 16 | 6 | 60 |
| *cloudy* | *number of cloudy days* | *d* | 149 | 136 | -13 | -9 | 149 | 137 | -12 | -8 | 141 | 130 | -11 | -8 | 143 | 134 | -9 | -6 | 145 | 137 | -8 | -6 |
| *clear* | *number of clear days* | *d* | 69 | 86 | +17 | +25 | 76 | 88 | +12 | +16 | 88 | 93 | +5 | +6 | 93 | 96 | +3 | +3 | 98 | 98 | 0 | 0 |
| *SPEI* | *climatic water balance (normalized)* | - | 0.10 | -0.10 | -0.20 | | -0.01 | 0.00 | 0.01 | | -0.01 | 0.00 | 0.01 | | 0.02 | 0.00 | -0.02 | | -0.02 | 0.08 | 0.10 | |
| *CWB* | *climatic water balance (abs)* | *mm* | -60 | -90 | -30 | +50 | +337 | +339 | +2 | +1 | +556 | +558 | +2 | +0 | +658 | +650 | -8 | -1 | +740 | +752 | +12 | +2 |

*Drought conditions*

Meteorological droughts are prolonged periods of below-normal water availability due to a lack of precipitation and/or increased atmospheric evaporative demand (i.e., potential evapotranspiration). An important driver of droughts are anomalies in atmospheric circulation that result in frequent and often persistent anticyclonic weather patterns (Haslinger et al., 2019; Lhotka et al., 2020). In northern Europe, the North Atlantic Oscillation (NAO) is of great importance in this respect, but less so in the Alpine region. In Austria, the East Atlantic-Western Russia (EAWR) circulation pattern explains the occurrence of early spring drought (Ionita et al., 2020; Haslinger and Mayer, 2022). Spring droughts often lead to soil moisture-temperature feedbacks, which may contribute to elevated temperatures during summer droughts (Seneviratne et al., 2010; Haslinger and Blöschl, 2017). When meridional circulation features dominate during the summer season, large-scale moisture transport is reduced and local moisture recycling is enhanced. In already dry soils, insufficient moisture is available for local evapotranspiration processes and precipitation deficits occur (soil moisture-precipitation feedback) (Haslinger et al., 2021). The seasonality of drought events has shifted from predominantly winter and spring events in the 19th century to late summer/autumn events. This seasonal shift is accompanied by a spatial change from the northwest to the southeast of Austria (Haslinger and Blöschl, 2017).

There are no significant trends in the frequency, duration and intensity of precipitation deficits in Austria over the last two centuries for which instrumental records are available (Haslinger and Blöschl, 2017; Hanel et al., 2018). However, periods with distinct negative precipitation anomalies are observed, most notably the 'drought decades' of the 1860s and 1940s (Brunetti et al., 2009; Haslinger et al., 2019). The current sequence of drought years (e.g., 2015, 2018, 2021) may be indicative of the manifestation of another drought decade, as drought drivers similar to those of the 1860s and 1940s are at play more recently; namely very dry springs followed by atmospheric circulation characteristics that favor a positive soil moisture-precipitation feedback during the summer. Furthermore, longer drought reconstructions for the last millennium and beyond based on paleoclimate archives such as tree-ring widths (Ionita et al., 2021) and stable isotopes in tree-rings (Büntgen et al., 2021) for Central Europe are contradictory and do not allow a definitive conclusion. However, potential evapotranspiration increased during the period 1977–2014, mainly due to changes in global radiation, but also due to increases in air temperature (Duethmann and Blöschl, 2018), leading to drier soil conditions during the summer half year (Trnka et al., 2009). Higher temperatures also resulted in an earlier onset of the vegetation period and thus a longer evaporation season (Duethmann and Blöschl, 2018), leading to drier conditions during the warm season and, in particular, promoting heat waves (Haslinger and Blöschl, 2017).

The climatic water balance (CWB) is defined as the difference between precipitation and atmospheric evaporative demand and is often used in drought research and monitoring (here mostly as a standardized indicator, e.g., Standardized Precipitation Evapotranspiration Index – SPEI). Comparing two 30-year periods (1961–1990 vs. 1991–2020), the annual CWB in lowland areas (<500 m a.s.l.) decreased by 30 mm, mainly due to an increase in atmospheric evaporative demand. This change is rather small compared to the inter-annual variability of 107 mm (standard deviation of the annual CWB 1961–2020). In contrast, higher elevation areas show no clear change, although in the high alpine regions (>2,000 m a.s.l.) an increase of 12 mm is visible, which is still a rather small increase compared to the mean annual CWB from 1991–2020 of 752 mm (see Table 1.2).

Drought impact inventories in the Alpine region, as well as for Austria specifically, show an increasing trend of reported impacts within the last 45 years, especially after 2000. However, this increase could be influenced by reporting behavior, accessibility as well as awareness of the drought hazard (Stephan et al., 2021).

*Precipitation, including convection and associated impacts*

Opposing long-term precipitation trends are found in different regions, especially in winter: In western (Vorarlberg, northern Tyrol) and southeastern Austria (parts of Carinthia, western and eastern Styria, southern Burgenland), precipitation totals have increased and decreased by about 10 % and 15 %, respectively, over the last 200 years (Auer, 2014).

An analysis based on the Austrian-wide gridded observation-based precipitation dataset SPARTACUS (Hiebl and Frei, 2018) shows an increase in the annual number of days with heavy (95–98th percentile) to extreme (>98th percentile) precipitation from 1961 to 2014, especially in autumn and summer. This corresponds to a shift in intensities, as the number of days with weak to moderate precipitation decreases. This finding is supported by homogenized daily station data. Table 1.2 shows that the number of heavy precipitation days and the maximum 5-day precipitation sum have increased by 11 %

and 5 %, respectively, in the period 1991–2020 compared to 1961–1990. Especially for large-scale heavy precipitation events caused by distinct low-pressure systems (e.g., 'Vb cyclones'), slightly increasing trends are found for the period 1961–2015 for the northern edge of the Alps (Hofstätter et al., 2018). In September 2024, such an event led to extreme precipitation totals in Central Europe. In Austria, new records for 5-day precipitation totals above 400 mm were set over Upper and Lower Austria and Vienna (Greilinger et al., 2024). In the Tulln area, the previous record of 143 mm was more than doubled. This led to very high water levels in the rivers, even in the Danube, where discharge values with a return period of 30 years were reached. Flood levels in the rivers of the Vienna Woods exceeded the 300-year return period (e.g., Traisen) (Krammer et al., 2024). According to the results of a preliminary attribution study, anthropogenic climate change doubled the probability of this event and made the rainfall 7 % more intense (Kimutai et al., 2024).

Small-scale heavy precipitation events are tied to convection and occur especially in the summer half year. Due to the low density of conventional meteorological measurement networks and the low temporal resolution of measurements before automation in the late 1980s, no reliable estimates of past trends in convective precipitation events and thunderstorms are currently possible in Austria (Pistotnik et al., 2020). This also applies to all phenomena associated with convective events such as hail and tornadoes.

An analysis of extreme hourly precipitation totals (99th percentile) at the Vienna Hohe Warte shows an increase of up to 10 % per °C temperature rise (Formayer and Fritz, 2016). Considering shorter time scales, Schroeer and Kirchengast (2018) found values of up to 14 % per °C based on extreme 10-minute precipitation sums (98th percentile) in southeastern Austria. Both rates clearly exceed the theoretical value given by the Clausius-Clapeyron law, which is confirmed by numerous studies of convective precipitation events (Ivancic and Shaw, 2016; Lochbihler et al., 2019). Increasing latent heat of condensation due to rising air humidity increases instability and thus intensifies convection and precipitation (Lenderink and Van Meijgaard, 2008, 2010).

From a European and global perspective, there is strong evidence that heavy precipitation has increased in recent decades due to anthropogenic forcing in many parts of Europe and the world, although regional differences are evident (Lehmann et al., 2015; Fischer and Knutti, 2016; Fowler et al., 2021; IPCC, 2021a; Robinson et al., 2021; De Vries et al., 2023). Results from a statistical model validated with event data and driven by gridded observational data in the period 1979 to 2016 (ERA-interim) show an increase in the probability of occurrence of thunderstorms, strong winds, and large hail events (Rädler et al., 2018). In addition, Maraun et al. (2024) set up a statistical model for the European domain that relates observed impacts of convective events (local flooding, hail, downbursts etc.) to atmospheric variables indicating convective potential (e.g., Lifted Index) to derive potential days with impactful convective events. The model is applied to ERA5 data from 1950 to 2022. A general increase in the number of days with convective events is found, independent of atmospheric circulation characteristics, due to increasing temperatures and potential for atmospheric instability and convection during the warm season. For example, convective events classified as 'severe' (associated with an orange weather warning (level 2 of 3)) increased by 15 % (1991–2020 vs. 1961–1990). Simon et al. (2023) found a corresponding increase in the annual and diurnal cycles of lightning in the high alpine region as well as on the northern and southern alpine rim.

Although no long-term change in annual precipitation totals can be detected for Austria, seasonal sums show clear regional trends. Multi-day, daily and short-duration (hourly) heavy precipitation events indicate clear increasing trends in recent decades with the latter being most strongly related to anthropogenic warming and associated with other potentially harmful small-scale but intense impacts (e.g., local flooding, strong wind gusts, hail and lightning).

*Sunshine duration*

Since the end of the 19th century, a two-stage increase in observed sunshine duration can be observed in Austria: The first until the middle of the 20th century, the second since the 1980s. A dimming phase between 1950 and 1980 interrupts these increases. The changes are more pronounced at low altitude stations (Auer et al., 2007; Kuhn and Olefs, 2020). The similarity of this trend with observed temperatures and solar surface radiation indicates an important role of solar radiation in explaining the larger temperature increase in Austria and parts of Europe compared to the global land areas (Scherrer and Begert, 2019; Philipona et al., 2023) (see also Figure 1.2 and Sections Air temperature as well as Radiation fluxes and cloudiness). Since 1961, observed sunshine duration in Austria has increased by 13.9 % to 14.8 %, according to a newly available gridded dataset and homogenized long-term time series (Hiebl et al., 2024). By definition, changes in sunshine duration are driven by changes in the direct component of surface solar radiation.

*Radiation fluxes and cloudiness*

There is strong observational evidence that the amount of solar radiation received at the Earth's surface undergoes significant multidecadal variations that are internal to the Earth's atmosphere and not externally forced by the Sun. Coherent periods and regions of dominant decreases ('dimming') and increases ('brightening') in surface solar radiation have been detected in the global observational networks (Wild, 2009; Wild et al., 2021), often coinciding with anthropogenic air pollution patterns (Nabat et al., 2014; Pfeifroth et al., 2018; Glantz et al., 2022). In Europe and Austria, three typical periods can be found in the observations: the 'early brightening' (1940s), the subsequent dimming (1950s to 1980s) and the still ongoing brightening phase (since the 1980s) (Manara et al., 2016; Kuhn and Olefs, 2020; Philipona et al., 2023).

In recent years, several studies have investigated and discussed the relative contributions of aerosol vs. large-scale circulation (i.e. cloudiness) changes in causing the current brightening phase in Central Europe (Sfîcă et al., 2021; Wild et al., 2021; Julsrud et al., 2022; Manara et al., 2023). Using satellite data, a recent study by Schilliger et al. (2024) attributes the increasing surface solar radiation in the periods 1983–2002 and 2001–2020 mainly to aerosol and cloudiness changes, respectively. The study by Ferreira Correa et al. (2024) points out that changes at low altitude stations are dominated by a strong clear sky forcing, in contrast to high altitude stations where changes are more related to cloud optical properties and surface albedo.

Based on data from twenty stations in Switzerland, the actual increase in net surface solar radiation is as much as 30 % greater than the observed increase in downward thermal longwave radiation due to increasing anthropogenic greenhouse gas concentrations in the atmosphere, which is the strongest regional-scale driver of climate change in central Europe since 1980 (Philipona et al., 2023). For Austria, surface solar radiation time series are currently being homogenized (Seitner et al., 2023) and downward thermal longwave time series have only been established since 2010 (Olefs et al., 2016).

*Storminess*

Existing studies show no long-term trend in past observed European storminess (extratropical storms with wind speeds of more than 75 km/h or 9 Beaufort) (Matulla et al., 2008, 2020; Feser et al., 2015).

### 1.2.2. Future changes

In the following, we present an overview of the projected changes in key climate indicators for Austria. These changes are driven by the interplay between large-scale changes in temperature and atmospheric circulation and local processes and feedbacks (Section 1.2). The projected changes in these processes are affected by various sources of uncertainty. Therefore, a discussion of projection uncertainties and the large-scale context of climate change in Austria is presented first. The indicators presented are, unless otherwise indicated, derived from the Austrian climate scenarios ÖKS15 (Chimani et al., 2016; Truhetz and Leuprecht, 2018; Chimani et al., 2019; Maraun et al., 2021), which are a bias-adjusted variant of a series of EURO-CORDEX simulations. Figures for a selection of indicators are shown below, with additional figures provided in the Appendix (Figures 1.A.4, 1.A.5, 1.A.6). Definitions of the indicators used in Chapter 1 are given in Table 1.A.1.

#### Uncertainties in regional climate projections

Climate projections are affected by three main sources of uncertainty (IPCC, 2021a): Forcing uncertainty, climate response uncertainty and internal variability. Forcing uncertainty refers to the fact that future climate forcings are inherently unpredictable. In particular, greenhouse gas emissions depend on current and future political, economic and social decisions. Therefore, a range of plausible concentration pathways and shared socio-economic pathways has been constructed to explore how different socio-economic developments may affect future climate. Uncertainty in climate response refers to the fact that we do not fully understand the climate system and also have limited computational resources to model it. This uncertainty is particularly important at the regional scale and for extreme events, and is influenced by global-scale uncertainty in climate sensitivity, uncertainties in changes in large-scale atmospheric circulation, and regional processes and feedbacks (Chen et al., 2021). A major contributor to uncertainty in climate response is tipping elements (see Chapter Box 1.2). Multi-model ensembles are used to capture uncertainty in climate response. However, these ensembles cannot fully quantify the uncertainty arising from systemic model bias, where model projections do not cover the true range of plausible future climate states.

Also, internal variability is a major source of uncertainty at the regional scale (Figure 1.3). As a result, multidecadal trends at the local scale may be substantially different –

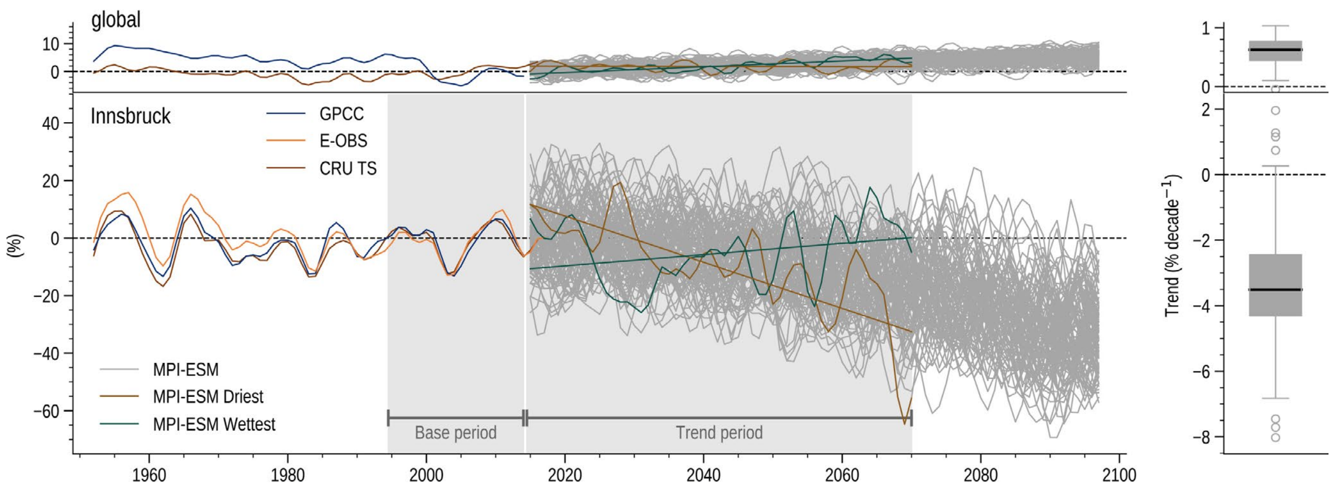



Figure 1.3 Internal variability as a source of uncertainty in regional climate projections. The left panels show observed and projected summer precipitation, globally (top) and for Innsbruck (bottom). Gray lines indicate individual simulations with different random realizations of internal climate variability. The green and brown lines depict the strongest positive and negative trends over 50 years. The right panels show the corresponding box plots of the 50-year trends. From Maraun and Jury (2022). This figure is based on data from the MPI large ensemble (Maher et al., 2019).

stronger, weaker or even opposite – to those expected from increasing greenhouse gas concentrations (Doblas-Reyes et al., 2021). Initial condition ensembles have been used to sample uncertainties due to internal variability. In general, uncertainties are not fully sampled by climate models, i.e., they are larger than the simulated model spread (Doblas-Reyes et al., 2021). Global warming levels have been proposed to resolve uncertainties in global forcing and climate sensitivity by expressing changes relative to a given level of global mean temperature increase (Chapter Box 1.1).

## Large-scale context of Austrian climate change

### *Global and European temperature and precipitation projections*

For all emission scenarios considered by the IPCC, the global surface temperature will continue to rise until at least mid-century (*high confidence*) (IPCC, 2021a). Global warming of 1.5°C and 2°C will be exceeded during the 21st century unless deep reductions in $CO_2$ and other greenhouse gas emissions occur in the coming decades (IPCC, 2021a). Assuming a continuation of current policies, anthropogenic greenhouse gas emissions are projected to lead to a median global warming of 2.7°C [2.2 to 3.4°C] by 2100 (Climate Action Tracker, 2024) (*high confidence*). In the worst-case scenario SSP5–8.5, the global mean surface temperature is projected to increase by 3.3 to 5.7°C (very likely range) in the period 2081–2100 compared to 1850–1900. Such increases would be associated with drastic changes in the climate system, including increased frequency and intensity of hot extremes, ocean heat waves, heavy precipitation, and, in some regions, agricultural and ecological droughts (IPCC, 2021a). Some tipping points are also likely to be crossed (see Chapter Box 1.2).

In Europe, mean temperatures are projected to increase more than the global average, as land surfaces warm faster than oceans (IPCC, 2021a). In winter, polar amplification causes the strongest changes towards the northeast, while in summer the strongest changes are expected over the Mediterranean. For the IPCC region Western Central Europe (WCS) to which Austria belongs, the annual mean changes from 1850–1900 to 2081–2100 under a worst-case scenario (SSP5–85) range from 5°C in the EURO-CORDEX ensemble to 5.8°C in the CMIP5 ensemble and 6.2°C in the CMIP6 ensemble. These changes are slightly higher in summer and lower in winter. Under a scenario compatible with the Paris Agreement (SSP1–2.6, with overshoot) these changes could be limited to values between 1.7°C (EURO-CORDEX), 1.9°C (CMIP5) and 2.0°C (CMIP6). Changes in EURO-CORDEX, and thus also in ÖKS15, are likely to be underestimated because several models may not have included changes in greenhouse gas concentrations in the European domain (Jerez et al., 2018).

Regional changes in precipitation are determined by the interplay of the Clausius-Clapeyron relationship (warmer air can hold about 7 % more water vapor) and regional changes in atmospheric circulation (Pfahl et al., 2017; Ritzhaupt and Maraun, 2024). As a result, a strong north-south gradient over Europe is expected: Mean precipitation is projected to increase in northern Europe and decrease in southern Europe. Although the exact location of the transition zone is uncertain, it robustly shifts to the north in summer and to the south in winter (Ritzhaupt and Maraun, 2023). On an annual average, Austria is close to this transition zone.

*Weather patterns and storm projections over the Atlantic and Europe*

As discussed in Section 1.2.1, regional climate and weather extremes in Austria are also controlled by large-scale weather patterns. In winter, the North Atlantic jet is projected to strengthen over the Atlantic and slightly expand into Europe (Harvey et al., 2020). These jet changes are associated with a strengthening of the North Atlantic storm track and its slight expansion into Europe. In the summer, the North Atlantic jet is expected to shift northward, associated with a weakening and slight northward shift of the storm track (Harvey et al., 2020).

In the winter season, climate models project a strong increase in the number of days with a positive North Atlantic Oscillation (NAO), a slight increase in the number of days with a negative NAO, and a significant decrease in the number of days with both Scandinavian blocking and the North Atlantic Ridge (Woollings et al., 2018; Davini and D'Andrea, 2020; Fabiano et al., 2021). The persistence of positive NAO regimes is projected to increase slightly, that of negative NAO to remain constant, and that of the Scandinavian blocking and the North Atlantic Ridge to decrease slightly (Fabiano et al., 2021; Dorrington et al., 2022). A slight decrease in the number of blocked days is also projected for summer (Woollings et al., 2018; Davini and D'Andrea, 2020). There are no studies on changes in the persistence of summer blocking. The frequency of cut-off lows over Europe is projected to increase slightly, with long-lasting events showing a substantial increase in spring and summer (Mishra et al., 2025).

All of the changes described above characterize the average changes across the CMIP climate model ensembles. Simulated changes for individual models may be much stronger, and for weak multi -model mean changes they may even be of opposite sign. Overall, there is only *medium confidence* in changes in atmospheric circulation, and they represent a large source of uncertainty in regional climate change (Shepherd, 2014; Doblas-Reyes et al., 2021).

Various regional feedbacks, including soil moisture-temperature coupling and snow-albedo feedbacks, can further amplify or dampen regional climate changes (Doblas-Reyes et al., 2021).

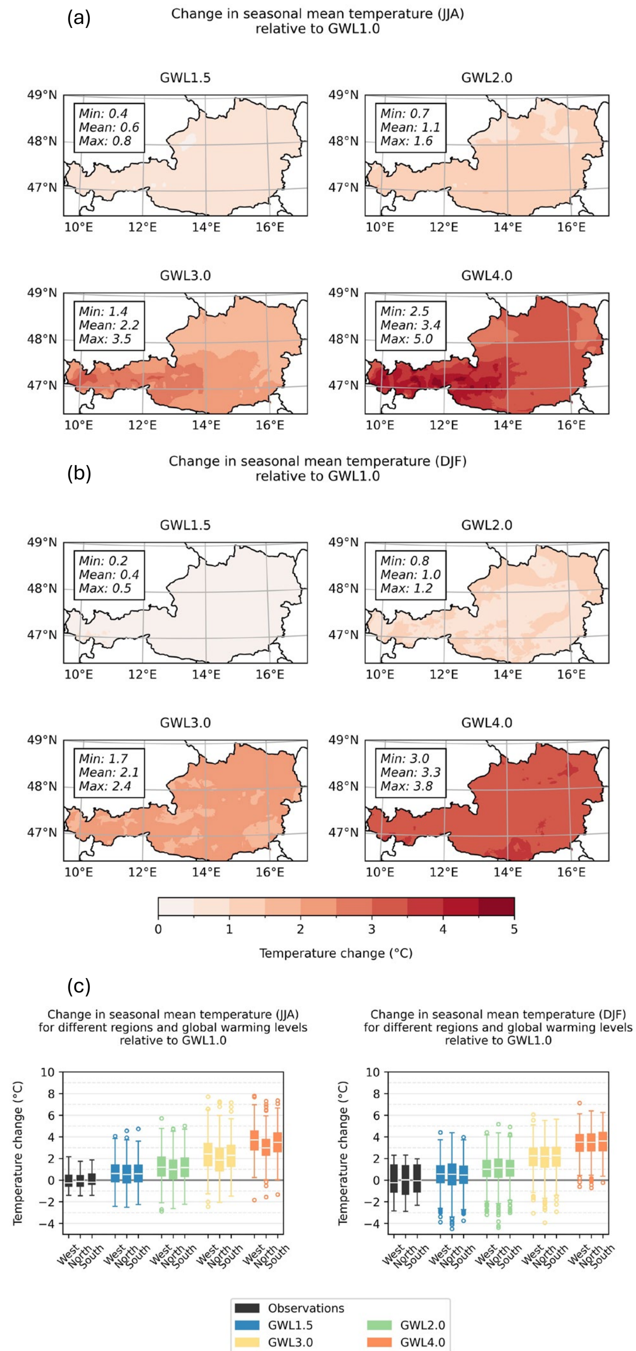



**Figure 1.4** Projected changes in seasonal mean temperature for (a) summer (July-August) and (b) winter (December–February) for different warming levels, based on ÖKS15 simulations. Observations are derived from SPARTACUS data. Maps depict ensemble mean changes, (c) boxplots show both inter-annual and ensemble range of changes for three regions in Austria. The regions associated with the labels 'West', 'North' and 'South' can be seen in Figure 1.A.3. The changes are calculated as averages (a, b) or annual values (c) of the periods at GWL 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C. They relate to averages at GWL 1.0°C, which corresponds to the period 2001–2020 for the observations and different periods for each ÖKS15 model. The black bar in the boxplots (c) shows annual anomalies from the average of the period 2001–2020. Observations for the indicators shown in this figure are presented in Figure 1.A.7. Data sources: ÖKS15 and SPARTACUS (Truhetz and Leuprecht, 2018; GeoSphere Austria, 2020).

## Temperature projections

Consistent with our physical understanding, seasonal mean temperatures over Austria are clearly projected to increase for all seasons with increasing levels of global warming (*high confidence*), based on simulations with CMIP3, 5 and 6 global climate models (Meehl et al., 2007; IPCC, 2014b; Lee et al., 2021), and the regional climate models PRUDENCE, ENSEMBLES and EURO-CORDEX (Christensen and Christensen, 2007; van der Linden and Mitchell, 2009; Jacob et al., 2014). These changes are most pronounced over high terrain, as can be seen for the ÖKS15 simulations (see Figure 1.4, see also Section Elevation dependencies). These changes are also higher than the global mean, mainly due to the stronger warming over land.

In addition to the warming that happened in Austria up to GWL 1.0°C (which occurred in the period 2001–2020), annual mean temperatures are expected to rise by 0.54°C, 1.08°C, 2.19°C and 3.36°C (average of the ÖKS15 ensemble at GWL 1.5°C, GWL 2.0°C, GWL 3.0°C, and GWL 4.0°C, respectively). Mean temperatures are projected to further increase in all seasons with increasing levels of global warming. At GWL 4.0°C, the warming is strongest in summer (+3.4°C), fall (+3.4°C), and winter (+3.3°C), and slightly weaker in spring (+2.7°C) according to the ÖKS15 simulations (Truhetz and Leuprecht, 2018) (Figure 1.4 and Figure 1.A.4).

These changes are accompanied by an increase in heat stress, indicated by a higher number of hot days and tropical nights (Figure 1.5), and a reduction in cold stress, exemplified by a reduced number of ice days and extreme ice days.

As a result of rising mean temperatures, the length and severity of heat waves are also projected to increase. Changes in heat extremes tend to be stronger than changes in mean temperatures because of an increase in temperature variability over central Europe in response to a strengthening of the soil moisture-temperature coupling (Seneviratne et al., 2006; Fischer et al., 2012). Overall, there is *high confidence* that heat extremes in Austria will become more severe in a warming climate. For example, the number of hot days in a very hot year occurring once in 10 years in the past (climate period 1961–1990) will likely multiply by 3.5 GWL 1.5°C, by 4.3 at GWL 2.0°C, by 5.7 at GWL 3.0°C, and even by 8.1 at GWL 4.0°C on average for Austria. In addition, the average temperature of heat waves will likely increase by 6.6°C at GWL 4.0°C compared to the climate period 1961–1990 (*robust evidence, low agreement*).

In response to rising temperatures, the vegetation period is projected to start earlier and become longer. The relevance

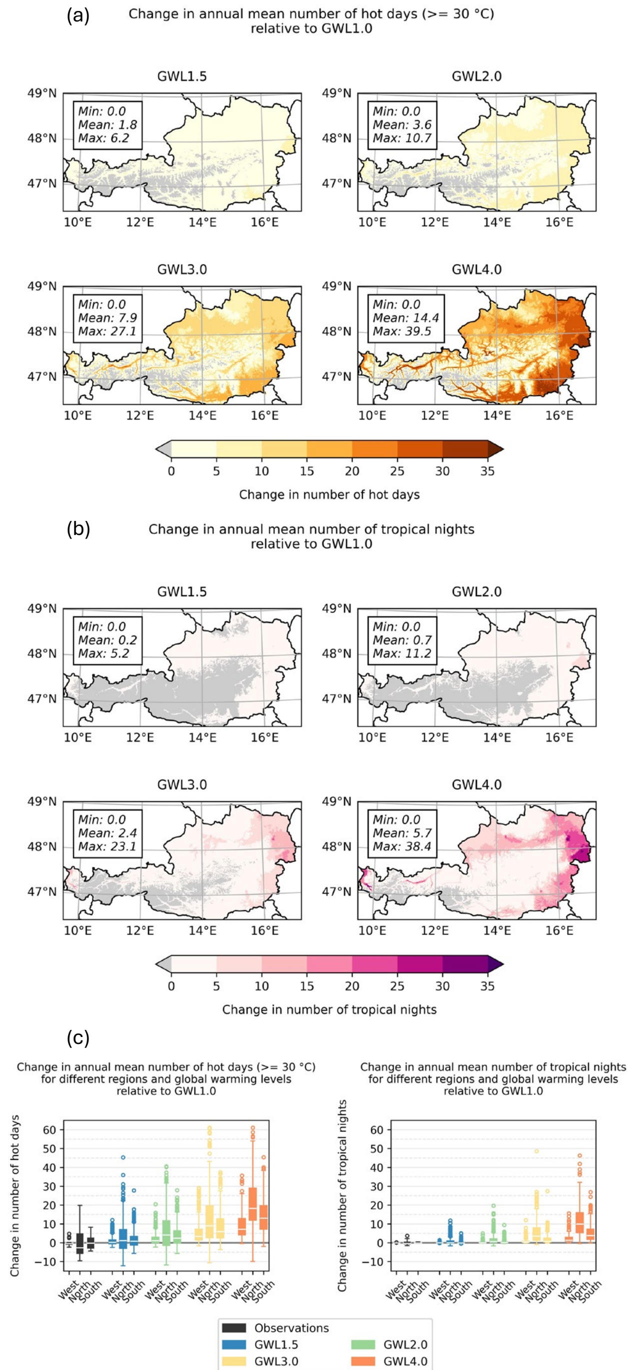



**Figure 1.5** Projected changes in annual mean number of (a) hot days and (b) tropical nights for different warming levels, based on ÖKS15 simulations. Observations are derived from SPARTACUS data. Maps depict ensemble mean changes, (c) boxplots show both inter-annual and ensemble range of changes for three regions in Austria. The regions associated with the labels 'West', 'North' and 'South' can be seen in Figure 1.A.3. The changes are calculated as averages (a, b) or annual values (c) of the periods at GWL 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C. They relate to averages at GWL 1.0°C, which corresponds to the period 2001–2020 for the observations and different periods for each ÖKS15 model. The black bar in the boxplots (c) shows annual anomalies from the average of the period 2001–2020. Observations for the indicators shown in this figure are presented in Figure 1.A.8. Data sources: ÖKS15 and SPARTACUS (Truhetz and Leuprecht, 2018; GeoSphere Austria, 2020).

of temperature changes for glacier and permafrost retreat is discussed in Section 1.3.

## Precipitation projections

As Austria is located in the transition region between the drying trends of the Mediterranean and the wetting trends of northern Europe, projections are affected by considerable uncertainties depending on the season.

For total annual precipitation, older ENSEMBLES models do not agree on the projected changes over Austria, nor are these changes significant (Jacob et al., 2014). However, the EURO-CORDEX ensemble projects an increase in total annual precipitation (Jacob et al., 2014; Haslinger et al., 2023).

For both winter and summer, projections of seasonal mean precipitation are robust across a range of different global and regional climate model ensembles (Jacob et al., 2014; Rajczak and Schär, 2017; Kotlarski et al., 2023; Ritzhaupt and Maraun, 2023). While most models simulate an increase in winter, a decrease is projected for summer (with some EURO-CORDEX models also showing significant increases). The decrease in summer is confirmed by ensemble projections with convection-permitting regional climate models (Pichelli et al., 2021). In both seasons, however, the contribution of internal variability is strong and may reverse the expected future trends for the next decades (Maraun, 2013). For spring and fall, there is no clear signal, and internal climate variability dominates (Maraun, 2013). Overall, there is *high confidence* for an increase in winter precipitation and *medium confidence* for a decrease in summer precipitation over Austria. These changes are clearly evident under high emission scenarios or global warming levels. Figure 1.6 illustrates these changes as projected by the ÖKS15 ensemble.

The number of wet days does not show a clear change signal in winter, spring and fall, but for summer many models agree on a reduced number of wet days under strong warming (Rajczak and Schär (2017): -10 % to -25 % based on ENSEMBLES and EURO-CORDEX; Pichelli et al. (2021): -4 % to -10 % based on CORDEX-FPS convection-permitting regional climate models, multi-model means for RCP8.5).

Changes in mean precipitation are also reflected in changes in extreme precipitation. Multi-model means for RCP8.5 daily precipitation intensities are projected to increase in winter (up to 25 %), spring and fall (up to 20 %), and with a similar but weaker trend in summer (up to 15 %), based on ENSEMBLES and EURO-CORDEX (Rajczak and

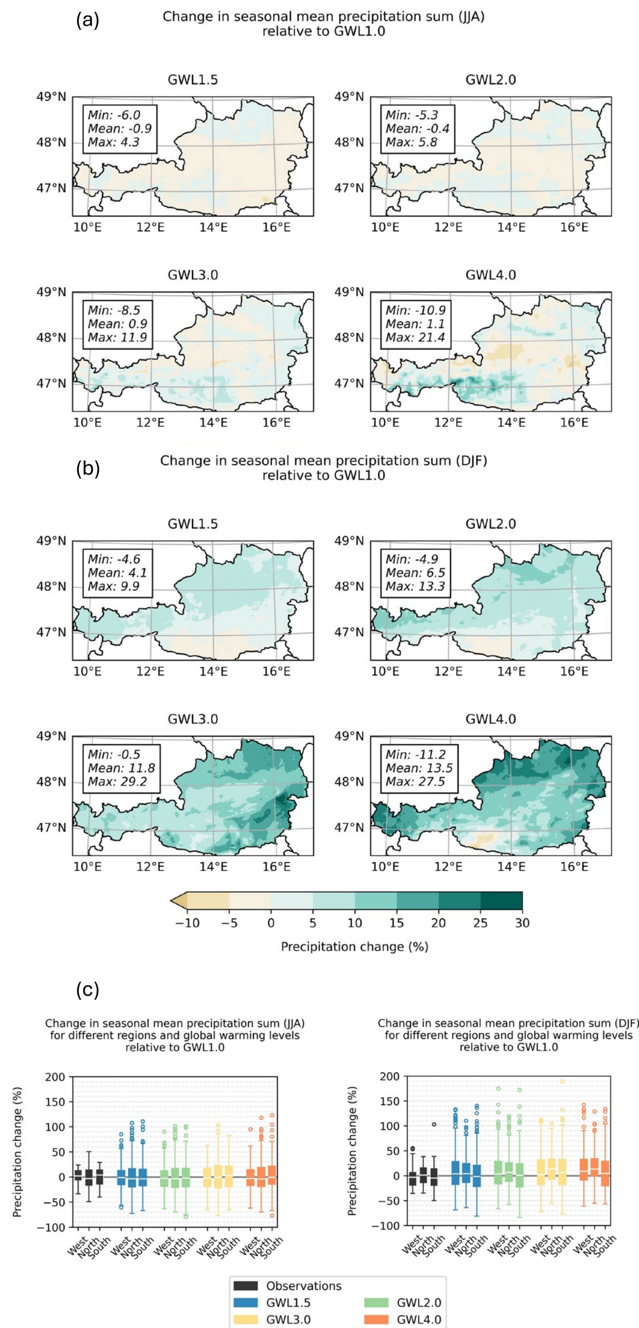



**Figure 1.6** Projected changes (in %) in seasonal mean precipitation sum for (a) summer (July-August) and (b) winter (December-February) for different warming levels, based on ÖKS15 simulations. Observations are derived from SPARTACUS data. Maps depict ensemble mean changes, (c) boxplots show both inter-annual and ensemble range of changes for three regions in Austria. The regions associated with the labels 'West', 'North' and 'South' can be seen in Figure 1.A.3. The changes are calculated as averages (a, b) or annual values (c) of the periods at GWL 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C. They relate to averages at GWL 1.0°C, which corresponds to the period 2001–2020 for the observations and different periods for each ÖKS15 model. The black bar in the boxplots (c) shows annual anomalies from the average of the period 2001–2020. Observations for the indicators shown in this figure are presented in Figure 1.A.9. Data sources: ÖKS15 and SPARTACUS (Truhetz and Leuprecht, 2018; GeoSphere Austria, 2020).

Schär, 2017). Extremes of daily precipitation are projected to increase in all seasons, though the strength of the signal varies considerably across the considered ensemble (as shown in Figure 1.7) and indicator (Rajczak and Schär, 2017; Ritzhaupt and Maraun, 2023). For summer, coarse-resolution climate models simulate a decrease in extreme precipitation, but there is evidence that their resolution is too coarse to represent topographic influences on convection, making their simulated changes implausible (Giorgi et al., 2016; Ritzhaupt and Maraun, 2023). Overall, there is *medium to high confidence* for an increase in extreme daily precipitation for winter, spring, and fall, and *medium confidence* for summer.

For extreme rainfall over 5-day periods, there is a clear signal for strong warming in winter (up to 25 %), spring, and fall (up to 20 %) (*medium confidence*), and no signal for summer (RCP8.5, multi-model means from ENSEMBLES and EURO-CORDEX) (Rajczak and Schär, 2017).

Newly available convection-permitting climate models with kilometer-scale resolution (Coppola et al., 2020) were evaluated for changes in hourly precipitation extremes for summer and fall (Pichelli et al., 2021). These models project higher intensities and extremes for both seasons (with a slight decrease in summer extremes over the eastern lowlands). However, the number of rainfall hours is projected to decrease in summer and fall (with a slight increase in the northeast). These results are broadly consistent with changes simulated by the driving EURO-CORDEX regional climate models, but have not been assessed for significance or robustness. Pseudo-global warming studies (e.g., Doblas-Reyes et al., 2021) of a single event suggest the possibility of a super-Clausius Clapeyron dependence (relative to global temperature increase) of extreme short-term summer rainfall, but this may be counteracted by a possible stabilization of the atmosphere (Maraun et al., 2022). Given the *limited evidence*, the lack of full physical interpretation, and the absence of uncertainty assessment, *confidence* in the projected increase in hourly rainfall extremes in summer and fall is currently *low*.

There has been little research on severe convective storms over Europe such as mesoscale convective systems and supercells, which can, in turn, cause hailstorms and tornadoes. One reason is the limited availability, until recently, of climate simulations representing such storms. As a way out, Brooks (2013) and Allen (2018) suggest the analysis of large-scale atmospheric environments conducive to such storm events, i.e., high instability and low-level moisture as well as strong deep-layer wind shear. EURO-CORDEX simulations

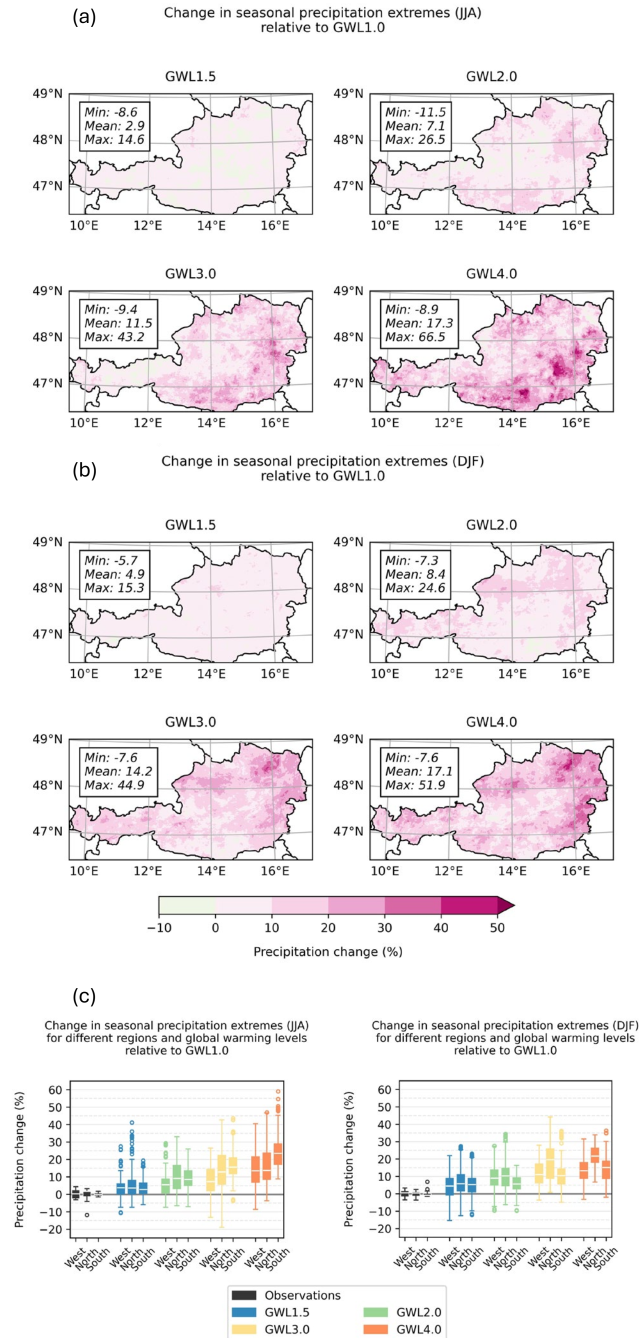



**Figure 1.7** Projected changes (in %) in seasonal extremes (99.9 percentile) of daily precipitation sums for (a) summer (July-August) and (b) winter (December-February) for different warming levels, based on ÖKS15 simulations. Observations are derived from SPARTACUS data. Maps depict ensemble mean changes, (c) boxplots show both inter-annual and ensemble range of changes for three regions in Austria. The regions associated with the labels 'West', 'North' and 'South' can be seen in Figure 1.A.3. The changes are calculated as averages (a, b) or annual values (c) of the periods at GWL 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C. They relate to averages at GWL 1.0°C, which corresponds to the period 2001–2020 for the observations and different periods for each ÖKS15 model. The black bar in the boxplots (c) shows annual anomalies from the average of the period 2001–2020. Observations for the indicators shown in this figure are presented in Figure 1.A.10. Data sources: ÖKS15 and SPARTACUS (Truhetz and Leuprecht, 2018; GeoSphere Austria, 2020).

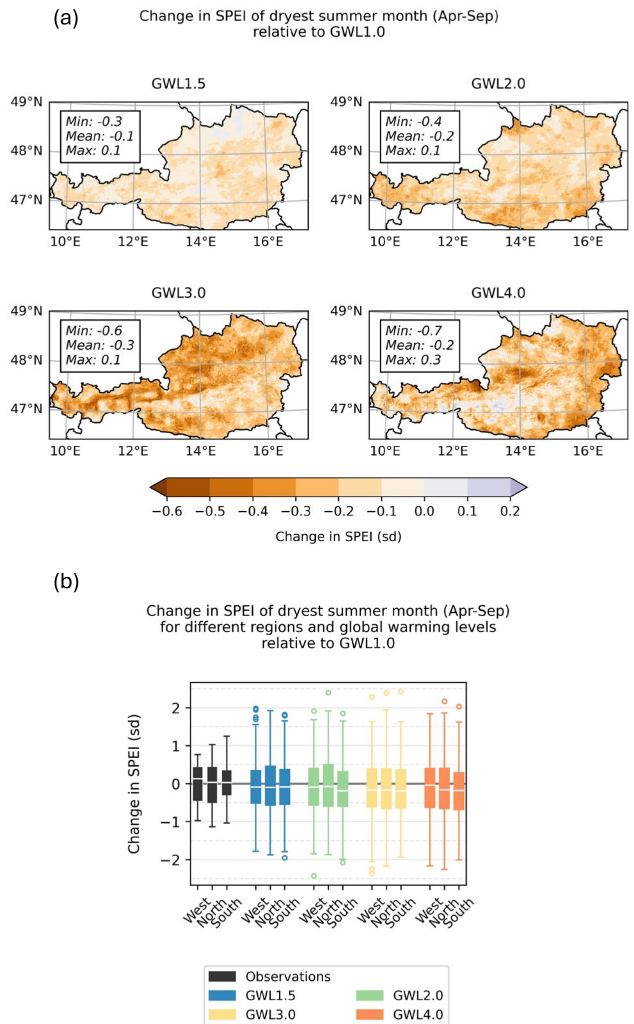



**Figure 1.8** Projected changes in the water balance surplus or deficit, represented by the standardized precipitation-evapotranspiration index (SPEI) of the driest month in the summer half-year (Apr-Sep) for different warming levels, based on ÖKS15 simulations. Observations are derived from SPARTACUS data. (a) Maps depict ensemble mean changes, (b) boxplots show both inter-annual and ensemble range of changes for three regions in Austria. The regions associated with the labels 'West', 'North' and 'South' can be seen in Figure 1.A.3. The changes are calculated for events with (a) a 10-year return period (10th percentile) or (b) annual values of the SPEI for the periods at GWL 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C. They relate to (a) the 10th percentiles or (b) averages of SPEI at GWL 1.0°C, which corresponds to the period 2001–2020 for the observations and different periods for each ÖKS15 model. The black bar in the boxplots (b) shows annual anomalies from the average of the period 2001–2020. Observations for the indicators shown in this figure are presented in Figure 1.A.11. Data sources: ÖKS15 and SPARTACUS (Truhetz and Leuprecht, 2018; GeoSphere Austria, 2020).

at 0.44° grid spacing project a robust increase in such environments under strong warming, except at high altitudes, due to an increase in low-level moisture (Púčik et al., 2017). Chan et al. (2023) analyzed projections of mesoscale convective systems over Europe in two convection-permitting models and found inconsistent changes in frequency, magnitude, and velocity, but a consistent increase in peak intensity, total precipitation volume, and temporal clustering.

## Drought projections

A simple and easy-to-interpret indicator of meteorological drought is the number of consecutive dry days within a season or year. For winter, there is no change in this indicator, but for summer, a robust increase is found in EURO-CORDEX simulations (Dosio, 2016).

Soil moisture or agricultural drought takes into account the drying of the soil caused by a lack of precipitation and strong evapotranspiration due to high temperatures. A study based on two hydrological and two land surface models driven by the CMIP5 global climate model ensemble shows an increase in the duration of extreme soil moisture drought events (from 30 to more than 100 months) and the average number of drought months (from 2–3 to 3–5 months per year) under 3°C warming (Samaniego et al., 2018). The latter changes are particularly large for eastern Austria. Similar results are found in other studies using the regional climate models ENSEMBLES and EURO-CORDEX (Heinrich and Gobiet, 2012; Haslinger et al., 2016; Spinoni et al., 2018; Haslinger et al., 2023). The driving factor for these robust changes is rising temperatures. Overall, there is *high confidence* for more severe agricultural droughts with global warming over Austria. Figure 1.8 shows the projected changes in the standardized precipitation-evapotranspiration index (SPEI) based on the ÖKS15 ensemble. The SPEI indicator shows negative values for all GWLs in the summer half-year, which corresponds to an increase in dry periods.

## Wind projections

Wind is a variable that directly represents atmospheric dynamics, and projections are therefore affected by high uncertainties. These uncertainties are exemplified by a wide range of plausible changes simulated for winter wind speed over Austria, including no change or a significant increase depending on the actual large-scale circulation changes (Zappa and Shepherd, 2017).

For the annual mean, no robust signal in wind speed changes is found in the EURO-CORDEX projections (Wohland, 2022). Consistent with this, Tobin et al. (2016) find a wide range of possible changes in the annual mean wind energy yield. Similar results are found for wind energy output, where two models suggest no change (Hueging et al., 2013) and an ensemble of nine combinations of two

RCMs and five GCMs projects a slight decrease (Moemken et al., 2018). The latter results vary over the seasons, with a consistent decrease in summer. Uncertainties are high for projections of sub-daily wind variability, although they tend to increase with strong warming. Monthly variability is projected to increase (Tobin et al., 2016).

For wind extremes, Outten and Sobolowski (2021) find a slight increase in 30-year return periods in the EURO-CORDEX simulations, but without explicit uncertainty assessment. An earlier study found a strong dependence of extreme wind gust projections on the driving GCM, with no robust signal emerging (Nikulin et al., 2011).

Only one study has analyzed climate projections for foehn winds in the Alps (Maier et al., 2025). In the EURO-CORDEX simulations, the frequency of southern foehn events over Tyrol is projected to decrease slightly, while widespread events are projected to increase in both Tyrol and Vorarlberg. A seasonal shift from July to October into the spring months is projected.

### Elevation dependencies

Climate change is known to be elevation dependent (Pepin et al., 2022) (see also Section 1.2.1 for observations). In both ENSEMBLES (Kotlarski et al., 2015) and EURO-CORDEX (Kotlarski et al., 2023), the warming rates have a maximum between about 1,500–2,000 m in spring and between about 2,000–2,500 m in summer. For winter, the warming rate saturates above 1,500 m, and for fall, the warming rate increases with elevation up to the resolved altitude. However, a comparison of global climate model simulations with resolutions varying from about 16–125 km found a strong but unsystematic dependence of the existence and strength of elevation-dependent warming on model resolution (Palazzi et al., 2019). These findings highlight the associated uncertainties.

Precipitation projections in the ENSEMBLES simulations also show a clear elevation dependence, but with strong regional and seasonal variations (Kotlarski et al., 2015). For the Eastern Alps, positive trends decrease with altitude and negative trends increase.

Not surprisingly, the number of snow days (Kotlarski et al., 2015) and snow water equivalent (Kotlarski et al., 2023) show clear elevation-dependent changes (*high confidence* based on simulations and physical understanding). Decreases in the number of snow days are greatest at intermediate elevations of about 1,000 m in winter, 1,500 m in spring, and 2,000 m in summer and fall. Decreases in snow water equivalent from September to May are higher at lower elevations. For low warming, almost no decrease is found above 2,500 m, while for high warming levels, significant decreases are found at all elevations.

Changes in snow are discussed in more detail in Section 1.3.1.

**Chapter Box 1.1. Global warming levels and their implications for Austria**

### Concept and method in AAR2

Since the adoption of the Paris Agreement in 2015, the global and regional implications of a 1.5°C or a 2.0°C warmer world gained traction in the public, political and scientific debate. In its Special Report on Global Warming of 1.5°C (IPCC, 2018), the IPCC assessed a range of climate change impacts at these two levels of global mean surface temperature (GMST) increase. In the sixth Assessment Report cycle, global warming levels (GWLs) are used as a 'robust and useful dimension of integration' (Chen et al., 2021) for comparing climate studies across many scientific disciplines and beyond.

This integrative property of GWLs stems from a different way of looking at climate projections. Most model-based climate projections are derived from models that simulate the climate system and its interactions on a global scale. Conventionally, climate change and its impacts are categorized in terms of time periods (e.g., mid-century) and underlying greenhouse gas (GHG) emission scenarios outlined in the IPCC Special Report on Emissions Scenarios (SRES) (Nakićenović et al., 2000), representative concentration pathways (RCPs) (Van Vuuren et al., 2011), or shared socio-economic pathways (SSPs) (Riahi et al., 2017). GWLs, on the other hand, are defined as a point in time when GMST exceeds a certain threshold relative to a (most often pre-industrial) reference period, as illustrated in Figure 1.A.1. All subsequent analyses refer to this period. The main difference to the conventional approach is that the same GWL can include model results from different time periods, emission or concentration scenarios. In a sense, the GWL perspective bypasses the uncertainties associated with the underlying forcing scenarios and model-internal climate sensitivity and looks directly at the resulting global temperature change.

The GWLs concept also involves some inherent assumptions and shortcomings. These are discussed extensively in the literature (e.g., James et al., 2017) but a few examples are presented here. First, while a number of regional climate impacts have been shown to be linearly related to GMST and therefore well represented by GWLs (Wartenburger et al., 2017; Seneviratne et al., 2018b; Lewis et al., 2019; Tebaldi et al., 2020; Iyakaremye et al., 2021), showing changes in terms of GWLs can mask substantial differences between variables with a strong dependence on local or regional aerosol concentrations, such as mean precipitation or local precipitation extremes (McCoy et al., 2022; Persad et al., 2022). Second, the transient (warming) or equilibrium (stabilized) state of the climate at a given GWL can lead to substantially different regional and local climate conditions (Seneviratne et al., 2018a; King et al., 2020, 2021; Zhang and Zhou, 2021). However, because equilibration occurs on centennial timescales (Rugenstein et al., 2019), transient behavior is more relevant to impact studies, and the AAR2 therefore only considers the 20-year period in which a global temperature threshold is first crossed. This, in turn, limits the ability to represent slow-changing or delayed impacts, such as glacial retreat, purely in terms of GWLs. In a few cases throughout AAR2, such impacts are therefore additionally characterized by time periods or forcing scenarios.

Details of the method used to identify GWLs from global climate model output are presented in Becsi and Formayer (2024). The main GWLs throughout the AAR2 are 1.5°C, 2.0°C, 3.0°C and 4.0°C of GMST increase relative to 1850–1900. Where study results were available only for predetermined periods, the approach was reversed to calculate discrete GWLs for the respective periods. GWL periods for the most commonly used models are provided in Table 1.A.2.

## The shift to CMIP6

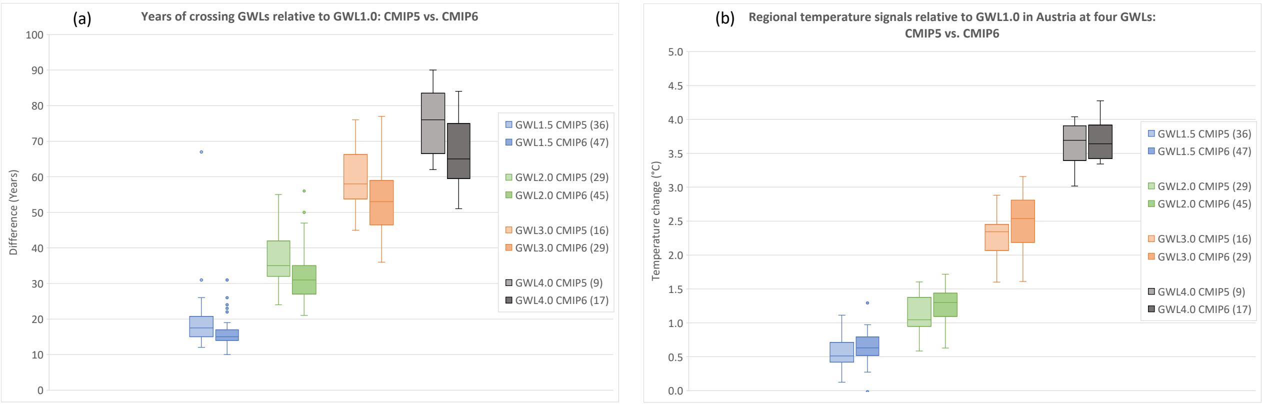
While the ÖKS15 climate scenarios were based on regional climate models forced by global climate models of the fifth coupled model intercomparison project cycle (CMIP5) (Taylor et al., 2012), global models of the newer generation CMIP6 (Eyring et al., 2016) have now been released. It will be years before local climate scenarios downscaled from the CMIP6 GCM/RCM chain are available[1]. However, Becsi and Formayer (2024) have shown with the Austrian climate scenarios ÖKS15 that GWLs are well suited to represent temperature changes at the regional scale, and that generational shifts in global climate models can be accounted for using the GWLs concept. There are two main conclusions of the study:

- Warming trends for future periods are significantly higher in CMIP6 than in CMIP5, and therefore future GWLs are reached earlier in CMIP6 than in CMIP5. This acceleration amounts up to a decade between the CMIP5 and CMIP6 ensemble medians at GWL 4.0°C, and less at lower GWLs.
- Since models usually either over- or underestimate temperature trends, the related errors in absolute temperatures can accumulate over time. Because the GWL concept characterizes climate projections on the basis of a silimar climate instead of similar timing, it can adjust for this type of error in downstream scenario analysis.

[1] The initiative 'Klimaszenarien.AT' is currently developing new Austrian climate scenarios. See klimaszenarien.at for more information.

Box 1.1 Figure 1 supports these findings. It shows the differences in timing between CMIP5 and CMIP6 in reaching a given GWL (a) and the differences in regional temperature signals at that GWL (b). The baseline for all changes is GWL 1.0°C rather than a fixed time period. As the figure shows, the GWL concept accounts for the different warming rates in the models and selects periods in such a way that regional temperature changes between GWLs are quite stable across model generations in Austria.

This approach of relating changes to GWLs instead of reference periods is adopted in the following sections, so that these changes can be assumed to be valid also in light of the transition from CMIP 5 to CMIP6. This underlines the integrative capacity of the GWLs concept to compare climate impacts across time periods, emissions scenarios and even model generations.



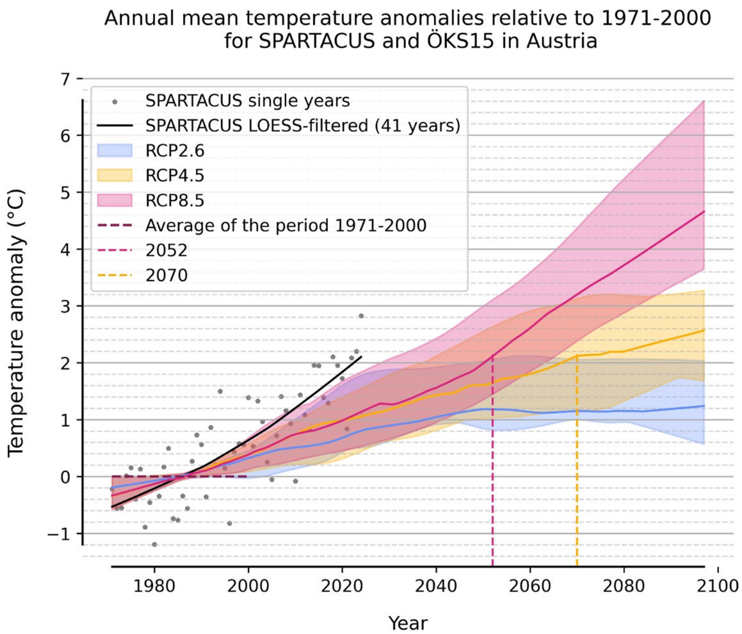

**Box 1.1 Figure 1** (a) Different timing of GWL periods and (b) associated temperature change at four global warming levels (GWLs) in comparison between selected CMIP5 and CMIP6 models in Austria. The boxes represent GWL 1.5°C, GWL 2.0°C, GWL 3.0°C and GWL 4.0°C for the CMIP5 and CMIP6 model ensembles (box pairs from left to right). All changes are relative to GWL 1.0°C, i.e., to a different 20-year period for each model. The numbers in parentheses after the legend entries indicate the number of models included. In the observational data, GLW 1.0°C corresponds to the period 2001 to 2020.

## The cold bias in ÖKS15

Recent warming trends are underestimated in the ÖKS15 ensemble. Since the downscaling approach applied in the scenario development (Switanek et al., 2017) preserves the change signals of the EURO-CORDEX models in the background, this cold bias is rooted in the RCMs and has also been identified in the literature (Kjellström et al., 2018; Schumacher et al., 2024).

It is further exacerbated by the fact that the period chosen to adjust the bias in the raw EURO-CORDEX models with observational data is 1971–2000, which is 20 years behind the current climate normal period (World Meteorological Organization (WMO), 2017). The cold bias in the model trends has therefore accumulated over time to a significant gap compared to the current observed warming.

Box 1.1 Figure 2 illustrates the lagged warming of the ÖKS15 scenarios compared to observations (reference period 1971–2000). This period is relevant for all applications that use the absolute values of the ÖKS15 temperature data. All temperature values are averaged over the area of Austria and the respective year. The reference point for the observed warming is the year 2024. It is calculated from annual observations using a 41-year LOESS filter (Clarke and Richardson, 2021), since the common approach of using averages of climate normal periods lags at least 15 years (for 30-year periods) behind current climatic conditions. The LOESS filter approach is better suited to represent recent warming. The same filter function was applied to the ÖKS15 temperature data. The figure highlights the temporal perspective of the cold bias rooted in ÖKS15: Current (2024) temperature levels are reached in 2050 in the ensemble median of RCP8.5 and in 2065 in the ensemble median of RCP4.5. The delay is 27 years (RCP8.5) and 42 years (RCP4.5), respectively. Almost all models in RCP2.6 are below recent levels of temperature increase by 2100.




**Box 1.1 Figure 2** Observed and modeled temperature anomalies in Austria, relative to the period 1971–2000. Shaded areas indicate the ensemble range for RCP2.6, RCP4.5 and RCP8.5, with thick lines indicating the ensemble median. Dashed vertical lines show the time when the ensemble's median reaches the 2024 warming level. Data sources: ÖKS15 and SPARTACUS (Truhetz and Leuprecht, 2018; GeoSphere Austria, 2020).

To mitigate errors accumulated over the past 40 years since the period used for bias-adustment, model trends can be compared against more recent observational data. Though even when relating changes to the current climate normal period (1991–2020), almost no model in the RCP2.6 ensemble reaches the observed temperature level of 2024 until 2100. By relating the changes to GWL 1.0°C instead of a fixed reference period, the resulting adjustment (see Section The shift to CMIP6) significantly reduces the delay to observed levels of warming.

As a guideline for interpreting ÖKS15-based climate studies in the light of this cold bias, Figure 1.A.2 quantifies the time lag of all ÖKS15 models for commonly used reference periods as well as for GWL 1.0°C. The corresponding data are shown in Table 1.A.3.

There are some general recommendations for handling the cold bias in ÖKS15 in future climate change studies. Foremost, it makes sense to minimise the period over which past errors accumulate by selecting an observational reference period as close to the current climate as possible, and only evaluating future model trends from that point on. In light of the recent warming rate of 0.6°C per decade in Austria, 30-year periods might be too long for averages to represent stationary conditions, and 20-year periods might be better suited for that purpose.

Where feasible, relating changes to GWLs instead of determined periods can reduce the timing-sensitive part of the error and has the benefit of being robust across model generations. However, there are cases where climatological averages do not provide the right scope. Some impact models require transient data on (sub)daily time scales as input. These cases could still benefit from the trend-adjusting properties of the GWLs concept, for example when time series are initialised at a given GWL rather than a fixed time period for each input model. Although the GWLs perspective provides a helpful way to maintain the usefulness of the ÖKS15 climate scenarios for the coming years, the issue of underestimated warming trends can ultimately only be addressed with the release of the next generation of Austrian climate scenarios.

## Chapter Box 1.2. Tipping points in the climate system

### What are tipping points?

The IPCC defines a tipping point as a critical threshold beyond which a system undergoes a significant and often abrupt or irreversible reorganization into a new state. A tipping element, in turn, refers to 'a component of the Earth system that is vulnerable to reaching such a tipping point' (Chen et al., 2021). Tipping points are characteristic of systems with amplifying feedbacks, where small disturbances can lead to disproportionately large responses. Moreover, once an irreversible tipping point is crossed, the system does not return to its previous state, even if the original forcing is reversed.

As early as the 2000s, the IPCC cautioned that tipping points could be reached within the coming centuries if greenhouse gas emissions continued to increase (IPCC, 2001). However, more recent evidence suggests that these thresholds could be crossed at lower levels of warming and much sooner – possibly within this century – raising the risk of cascading effects that could impact other critical components of the climate system (Möller et al., 2024).

Tipping points are identified through expert judgement that integrates observational data, paleoclimatic evidence, and Earth system model simulations. This evaluation is complemented by an assessment of the feedback mechanisms specific to each tipping element, the global temperature thresholds that could trigger them, their potential irreversibility, the timescales of their transitions, and their likely global and regional impacts (Lenton et al., 2008; Armstrong McKay et al., 2022). Based on these criteria, tipping points have been identified in the biosphere, cryosphere, and ocean-atmosphere systems (see Box 1.2 Table 1).

While tipping points have occurred in the past without human influence – such as the abrupt climate shift 11,700 years ago that marked the beginning of the Holocene epoch – this report focuses on tipping elements that are vulnerable to human activities, including greenhouse gas emissions and land-use change, that have the potential to influence the global climate system. Given Austria's integration into the global climate and societal system, any tipping point affecting the planets' climate is likely to have an impact on the country.

Below, we introduce two tipping elements that could greatly impact Austria. Box 1.2 Table 1 provides a summary of the major climate tipping points identified to date, along with their associated global temperature thresholds. These tipping elements have the capacity to cause profound disruptions to Earth's systems and human societies.

### Tipping elements with potentially high impacts on Austria

*A collapse of the Atlantic Meridional Overturning Circulation (AMOC)*

The AMOC is a critical ocean current system that regulates climate patterns globally. Its surface branch transports warm, salty water northward, while its deep branch transports cold water southward. This circulation is primarily driven by deep water formation, which occurs when surface water cools and sinks in the northern Atlantic.

The AMOC is vulnerable to climate change, as rising temperatures slow the cooling of surface water, weaken deep water formation, and reduce the strength of the current. Evidence suggests that the AMOC has weakened by about 15 % since the mid-20th century (Caesar et al., 2018; Thornalley et al., 2018), with further declines projected by Earth system models, including those from the CMIP projects (Weijer et al., 2020).

Paleoclimate records and theoretical and modeling studies suggest that the AMOC may be reaching a tipping point. Stommel (1961) proposed that the stability of the AMOC depends on the delicate balance between the effects of temperature and salinity on water density. Currently, the system is primarily temperature driven, with cold water in the northern latitudes maintaining a strong AMOC. However, a significant influx of freshwater – resulting from accelerated melting of the Greenland ice sheet or increased precipitation – could disrupt this balance, increasing the risk of AMOC collapse.

While most current climate models do not predict a complete AMOC shutdown during the 21st century, some projections suggest that a collapse could occur before 2300 if greenhouse gas emissions continue to increase (Bakker et al., 2016). A recent study, based on a single model, simulated an AMOC collapse and identified the processes that unfolded both near and during the tipping event. By comparing the tipping 'fingerprints' identified by the model with reanalysis data, the authors concluded that a tipping event could occur within this century (Van Westen et al., 2024). However, the temperature threshold for such a collapse remains highly uncertain, with considerable variability among model projections. An AMOC collapse would have profound consequences, including substantial cooling in the North Atlantic and Europe, disrupted rainfall patterns, and stronger winter storms, positioning the AMOC as a low-probability but high-impact tipping point in the near future.

*Collapse of the Greenland Ice Sheet (GIS)*

The GIS is shrinking at an accelerating rate due to increased surface melting and increased ice calving into the ocean, both driven by rising global and regional temperatures (IPCC, 2019b). Although complete melting of the GIS is unlikely to occur abruptly and would take at least the entire millennium, there is strong evidence that the GIS may be approaching – or may have already passed – a critical tipping point beyond which its melting could become irreversible (Höning et al., 2023). This process is strongly influenced by feedback mechanisms, with elevation feedback playing a key role. As the ice sheet melts and loses elevation, its surface becomes more exposed to the warmer temperatures at lower altitudes, further accelerating the rate of melting.

The complete melting of the GIS would result in a global sea level rise of about 7.2 meters, with far-reaching consequences, including potential disruptions to ocean and atmospheric circulation patterns that could significantly affect Europe (IPCC, 2019b).

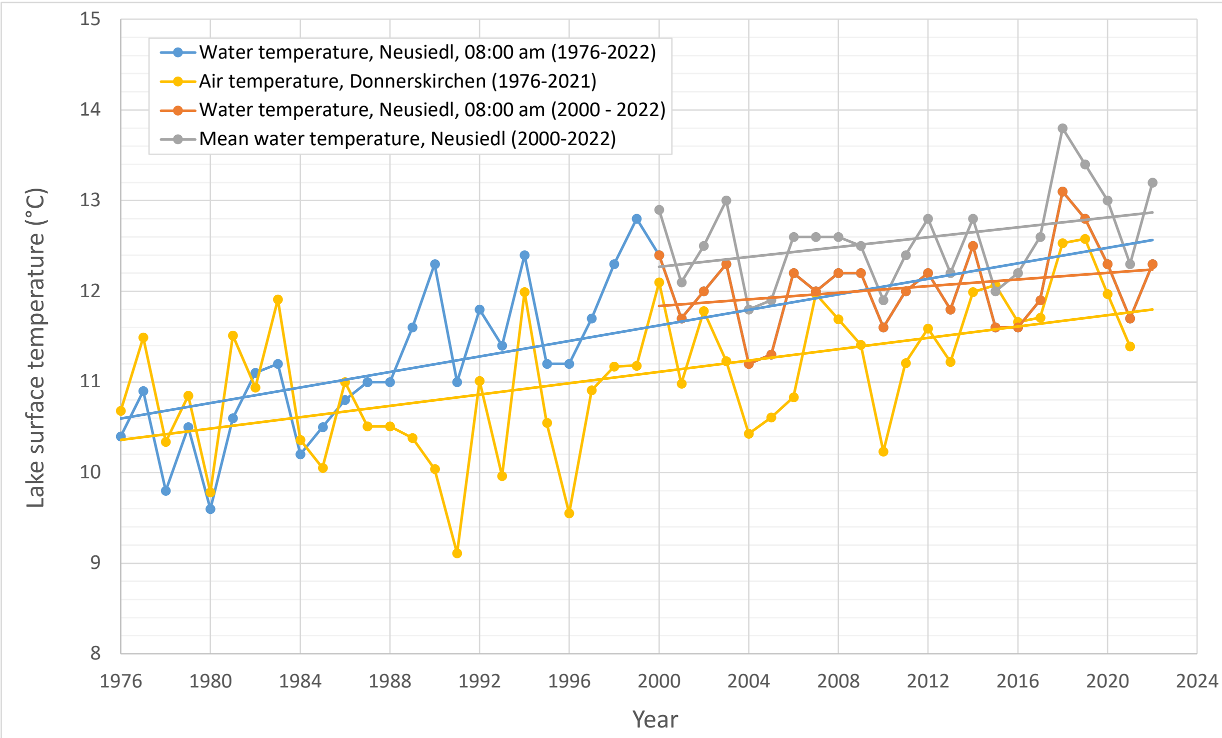
**Box 1.2 Table 1** Overview of the changes in global mean surface temperature at which global tipping points may be triggered, the timescales associated with transitions between states, and the estimated impacts (global and local additional warming) of the global core tipping points identified by Armstrong MacKay et al. (2022). The leftmost categories represent Earth system domains: CR for cryosphere, BI for biosphere, and AO for atmosphere-ocean. In addition, colors assigned to element names and estimates indicate the subjective confidence levels. Table from Ossó and Roither (2024).

* SPG: Subpolar Gyre

| Earth system domain | Proposed climate tipping element and (tipping point) | Threshold (°C) | | | Timescale (years) | | | Maximum impact (°C) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Best Estimate | Min. | Max. | Best Estimate | Min. | Max. | Global | Regional |
| CR | Greenland Ice Sheet (collapse) | 1.5 | 0.8 | 3.0 | 10k | 1k | 15k | 0.13 | 0.5 to 3.0 |
| CR | West Antarctic Ice Sheet (collapse) | 1.5 | 1.0 | 3.0 | 2k | 500 | 13k | 0.05 | 1.0 |
| CR | East Antarctic Subglacial Basins (collapse) | 3.0 | 2.0 | 6.0 | 2k | 500 | 10k | 0.05 | ? |
| CR | Arctic Winter Sea Ice (collapse) | 6.3 | 4.5 | 8.7 | 20 | 10 | 100 | 0.60 | 0.6 to 1.2 |
| CR | East Antarctic Ice Sheet (collapse) | 7.5 | 5.0 | 10.0 | ? | 10k | ? | 0.60 | 2.0 |
| BI | Labrador-Irminger Seas/ SPG* Convection (collapse) | 1.8 | 1.1 | 3.8 | 10 | 5 | 50 | -0.5 | 3.0 |
| BI | Atlantic Meridional Overturning Circulation (collapse) | 4.0 | 1.4 | 8.0 | 50 | 15 | 300 | -0.50 | -4 to -10 |
| AO | Amazon rainforest (dieback) | 3.5 | 2.0 | 6.0 | 100 | 50 | 200 | Partial 0.1 Total 0.2 | 0.4 to 2.0 |
| AO | Boreal Permafrost (collapse) | 4.0 | 3.0 | 6.0 | 50 | 10 | 300 | 0.2 to 0.4 | -- |

High confidence | Medium confidence | Low confidence

## Chapter Box 1.3. Case study: Lake Neusiedl as sentinel of climate change




**Box 1.3 Figure 1** Mean annual changes in surface water temperatures of Lake Neusiedl. From 1976 to 2022, the water temperature has increased by 1.9°C (data source: Hydrographischer Dienst Burgenland, wasser.bgld.gv.at/).

Lake Neusiedl, Austria's largest lake, is exposed to wind, extremely shallow, and is currently losing substantial amounts of lake water due to rising air temperatures that increase evaporation. Large floods and several droughts have been recorded at Lake Neusiedl in the past, and it last dried up in 1865–1868 (Draganits et al., 2022). Unlike other lakes in Austria, Lake Neusiedl receives most of its water from direct precipitation and is disconnected from groundwater inflow (Tchaikovsky et al., 2019). Thus, the current loss of lake water is mainly the result of water evaporation due to high temperatures (Box 1.3 Figure 1) and decreasing precipitation. Compared to its average, long-term (since 1965) lake surface water level of ~115.5 m a.s.l., Lake Neusiedl in 2022 was ~10–50 cm below this long-term average water level[2] (*high confidence*).

Ongoing climate change will have a major impact on the future of Lake Neusiedl and its surrounding ecosystems. Current climate change models, such as the ÖKS15 for Burgenland, show that lower average water levels can be expected, especially during the summer months. This applies not only to Lake Neusiedl, but also to neighboring water bodies such as the soda pans. The maximum water temperatures of Lake Neusiedl have continued to increase and often exceed 30°C in summer. Therefore, higher evaporation rates are to be expected with as yet unknown effects on the biocoenosis.

2 wasser.bgld.gv.at/hydrographie/die-seen/mittler-wasserstand-neusiedler-see

## 1.3. Cryosphere

This chapter focuses on the description of the Austrian cryosphere, including the regional/temporal occurrence, drivers, and magnitude of historical and future changes in response to climate forcing. Interactions and impacts on other natural and socio-economic systems are briefly mentioned, but as the perennial cryosphere in Austria is limited to high elevations, the broader context of the relevance of the cryosphere and the impacts of its change are discussed in Chapter 7.

### 1.3.1. Snow

Snow plays an important role in Austria, as its extent and duration are relevant for soil moisture, river flow characteristics, landscape appearance, and winter tourism. These factors in turn influence regional ecology, economy, agriculture and forestry (drought risk, forest fire risk), vegetation distribution, reservoir recharge, flood risk, snow avalanche and snow load risk, and hydropower yield.

#### Observed snow depth and snow cover duration

There is a growing body of literature on observed trends in snow-related indicators in the Alpine region, including Austria. For example, Klein et al. (2016) analyzed Swiss station data for the period 1970–2015 and found an average reduction in snow cover duration (SCD) of 8.9 days per decade. Schöner et al. (2019) found stronger negative trends in snow depth (SD; up to -12 cm per decade) in the southern parts of the Alps than in the northern parts between 1961 and 2012. This is also confirmed by Bozzoli et al. (2024), who evaluated snowfall depth over the European Alps between 1920 and 2020 and found reductions of about 4–5 % per decade in the southern Alps and about 2.3 % per decade in the northern Alpine region. Olefs et al. (2021) found a consistent decrease in SD across Austria of about 3 cm per decade on average and a decrease in SCD of about 7 days per decade in the period 1961–2020 (see also Figure 1.9: Gray bars, for the change within the last 30 years). In an alpine-wide analysis for the period 1971–2019, Matiu et al. (2021) found negative trends in all snow indicators below 2,000 m a.s.l., e.g., a decrease in SCD of about 5 days per decade. Marty et al. (2017b, 2023) analyzed long-term SWE time series in several Alpine countries, including Austria, and found, e.g., trends in the date of end of snow cover of about -3 days per decade in the period 1957–2022. Vorkauf et al. (2021) found earlier snowmelt dates of -2.8 days per decade between 1958 and 2019, which is consistent with the SCD trends noted above. In general, most studies find stronger changes in spring (earlier melting) than in fall (later onset of snow cover). In summary, estimates for recent changes in snow cover duration (SCD) in Austria and the entire Alpine region range from about -5 to -10 days per decade.

#### Future snow depth and snow cover duration

There are few studies on future snow conditions in Austria. Earlier studies for neighboring regions include Marty et al. (2017a, 2017b, 2023), who analyzed two catchments in the Swiss Alps and found that a decrease in SCD of about 10 days per decade can be expected at an elevation of about 1,500 m a.s.l. by the end of the 21st century, assuming the A2 scenario. In an early Austrian case study for a ski resort in Styria, Marke et al. (2014) found a decrease in SCD of 5 to 6 days per decade in the first half of the 21st century, assuming the A1B scenario. Frei et al. (2018) found an area-averaged decrease in snowfall over the Alps of about 25 % for the RCP4.5 scenario and 45 % for the RCP8.5 scenario. Matiu and Hanzer (2022) found an overall reduction in snow cover fraction of 14 % for RCP2.6 and 48 % for RCP8.5 for 2071–2100 compared to 2001–2020. Le Roux et al. (2023) projected snowfall extremes in the French Alps and concluded that annual maxima of daily snowfall are expected to decrease below 3,000 m a.s.l., but even increase above 3,600 m a.s.l. in the second half of the 21st century under the RCP8.5 scenario. Kotlarski et al. (2023) analyzed the loss of snow water equivalent (SWE) in the Alps and found, e.g., a reduction of about 20 % in the low-end scenario RCP2.6 and 80 to 90 % in the high-end scenario RCP8.5 at altitudes below 500 m a.s.l. by the end of the 21st century. Recently, a set of snow cover scenarios based on observations and the regional, bias-adjusted ÖKS15 climate simulations was published for Austria (Project FuSE-AT) (Koch, 2021b), used as a basis for climate change impact studies (e.g., Kiem et al., 2024) and expert opinions in the winter tourism sector.[3] Figure 1.9 shows the estimates of SCD averaged over Austria at different elevation levels based on the FuSE-AT results. From the previous (1961–1990) to the current climate normal period (1991–2020), SCD decreased significantly at all elevation levels, on average by about 7 days per decade (Olefs et al., 2021). By the year 2050, the SCD in Austria will most likely continue to decrease by at least 5 days per decade on average. With respect to the GWLs, we expect a further decrease of the SCD by 10 to 15 days at

[3] Examples are given at fuse-at.ccca.ac.at

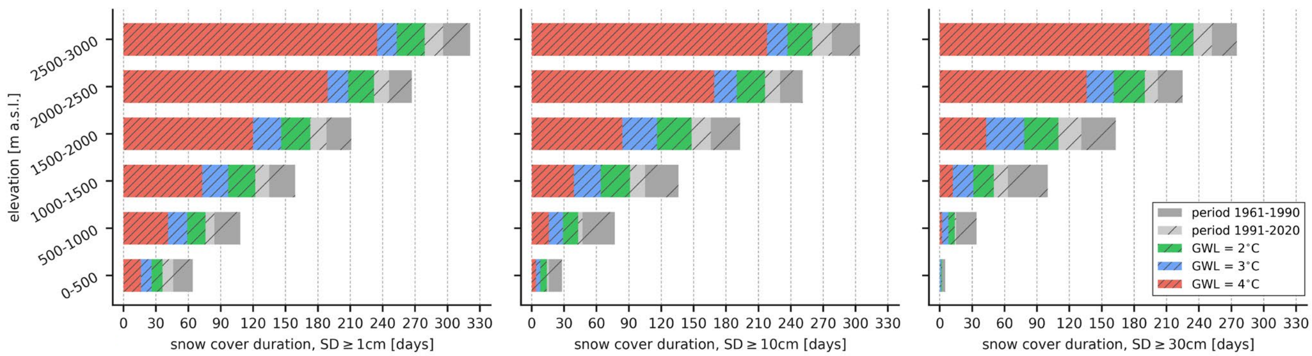



**Figure 1.9** Snow cover duration (SCD) in Austria at different elevation levels. Left: Days with SD >1 cm; Middle: Days with SD >10 cm; Right: Days with SD >30 cm (Source: GeoSphere Austria).

GWL 2.0°C, by 35 to 45 days at GWL 3.0°C, and by 60 to 80 days at GWL 4.0°C. This estimate applies for all except for the lowest elevations, where the current SCD is already shorter than the projected changes for higher elevations.

## Related consequences

Feedback on radiative forcing: Kiem et al. (2024) showed that the additional radiative forcing due to decreasing albedo caused by snow cover retreat within 80 years (2021–2100) corresponds to 25–500 % (depending on emission scenario and climate model) of the radiative forcing effect of Austria's total annual $CO_2$eq emissions in 2021.

Natural hazards: Snow is associated with a number of natural hazards, including droughts (Sections 1.2, 1.4.3), floods (Section 1.4.1), wildfires (Cross-Chapter Box 1), and snow avalanches (Sections 2.2.1, 7.4.1).

Winter tourism and recreation (see also Sections 2.2.1 and 4.7.2): The FuSE-AT project assessed the meteorological conditions necessary for the production of technical snow (Koch, 2021a). Over two consecutive 30-year periods (1991–2020 vs. mid-century 2021–2050), the number of hours in December (a critical period for base snowmaking) with favorable conditions for technical snow production is estimated to decrease by 10–15 % at 1,000 m and 5–10 % at 2,000 m a.s.l.

## Cross-Chapter Box 1. Evaluation of climate-related risks and key risks

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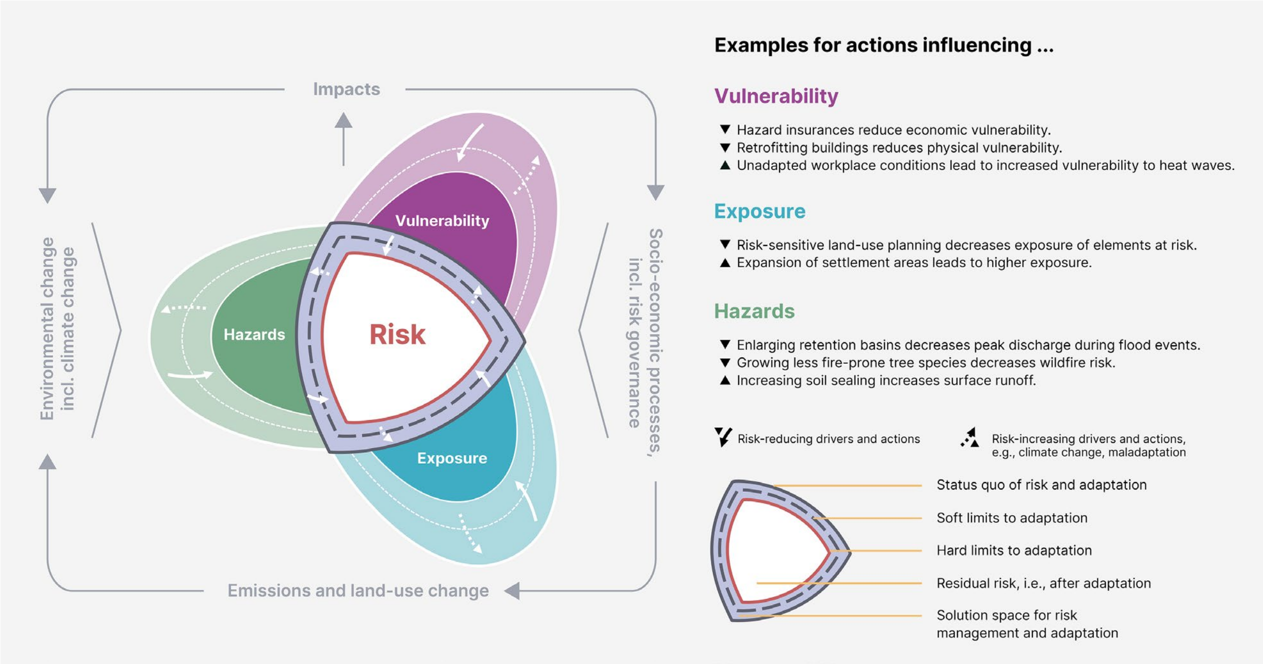
This box provides an overview of the concepts used to derive risks and key risks relevant to the AAR2 and builds on the concepts and terminology used in recent IPCC reports (Garschagen et al., 2019; IPCC, 2022b). Burning ember diagrams of key risks for Austria are provided. Key terms used for risk assessment in the AAR2 are listed in the glossary, which is based on IPCC (2022a). Further details on the used approach are provided in the 1.A.3.

### The nature of climate-related risk

Throughout the chapters of the AAR2, risk provides a framework for understanding the potentially severe impacts of climate change on ecosystems and the human system, and how adverse consequences can be reduced for the future. ***Risk*** – defined as the potential for adverse consequences – results from the interaction of ***vulnerability*** (of the affected system), its ***exposure*** over time (to the hazard), and the (climate-related) ***hazard*** and the likelihood of its occurrence (CCBox 1 Figure 1). ***Impacts*** are the consequences of realized (materialized) risks on natural and human systems, such as observed losses and damage related to hazard events.




CCBox 1 Figure 1 Core components of risk and related terms. The figure is based on the initial IPCC risk figure and the conceptual framework of risk-adaptation relationships used in the SROCC (Garschagen et al., 2019), but has been slightly adapted for the AAR2 (for further discussion, see Fuchs et al., 2024). The white arrows illustrate actions affecting hazard, exposure, and vulnerability that shape risks over time (increase, decrease). The red line in the center illustrates hard limits to adaptation, and the outer dark gray solid line illustrates the status quo of risk. The dark gray dashed line illustrates the soft limits of adaptation. The area between the red and dark gray lines (light purple) is the solution space. The remaining residual risk is the inner core of the risk figure (white), defined by the red line. Illustrative examples for risk management actions addressing each of the three risk components are provided.

The AAR2 assessment recognizes the complex nature of climate-related risks by addressing changes in hazard, exposure and vulnerability, including feedback and possible cascading processes of overall ecosystem and anthroposphere impacts. Hazard, exposure and vulnerability may each be subject to uncertainty and may vary in time and space due to socio-economic dynamics and human decision-making. Thus, risk may increase or decrease over time in relation to the dynamic interactions between the three risk components, which in turn may increase or decrease over time. ***Adaptation*** and risk management play an important role in reducing the overall risk associated with climate change. However, there are also limits to adaptation due to hard limits (no adaptive action is possible to avoid intolerable risks) or soft limits (options may exist but are not currently available to avoid intolerable risks through adaptive action) that will result in increasing losses and damages. The remaining solution space (CCBox 1 Figure 1) includes options for strategies and measures that are available and appropriate to address climate risks.

## Climate-related risks as assessed in this report

Our understanding of climate-related risks is based on multiple and diverse sources of information, including climate change science, natural sciences, engineering, social sciences, and economics. The standardized workflow for climate-related risk assessment in Austria is based on the corresponding IPCC framework and workflow (IPCC, 2022b: Chapter 16). Following the structure of the AAR2, the assessment of climate-related risks and the identification of key risks are organized in a cross-chapter approach. Chapter 1 provided information on climate change, climate-related hazards and ecosystem impacts (see Table 1.A.4). Based on the information provided in Chapter 1, Chapter 2, Chapter 3, Chapter 4 and Chapter 7, we evaluated the observed impacts within their respective subsystems and assessed the future evolution of climate-related risks, shaped by changes in climate-related hazards as well as exposure and vulnerability. These risks were further evaluated through the filters of *severity* and *urgency* to identify and describe Austria's key risks. While some key risks may already reflect dangerous disruptions today, they may typically become more severe over time due to changes in the nature of the hazards and/or the exposure/vulnerability of societies or ecosystems to these hazards. They may also become severe due to the adverse consequences of adaptation or mitigation responses to the risk. Key risks are identified as potentially urgent to determine the priority for action with different adaptation/risk management strategies according to (societal) risk preference/tolerance and soft/hard adaptation limits to be crossed. In the next step, these results were assessed in Chapter 5 and Chapter 6, taking into account the needs in the context of societal adaptation options and from a governance perspective, and fed into Chapter 8.

### Resulting climate-related key risks for Austria

**Rising temperatures lead to health risks, especially in urban areas and to reduced labor productivity:** Increasing frequency and duration of heat waves, including tropical nights, pose a risk to human health, especially for people living in urban areas and those exposed to heat in their working environment (*high confidence*). A GWL 4.0°C leads to an increase in the number of hot days (>30°C) from 25 to 60 per year in the hottest regions of Austria (see CCBox 1 Figure 2). Potential impacts include an increase in heat-related morbidity and mortality, a decrease in quality of life, out-migration, and a decrease in labor productivity, resulting in economic losses for various economic sectors and households. Heat exposure is greatest in densely populated urban areas because their natural cooling capacity is reduced by a lack of open and green spaces and often limited building quality. Work-related heat impacts are higher for those who perform physical work outdoors or work in non-air-conditioned indoor environments. Individuals in the low and high age groups, and especially those with lower socio-economic status or chronic illnesses, are particularly vulnerable to extremely high temperatures. Possible adaptation options to address heat exposure include increasing green and shaded areas or technical solutions for cooling. In the working environment, adaptation options include providing air conditioning at workplaces or, if this is not possible, shifting working hours to cooler times of the day, reducing working hours, increasing breaks and ensuring health recovery and relaxation during breaks (Cross-Chapter Box 2 and Sections 3.2 and 4.4.3).

**The risk of drought will increase in Austria:** Increasing evapotranspiration and precipitation variability will increase the risk of droughts seasonally and regionally. This will considerably increase the uncertainty of agricultural production (quantity and quality of certain profitable crops) and severely affect highly vulnerable ecosystems, leading to potentially irreversible losses (*medium evidence, high agreement*). As a result, agricultural irrigation needs will increase, especially in eastern Austria, which may further degrade fragile ecosystems, associated biodiversity, and other sectoral water needs. This may also lead to more frequent water shortages (*limited evidence, high agreement*). Households, businesses and services that depend on water availability in these regions will be more likely to experience water scarcity. Possible adaptation measures include adapted crop rotations (including drought-tolerant crops), sustainable soil management, a networked expansion of water supply, the use of rainwater for irrigation and water-saving production (see Sections 1.2.2, 1.6, 1.8 and 2.2.1).

**Risk of pluvial and river flooding will increase in Austria:** There is evidence that pluvial floods, and to some extent river floods, will become more frequent and more intense in Austria (*medium confidence*). This will affect communities by causing major economic losses, especially those that expand their built environment. In particular, areas with a high degree of surface sealing are vulnerable to pluvial flooding. In addition, floods affect transport infrastructure and services, and thus the mobility of the population and the accessibility of communities, and can interrupt pan-European transport routes. The elements at risk have different (physical) vulnerabilities to flood processes. Social and economic aspects of vulnerability can increase the overall susceptibility. A lack of (compulsory) building insurance is the bottleneck of economic vulnerability. Strengthening and implementing spatial planning, unsealing urban and rural areas, efficient rainwater drainage in urban areas and upgrading drainage infrastructure are effective adaptation tools for both fluvial and pluvial floods. Further improvements in monitoring systems could improve warning and preparedness (see Sections 1.4, 1.8, 3.2.3 and 7.4.1).

**The risk of torrential floods will increase in Austrian mountain valleys:** In the Alpine region, torrential floods will become more frequent and more intense in the future (*robust evidence, medium agreement*), driven by an increase in intense precipitation events and in catchments with increased sediment availability. Sediment availability is expected to increase at high elevations where (i) glacier retreat, (ii) permafrost degradation and (iii) increased physical weathering occur. Torrential floods and related cascading events will affect alpine communities at local and regional levels, causing significant economic losses, especially as the built environment and land use expand. They will also affect transport infrastructure and services, thus affecting population mobility and the accessibility of mountain communities and economics, and may disrupt pan-European transport routes. The trend in torrential events is also strongly related to risk management, as financial resources for maintaining existing technical protection are limited. Therefore, current measures could be complemented by a portfolio of adaptation options to reduce the risk of torrential floods, such as enforcement of land use regulations, mandatory building insurance, pooled prevention funds to also encourage non-governmental investment in local (property) protection (see Sections 1.4, 1.8 and 7.4.1).

**The risk of wildfire will increase in Austria:** The effects of climate change are expected to lead to an increase in heat waves and changes in precipitation patterns and thus to an increase in fire weather days, which will ultimately increase the risk of wildfire in Austria (*high confidence*). This will affect local communities through economic losses, especially as the built environment and land use expand and the wildland-urban interface increases. It will also affect transportation infrastructure and services, thus affecting population mobility and accessibility of communities, and may disrupt pan-European transportation routes (especially railways). In addition, wildfires are a source of massive increases in health-threatening particulate matter, both locally and along wind paths. Wildfire-adapted assets and fire-resistant vegetation may be less vulnerable depending on the type of wildfire. Adaptation includes shifting to less fire-prone tree species (e.g., hardwoods) and organizational preparedness. Furthermore, information and awareness-raising of the population are important, as about 85 % of forest fires in Austria are directly or indirectly caused by human activities. With regard to the residual risk, the agricultural and forestry sector can be compensated by insurance (e.g., hail insurance/ *Hagelversicherung*), and some damage to the built environment can be compensated by insurers (see Sections 1.7, 2.2.2 and 7.4.1).

**Risk of decreasing quantity and quality of protection forests:** Rising air temperatures and more frequent and severe droughts will lead to shifts in tree species distribution and forest composition, which may have negative consequences for the protective function of forests at elevations <1,000 m a.s.l. In parallel with the dynamics of natural forest disturbances, e.g., by wind, fire, pests and insects, their protective function will decrease at higher elevations, e.g., during the ongoing unprecedented bark beetle outbreak in Austria (*high confidence*). Monocultures are more susceptible to disturbances and thus more exposed to wind, fire, pests and insects than mixed stands. Tangible and intangible losses to infrastructure, buildings, and human lives can result from the increased hazard potential downslope of a degenerated protective forest. Furthermore, secondary hazards (such as snow avalanches and debris flows) may develop on affected areas, and soil loss and increased surface runoff may be observed. These secondary effects may eventually pose existential risks to exposed communities in the valleys below, requiring transformative risk management measures such as planned resettlement. Post-disturbance management decisions can have an important impact on protection. If left in the stand, deadwood could maintain the protective function of forests after windthrow and bark beetle disturbances, especially during the first 15 years. To better adapt to these threats, uneven and multi-layered stands with trees of all sizes and age classes, a minimum canopy cover of about 40 %, only small openings and a sufficient presence of natural regeneration should be considered (see Sections 1.6.2, 2.2.2 and 7.4.2).

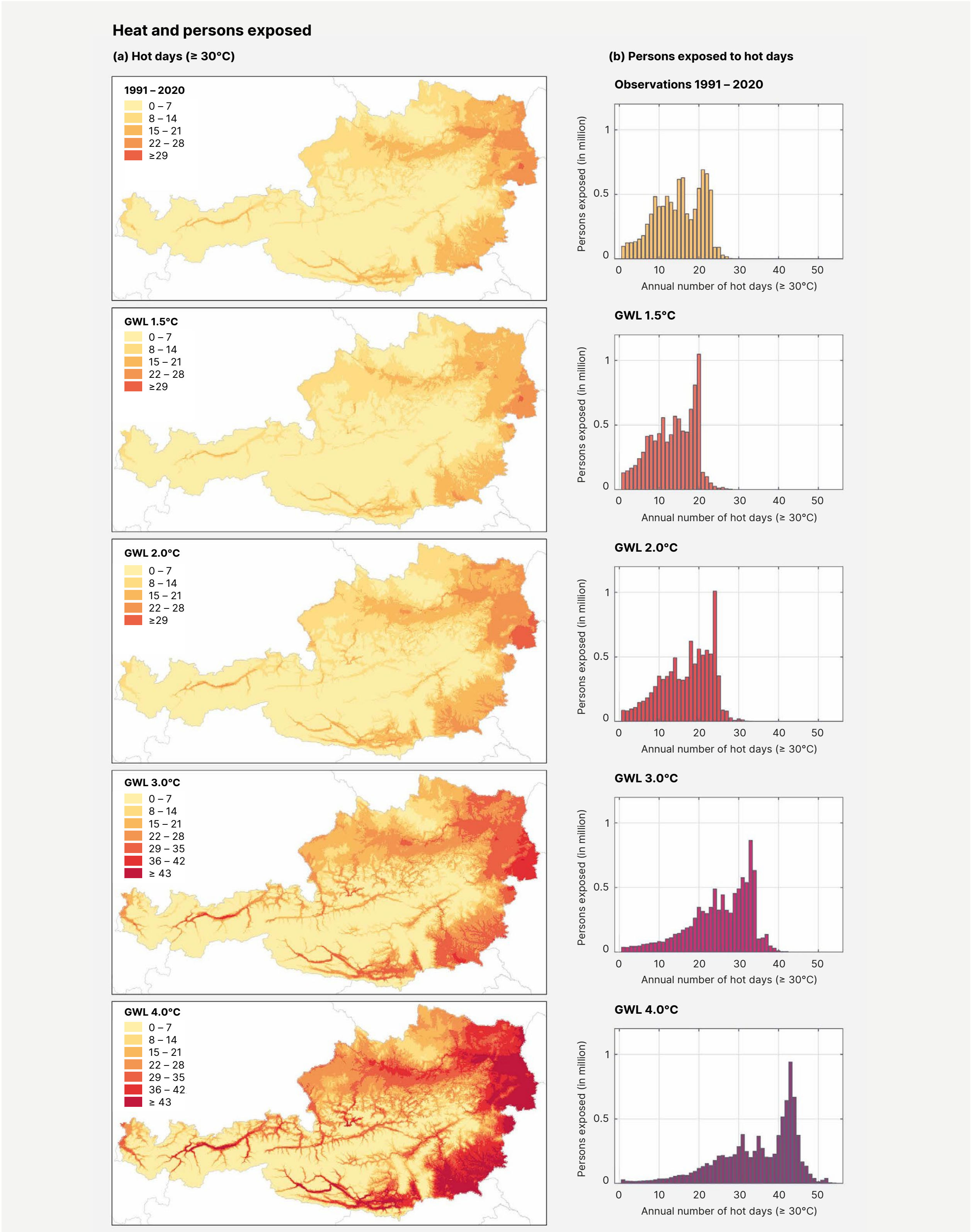
**Risk of biodiversity loss:** There is evidence of upward migration of mountain species due to warmer conditions. Therefore, cold environments above the tree line will shrink and this will lead to biodiversity loss. Long-ranged, warm-demanding species will replace short-ranged, cold-adapted species (some of them endemic, restricted to the Austrian Alps), especially at elevations >2,600 m a.s.l. There is an increasing risk of mismatched interactions between organism groups (e.g., plants and pollinators) and physiological stress of high-elevation species due to warming. Furthermore, weakening of tree vitality and increased susceptibility to bark beetles can be expected, leading to a reduction in the protective function of forests. The magnitude and likelihood of adverse consequences are high due to the pervasiveness of impacts across the Austrian Alps. There is a high potential for irreversible consequences due to the loss of intraspecific genetic diversity prior to eventual extinction. Although the likelihood is high, the effects will only become manifest in the coming decades because many alpine plants are long-lived species, and some may persist even when habitat conditions are no longer suitable. The lack of awareness of the many cascading effects of biodiversity loss leads to a lack of public attention. There is an increasing need for nature conservation in many alpine areas to avoid additional pressures from human land use (see Sections 1.6.4, 2.2.2 and 7.4.1).

**The increasing risk to the infrastructure of the energy system limits Austria's energy security:** Increasing electrification and thus grid-connected energy infrastructure threatened by climate-related extreme events pose an increasing risk to energy security (*high confidence*). Potential impacts include damage to energy generation (PV panels, wind turbines) and transmission infrastructure (overhead power lines, pipelines), resulting in energy supply disruptions to households, industry and infrastructure. Thermal generation units are will also be affected due to increased cooling demand and efficiency losses due to higher temperatures. Climate change impacts on energy demand, supply and infrastructure can lead to cascading effects and large-scale disruptions due to the high degree of interconnectedness between the energy system and all components of modern societies. Long investment cycles in energy infrastructure assets require early adaptation of planning, construction and operation to avoid lock-in effects. Possible adaptation measures to address this risk include designing energy infrastructure assets more climate-resilient, diversifying energy supply sources, increasing the degree of interconnection of European energy systems, decentralization, and climate-adapted network planning (see Section 4.5.1).

**Increasing risk of power shortage due to compound weather events:** Compound weather events, such as Europe-wide cold spells in winter combined with low river discharge, lead to high energy demand and low energy production in a highly electrified and renewables-based energy system, resulting in power shortages (*high confidence*). Fluctuations in demand and supply due to compound events may further threaten the stability of the electricity system. Coupled with an expected shift in electricity load towards summer months (increased cooling demand), power shortages will be exacerbated and economic losses and costs **may** occur due to the need for balancing energy and/or higher electricity prices. Possible adaptation measures include increasing the degree of interconnection of the European energy system, reducing energy and cooling water demand, increasing back-up capacities, spatial and technological diversification of energy sources and flexibility options (see Section 4.5.1).

**Climate change leads to a loss of competitiveness in the Austrian tourism industry (snow and ice sports):** Decreased snowfall and snow cover at lower altitudes due to rising temperatures, together with deteriorating conditions for technical snow production, will lead to a loss of competitiveness in snow- and ice-related tourism activities (*high confidence*). The natural snow season has decreased by an average of 7 days per decade (1961–1990 vs. 1991–2020) and will continue to decrease by 60–80 days (GWL 4.0°C). There is strong evidence that winter tourism based on snow and ice sports will be severely affected by shortening ski seasons and deteriorating snowmaking conditions. Households, businesses, and services in lower elevation ski resorts will be particularly affected. The high dependence of local economies on snow and ice sports and the lack of economic alternatives will increase the economic and social vulnerability of Austria's mountain regions. The associated loss of jobs in regions dependent on winter tourism will increase commuting and out-migration. Opportunities for adaptation and transition include the development of and investment in snow-independent tourism (see Sections 1.3, 4.3.3, 4.3.4 and 7.4.2).

**Human responses to climate-related risks can amplify or reduce the expected impacts:** Disaster and crisis management plans, contingency plans for energy and natural resource shortages, or extreme weather events can limit expected impacts. Behavior-based communication and compliance strategies for management plans are critical to their effectiveness (e.g., emergency notification standards, support from societal role models, etc.). These can be built on existing risk management structures (e.g., training courses on climate impact responses as part of work safety).

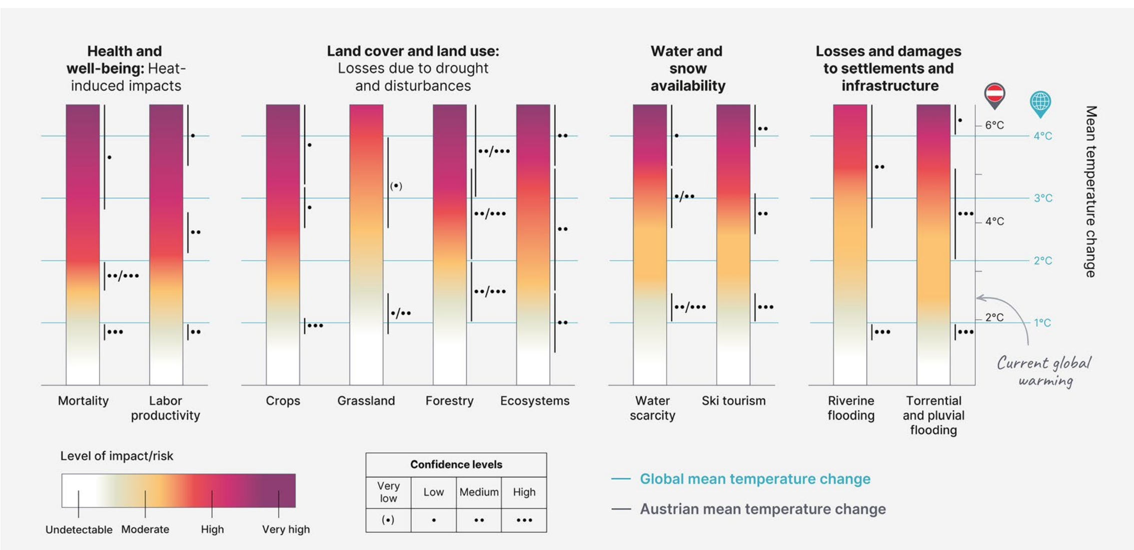



CCBox 1 Figure 2 Heat and persons exposed in Austria: (a) Number of hot days (≥30°C) in Austria at present (1991–2020) and for the future according to different Global Warming Levels (GWLs) (Becsi and Formayer, 2024; Chimani et al., 2016; GeoSphere Austria, 2020), (b) number of people exposed to hot days at present and at different GWLs considering the population for year 2050 under Shared Socioeconomic Pathway 2 (Riahi et al., 2017; Wang et al., 2022; data for Austria provided by Marbler, 2024).

**Austria is currently affected by climate-related damage and losses, and future climate change together with socio-economic development, will intensify these effects:** Losses due to climate change (damage caused by extreme weather events as well as negative consequences of climate change) are currently estimated at an average of EUR 2 billion per year and are expected to increase to at least EUR 2.5 to 5.2 billion per year by 2030 and to EUR 4.3 to 10.8 billion per year by 2050. However, there is little quantitative evidence from Austrian studies. International studies provide some insights, but their relevance for subnational and sector-specific assessments in Austria is limited. Standardized documentation of losses is needed, and more research is needed to better quantify and provide robust figures on potential climate-related direct and indirect impacts on society, livelihoods, economic sectors and services.

## Resulting burning embers for Austria

At the current GWL 1.4°C [1.2–1.6°C] in the year 2024, corresponding to a mean temperature change in Austria of 3.1°C in 2024, moderate risk levels have already been identified and attributed to climate change for a number of key risks (CCBox 1 Figure 3): Mortality due to heat; agricultural crop yield losses due to drought; ecosystem disturbances (such as changes in species numbers and composition, ecosystem functions, or range shifts); and loss and damage due to riverine, torrential, and pluvial floods. For grassland yields, water scarcity and ski tourism, moderate levels of risk have been observed in some regions (drought risk and water scarcity in some regions and some years; ski tourism at lower altitudes); these risks are projected to intensify and spread to other regions and higher altitudes (*medium confidence*). Most of the key risks are characterized by high risk levels around GWL 3.0°C, due to the larger areas affected by the risk and the persistence and severity of the impacts. For some key risks, such as mortality, crop and forest yields, ecosystems, water supply, and ski tourism, very high risks cannot be excluded at current levels of adaptation; however, confidence in the GWL at which the transition from high to very high risk is projected to occur is low (*high agreement* that the transition cannot be excluded, but low number of publications).




CCBox 1 Figure 3 Burning ember diagram of selected key risks for Austria, clustered by sector or system at risk. Diagrams show the change in the levels of impacts and risks assessed for global warming of 0–4.5°C global surface temperature change relative to the pre-industrial period (1850–1900). The global warming is also converted to mean Austrian surface temperature change. For a number of key risks, confidence levels are given as ranges to indicate that the risk transition will be at a lower global warming level in some regions or altitudes and at a higher global warming level in others. For some key risks, burning ember diagrams could not be generated due to insufficient quantitative data across global warming levels, too few studies for Austria, or insufficient process understanding. Confidence levels: High [•••], medium [••], low [•], very low [(•)]. In addition to the authors of the Cross-Chapter Box, the following authors contributed to the development of the Burning Embers: Maria Balas, Johanna Schauer-Berg, Katharina Brugger, Hermine Mitter, Manfred Lexer, Manfred Kleidorfer, Jana Petermann, Stefan Dullinger, Roman Neunteufel, Anna Burton, Judith Köberl, Nina Knittel, Anna Viktoria Rohrer, Valentin Schalk (data extraction), Johanna Wittholm (data extraction), Jonas Peisker (data extraction).

## 1.3.2. Glaciers

Glaciers exist where snowfall can survive the summer and accumulate over successive years. Glaciers act as seasonal and multiannual water reservoirs, gaining mass and growing when climatic conditions are more favorable for snowfall and its survival. Glaciers and their changes are relevant to mountain hydrology, tourism, natural hazards, and mountain ecosystems.

### Observed trends

Glaciers of the European Alps have been retreating since the Little Ice Age (ca. 1850), and the rate of retreat has increased in recent decades (Sommer et al., 2020). Geomorphological mapping indicates that the maximum extent of Austrian glaciers during the Little Ice Age (ca. 1850) was 941 $km^2$ (Fischer et al., 2015). Subsequent Austrian national glacier inventories were mapped from satellite imagery centered around 1969, 1998, 2006, and 2015, respectively (Buckel et al., 2018). Some inconsistencies may arise from the specific delineation methods used, but the pattern is clear, with ice extent decreasing from 555 to 479 to 415 to 329 $km^2$ over the four successive inventories, representing a loss of 40 % of the 1969 glacier area by 2015, with the highest percentage losses in the most recent time interval (*high confidence*). Although changes in glacier mass or volume are better measures of climate-induced glacier change, changes in length of over 100 Austrian glaciers show that all measured glaciers have receded since 1970 (Lieb and Kellerer-Pirklbauer, 2023). Austrian glaciers were estimated to store 12.4 $km^3$ of freshwater in 2016 (Helfricht et al., 2019). Eight Austrian glaciers have mass balance records longer than 30 years (World Glacier Monitoring Service (WGMS), 2022). These glaciers lost mass at an average rate of 1092 $kg/m^2$ per year during 2011–2020, which is almost double the annual rate of loss during 1960–2000. 2022 was a particularly negative mass balance year, driven by low snow amounts and positive summer temperature anomalies. For example, the Hintereisferner in the Ötztal lost 5 % of its ice volume in one year (Voordendag et al., 2023), compared to a typical volume loss of 30 % for Austrian glaciers during 1969–2006 (Helfricht et al., 2019). Glacier recession can lead to the formation of new alpine lakes, which have increased in number over the last century and at an increasing rate in the last 30 years (Buckel et al., 2018). Glacier retreat in Austria is associated with glacier fragmentation, and more of the remaining ice is buried by rock debris and survives only in shadowed cirques (Fischer et al., 2021). In other parts of the Alps, observations of glacier temperatures indicate warming ice (e.g., Gilbert et al., 2014) and more meltwater production at high elevations, which are associated with triggering (Bondesan and Francese, 2023) and increasing (Chiarle et al., 2022) collapses of remnant hanging glaciers, but significant ice avalanches or glacier collapses are very rare in Austria (Kellerer-Pirklbauer et al., 2012b).

### Future changes

Part of future glacier mass loss is a delayed response to climate change that has already occurred. State-of-the-art modeling indicates that 35 % of European glacier volume will be lost by 2050 under current climate conditions (Huss and Hock, 2018), and in all future climate scenarios half of the glacier mass will be lost within the next two decades (Rounce et al., 2023). Thereafter, the GWL (see Chapter Box 1.1) determines how much glacier ice will remain by the end of the century: Glacier models show that for GWLs of 1.5, 2, 3 and 4°C in 2100 compared to pre-industrial levels, the proportion of glacier mass remaining at the end of the century in central Europe is about 20 %, 15 %, 5 % and none, respectively (Rounce et al., 2023) (Figure 1.10). As Austrian glaciers are typically smaller and have lower maximum elevations than glaciers in the western Alps (Sommer et al., 2020), glacier loss in Austria is more pronounced than the European Alpine average (*high confidence*), and at GWL 1.5°C a maximum of 6 % of Austrian glacier mass remains (Figure 1.10). These are likely to be conservative estimates, as the models used to make these projections do not include positive feedbacks on glacier retreat rates due to ongoing glacier fragmentation, and regional-scale assessments in Austria using higher-resolution local datasets indicate greater glacier retreat (Hartl et al., 2024). The formation of new alpine lakes and remaining ice is more likely to be debris-covered, so glacier meltwater runoff is expected to decrease in the coming decades. Glacier ice is expected to warm, and associated changes in basal conditions could affect the stability of the remaining ice (Gilbert et al., 2014).

### Related consequences

Continued deglaciation will (i) shift seasonal peak runoff to earlier in the year (*high confidence*), coinciding with peak snowmelt (Hanus et al., 2021) (see Sections 1.3.1 and 7.4.1); (ii) affect the infrastructure and operation of ski resorts (Mayer and Abegg, 2024) (Sections 2.2.1, 4.7.2 and

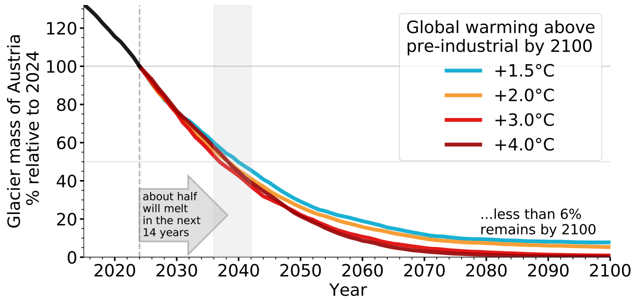



**Figure 1.10** Projections of total glacier mass change over time for all glaciers in Austria corresponding to four global warming levels at the end of the century. Note that due to the time lag in the adjustment of glacier mass to the forcing, the end-of-century mass does not include the full adjustment to the end-of-century GWL (see Chapter Box 1.1 for further explanation of GWLs). Figure created by Lilian Schuster (github.com/lilianschuster/glacier_climate_plots/tree/main/glacier_projections_for_austria_rounce_et_al_2023) using openly available data from Rounce et al. (2023).

7.4.2); (iii) facilitate natural hazards such as landslides, glacier collapse, and glacier lake outburst floods (e.g., Kellerer-Pirklbauer et al., 2012a; Piroton et al., 2024) (see Sections 1.8, 7.4.1 and Table 1.A.4) and (iv) alter conditions for mountain ecosystems through changes in water temperature, nutrient and sediment supply (e.g., Brighenti et al., 2019) (Section 7.4.1). Together, these contribute to changes in societal services provided by mountain regions (see Section 7.4.2).

## 1.3.3. Permafrost

Rock, sediment, or soil that freezes and thaws seasonally is called the active layer, while permafrost is rock, sediment, or soil that does not undergo seasonal melting, and remains at freezing temperatures throughout the year. In Austria permafrost occurs only in discontinuous patches at high elevations under favorable conditions.

### Observed trends

Estimates of permafrost coverage are based on statistical models of potential permafrost distribution that have been optimized for a small, well-studied region (the Hohe Tauern range) and applied to a larger area. Different models yield estimates of the maximum area potentially suitable for permafrost in Austria of between 1,400 and 3,000 km$^2$, with large uncertainties (Otto et al., 2020). For mountainous regions such as the Hohe Tauern National Park, 25 % of the area is potentially suitable for discontinuous permafrost (Schrott et al., 2012). Isolated patches of permafrost have been identified well below the regional lower limit of permafrost, suggesting that patches of permafrost persist outside the climate zones identified by statistical models (Stiegler et al., 2014). Rock glaciers have only recently been consistently inventoried at the national scale (Wagner et al., 2020), revealing 303 km$^2$ of rock glacier area, but 60 % by number are relict features that no longer contain ice. The volume of ice stored in rock glaciers within Austria was just over 1 km$^3$ in 2019, which is 1/12 of the volume of Austrian glaciers (Wagner et al., 2021) (see Section 1.3.2). Rock glacier volume and velocity have generally decreased at Austrian sites since 2000 (Fleischer et al., 2021; Kellerer-Pirklbauer et al., 2024). Peak velocities and periods of deceleration are synchronous with other Alpine regions (Kellerer-Pirklbauer et al., 2024). Rock glaciers can undergo destabilization processes that result in extreme acceleration and a shift in the dynamic regime from permafrost creep to landslide-like movement (e.g., Marcer et al., 2019). For example, the lower sector of the Äußeres Hochebenkar in the Ötztal has destabilized and shows very rapid movement of 20–30 m/yr in the fastest section (Hartl et al., 2023). The destabilization of this rock glacier leads to an increased rock fall hazard affecting a nearby access road. Borehole temperature data in Austria are available from Sonnblick (since 2008) and Kitzsteinhorn (since 2010) (Global Terrestrial Network for Permafrost, 2023) and show that the seasonal melt layer has tended to penetrate deeper in recent years, reaching 4 m at Kitzsteinhorn in 2022 (Hansche et al., 2023). Data from the extensive 'Swiss Permafrost Monitoring Network' (Swiss Permafrost Monitoring Network, 2022), which go back further in time, show increasing ground temperatures, active layer depths and rock glacier velocities associated with warming temperatures (Haberkorn et al., 2021), confirming the trends observed in the sparser observations in Austria.

### Future changes

Robust distributed projections of future permafrost distribution are not currently available, in part due to insufficient present-day permafrost mapping and borehole data, but also due to the strong heterogeneity of mountain permafrost (e.g., Stiegler et al., 2014). Future permafrost evolution has been simulated for Swiss sites, indicating continued warming and deepening of the active layer (Marmy et al., 2016), although the slow rates of change imply that permafrost patches will still exist at the end of the century (Beniston et al., 2018).

### Related consequences

Continued permafrost degradation is variously associated with surface drying, increased landslide formation, gravitational slope failure, and release of heavy metals in runoff (Beniston et al., 2018), all of which require further research to understand the processes and uncertainties involved, connected with changing natural hazards (Fuchs et al., 2022) (see Sections 1.8 and 7.4.1) and impacts on local infrastructure (Pläsken et al., 2020) (Section 7.4.2).

## 1.4. Hydrosphere

This subchapter summarizes the understanding and assessment of the impacts of climate change on runoff generation processes and on the magnitude, seasonality and frequency of water fluxes in streams, groundwater and lakes (including extremes and water quality).

### 1.4.1. Rivers and streams

This section discusses the observed and projected changes in river discharge in Austria and in the European context. The current state of knowledge is based on the first Austrian Assessment Report published in 2014 (Volume 2, Chapter 2; Nachtnebel et al., 2014), updated by the GeoSphere/TU Vienna follow-up study on climate change in water management (Blöschl et al., 2017) and recent studies from the scientific literature. The results are summarized for the main characteristics: Mean flow, high flow and low flow extremes, with impacts on stream temperature and aquatic biodiversity.

### Mean flow

The mean flow describes the water resources available in a catchment on average over the course of a year. It is closely related to the climatic water balance between precipitation and evaporation, with negligible changes in storage (Blöschl et al., 2017). On a pan-European scale, climates without a frost season show decreasing streamflow trends throughout the year, while climates with a frost season show decreasing trends in summer and increasing trends in winter (Peña-Angulo et al., 2022). The trends are regionally consistent but mostly insignificant, with significant winter trends in the Alps, northern and western Europe, and significant summer trends in southwestern Europe (see Figure 1.11).

*Observed trends*

For the Austrian domain, trends in water balance components for the period 1978–2013 were recently re-evaluated by Duethmann et al. (2020). Average precipitation has increased by a total of about 120 mm over 35 years. The increased precipitation compensates the evaporation trends of about +110 mm over 35 years. Thus, the average annual runoff has not changed. Although there are decreases and increases in CWB at low and high elevations (Section 1.2.1), these changes balance out at all elevations. This confirms

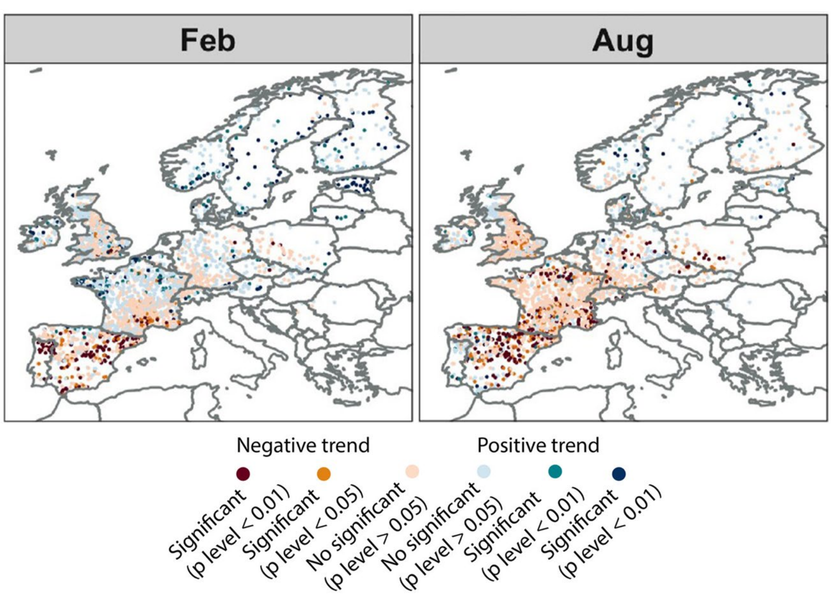



Figure 1.11 Direction and significance of trends in the monthly Standardized Streamflow Index over the period 1962–2017 from a European dataset of climate-sensitive and anthropogenically influenced gauges. Climates without a frost season show decreasing streamflow trends throughout the year, climates with a frost season show decreasing trends in summer and increasing trends in winter (Peña-Angulo et al., 2022).

the results of previous assessments (Blöschl et al., 2017) and is also supported by the most recent data (Haslinger et al., 2023; Laaha et al., 2025). The observed increase in evaporation can be attributed to increases in temperature and solar radiation, as well as to changes in vegetation dynamics, such as the lengthening of the growing season (*high confidence*).

With respect to regional trends, the first Austrian Assessment Report (APCC, 2014) is slightly tempered due to some changes in trend patterns. Current observations indicate decreasing trends especially in the northwest (Bregenzerwald, Salzburg), and increasing trends in the main Alps (*medium confidence*). Apart from the northwest, trends are mostly insignificant, but there is *high confidence* in a pronounced seasonal behavior with mostly significant increasing winter trends in the Alps due to frost attenuation (APCC, 2014; Laaha et al., 2025).

*Future changes*

For the future, the water balance assessment of APCC (2014) remains essentially valid: According to Blöschl et al. (2017) and Haslinger et al. (2023), there is a trend towards slightly decreasing annual runoff in the south and southeast (*low confidence*), decreasing winter runoff in the south (*low confidence*), and increasing winter runoff in the Alps (*medium confidence*). However, the projected trends are of *low confidence* because hydrological model projections have been shown to overestimate discharge trends especially in central Austria, southern Carinthia and western Austria. This is mainly due to inhomogeneities such as a variable number of stations in the precipitation data used for calibration and a model structure that neglects evaporation-relevant changes in vegetation dynamics (Duethmann et al., 2020). Zhang et al. (2023) expect global streamflow to be lower than predicted by Earth System Models in the near future (2021–2050), corresponding to a GWL 1.4°C/2.0°C (RCP4.5/8.5), due to smaller contributions from precipitation and greater sensitivity of streamflow to changes in evapotranspiration. However, this effect tends to be less pronounced for the European continent.

## High flows/floods

Floods (fluvial flooding) are generated by combinations of rainfall and runoff generation processes (Blöschl et al., 2013). The magnitude of floods is initiated by precipitation, but determined by the interplay of its magnitude and seasonality with snowmelt and catchment pre-wetness (Blöschl et al., 2011). Among the dominant meteorological drivers, weather patterns relevant for large-scale heavy precipitation have not increased in frequency in recent decades, but have been observed to bring more intense precipitation in fall and winter (Hofstätter et al., 2018) (Section 1.2.1).

*Observed trends*

At the European scale, Blöschl et al. (2019) observed flood discharge trends (variable observation periods) range from an increase of about 11 % per decade to a decrease of 23 %. Three distinct regions with roughly similar trend behavior can be observed: Increasing floods in northwestern Europe due to increasing fall and winter precipitation; decreasing floods in medium and large catchments in southern Europe due to decreasing precipitation and increasing evaporation; and decreasing floods in eastern Europe due to decreasing and earlier snowmelt resulting from warmer spring temperatures (see Figure 1.A.12). Austria lies at the intersection of these regions with the Alpine topography, resulting in a complex interplay of flood-generating processes.

For the Austrian domain, the increasing trends in observed flood discharges for the period 1976–2007 (APCC, 2014) have slightly intensified in recent years (Laaha et al., 2025). This has also exacerbated the flood problem (*robust evidence, medium agreement*). Over 43 years (1978–2020), floods have increased significantly in about 22 % (vs. 16 % for 1976–2007) of the catchments. Overall, there is a clear seasonal shift from winter and spring floods to summer floods, so that summer is now also the dominant flood season in the eastern half of Austria. Overall, 24 % of the catchments <500 km² show an increasing trend. The trend is more pronounced in smaller catchments than in larger ones, and more pronounced in the (mostly non-dominant) fall and winter seasons. Especially in southern Lower Austria and Upper Styria, as well as in areas along the main Alpine ridge, there is a significant increase in annual flood events, often exceeding 20 % in 43 years (+5% per decade). Overall, the average trend is +11.8 % in 43 years (+2.7 % per decade), with a stronger average trend of +22.5 % in 43 years (+5.2 % per decade) observed in the winter season (previous studies: annual trend of 6.8 and 6.6 % increase per decade).

*Future changes*

Projections of changes in floods are challenging with the current state of knowledge, because future trends in climate extremes, especially small-scale heavy precipitation, are not simulated with sufficient reliability in the currently available bias-corrected regional climate simulations for Austria. The most recent nationwide assessment of climate impacts on floods in Austria (Blöschl et al., 2017) therefore projects future changes based on a synopsis of the ÖKS15 and expert scenarios that focus on mechanisms and cause-effect relationships. It only allows statements in terms of time periods rather than GWLs (here the period 2021–2050 is used to make the statements comparable), as the attribution of GWLs is not directly possible for the combination of approaches.

Among the climate drivers, large-scale daily precipitation shows a strong dependence on mean air temperature (see Section 1.2.1). In the future, therefore, an increase in precipitation amounts of large-scale events is mostly expected (see Section 1.2.2). However, heavy precipitation-relevant weather trajectories will tend to become less frequent in the coming decades, but could produce heavier amounts of precipitation (see Section 1.2.2). To better quantify the impacts of heavy precipitation changes on floods, the representation of convection-relevant processes in climate models needs to be improved (Blöschl et al., 2017).

When the mechanisms for possible changes in flood generation are analyzed in the form of scenarios (see Figure 1.A.13), the following picture emerges (projected change in $HQ_{100}$ floods in 2021–2050 compared to 1997–2007):

- Changes in seasonal precipitation hardly lead to any projected changes in design flood estimates such as the 100-year flood ($HQ_{100}$): -2 to +2 % (vs. -3 to +2 % in APCC, 2014) (*medium evidence, low/medium agreement*).
- An increase in the convective fraction of precipitation results in increased flooding everywhere, especially in small catchments: +2 to +8 % (vs. +2 to +10 %) (*robust evidence, medium agreement*).
- An increase in the snow line has almost no effect on floods: 0 to +4 % (APCC, 2014: ditto) (*high confidence*).
- The influence of earlier snowmelt and thus lower runoff coefficients in summer, combined with higher evaporation, slightly reduces floods, especially in the Alps: -5 to +2 % (APCC, 2014: ditto) (*medium confidence*).

The combination of all mechanisms is expected to result in regionally varying changes in extreme flood discharges ($HQ_{100}$), ranging from -5 to +8 % (*medium evidence, low/medium agreement*). The projections show hardly any decreases (previous study: small decreases) of floods along the northern rim of the Alps, because the projected shifts in seasonal precipitation are small and the rise of the snow line should have little effect. In the rest of Austria, the scenarios show increases in floods that are generally small, but slightly larger increases are expected in the Innviertel and Mühlviertel regions. A slight shift of flooding from summer to winter in these regions may be due to an increase in air temperature as a result of climate change, leading to less snow and more winter rain.

*Other types of floods*

National flood assessments in Austria have so far focused on river floods, while other types of floods have rarely been analyzed. First studies for the contiguous United States suggest that they will become more prone to flash floods in a high-end emissions scenario (Li et al., 2022), while Bates et al. (2021) found that the combined flood risk of different flood types (pluvial, fluvial and coastal flooding) for the USA will increase even under a stabilizing emission scenario (RCP4.5). In particular, changes in pluvial floods associated with projected increases in precipitation intensity need to be better understood. Some attempts have been evaluated for Upper Austria, where Nocker and Laaha (2019) found that during the observation period 2007–2013, the most severe damage to agriculture from pluvial floods was caused by intense rainfall events. Prolonged low-intensity precipitation events played a minor role. Although pluvial floods are triggered by high rainfall intensity, their magnitude is also strongly dependent on the antecedent soil wetness, as this influences the proportion of rainfall that exceeds the infiltration capacity of the soil and produces surface runoff. The impact of varying precipitation inputs and antecedent conditions were also analyzed by Humer et al. (2017). They found that rainfall above a certain amount can trigger a flash flood regardless of preconditions, although the influence of preconditions on the discharge of a flash flood is very significant.

Changes in temporal precipitation patterns are considered to be of key importance for assessing future changes in pluvial flood risk in Austria. However, they are simulated with low confidence in climate projections and still represent a knowledge gap in climate studies. Overall, however, heavy precipitation intensities are expected to increase due to global warming, as shown by recent events (see Section 1.2.2), which is expected to intensify pluvial floods.

## Low flows

Low flow generation processes in Austria differ mainly by elevation: Summer low flows are triggered by precipitation deficits in the lowlands, winter low flows are caused by freezing and temporary snow storage in the Alps (Laaha and Blöschl, 2006). As these processes are fundamentally different, seasonality must be taken into account when interpreting the impacts of climate change on low flow events (Laaha et al., 2016; Tallaksen and Van Lanen, 2023). Summer and mixed regimes dominate below a mean catchment elevation of 900 m a.s.l., while winter regimes dominate in the higher catchments. Summer low flows generally lead to higher impacts on water-related sectors.

*Observed trends*

For the Austrian domain, low flow trends were reassessed for the period 1976–2014 by Laaha et al. (2016) and Blöschl et al. (2017) and further updated for the period 1977–2019 (43 years) in Laaha et al. (2025). Compared to the previous assessment (APCC, 2014), the low flow trends in Austria have become more pronounced in recent years. This applies to both the magnitude and the number of stations affected. The effects are more pronounced in the alpine catchments than in the lowlands.

Drying trends can be observed below 900 m a.s.l., where low flow (measured by the 5th percentile of the daily runoff, Q95) has decreased in about 16 % (previously 10 %) of the catchments in Austria during the last 43 years (*high confidence*). This is expected to increase the incidence of zero flow and increased water stress in intermittent streams, with potential impacts on biota and biogeochemistry (Straka et al., 2021; Tramblay et al., 2021). In contrast, low flows have increased in 6 % (previously 5 %) of the catchments. Significant decreasing trends are observed especially in southeastern Austria and in the Innviertel region in the north. Wetting trends dominate in alpine catchments above 900 m a.s.l., where low flows have increased in about 41 % (previously 14 %) of the catchments in Austria over the last 43 years. In contrast, only 3 % of the catchments (unchanged) experienced a decrease in low flows. An increase is particularly evident in the Central Alps due to frost attenuation (*high confidence*). This applies to areas without significant influence from water management reservoirs.

In terms of the overall magnitude of change, the mean low flow trend of all stations in Austria has intensified: Below 900 m a.s.l. -17 % over 43 years (-3.9 % per decade). Above 900 m a.s.l. +23 % over 43 years (+5.3 % per decade). Similar but more pronounced patterns than for annual low flows are observed for seasonal low flows, with summer low flows showing decreasing trends at lower elevations and winter low flows showing increasing trends in the Alps. Overall, summer and winter low flows show consistent patterns of increase/decrease across Austria, with the exception of Lower Carinthia, where winter wetting trends exceed summer drying trends.

*Future changes*

For future low flow scenarios in Austria (Laaha et al., 2016), the regional trend patterns concluded in ARR14 remain essentially valid (see Figure 1.12). However, the observed trends over 43 years already exceed the projected trends for the 45-year horizon, so the magnitude needs to be revised. In the Austrian Alps (high areas, winter low flow regime), the scenario calculations show a significant increase in low flows for the period 2021–2050 compared to 1976–2006, with an increase of about 20–30 % (previously 10–25 %; *high confidence*). In the Austrian lowlands as well as in the Alpine foreland, the scenario calculations show mostly decreasing trends (*medium evidence, low/medium agreement*). In some catchments a slight increase is expected (e.g., Mühlviertel). In other areas a decrease of low flows of about 15–20 % (previously 10–15 %) is expected (e.g., Weinviertel, northern Burgenland, parts of southern Styria, parts of the Lower Austrian Alpine foreland). In exceptional cases, the decrease will be somewhat higher. In the southeast, the scenarios show slightly larger decreases than in the previous study. The decrease in low flows in the east affects all seasons, while the increase in the west affects winter and spring.

*Low flows and stream temperature*

During heat waves, low flows are typically associated with high stream temperatures, leading to water quality degradation and potential threats to ecosystems and public health (Cross-Chapter Box 2). When flow and temperature regimes are sufficiently altered, biological indicators normally found under reference conditions may be endangered (Solheim et al., 2010), and biodiversity and ecological status may be affected (Pletterbauer et al., 2018). In warmer, drier regions, major biodiversity losses are expected due to increased droughts and hot weather. This is particularly true for small rivers (e.g., in southeastern Austria), where the type of water body may change from permanent to temporary (i.e. intermittent), drying-out in summer (Straka et al., 2021; Tramblay et al., 2021). Higher temperatures combined with increased nutrient inputs from more extreme precipitation events can lead to lower oxygen levels, which can cause stress and habitat degradation, especially for coldwater species such as salmonids. River warming is driven by the energy input of air temperature and solar radiation, resulting in a characteristic diurnal variation of the temperature regime. Warming is greatest at low flow and low water levels and can be enhanced by surface water inflow. However, shading by trees and inflow from groundwater and other sources can have a cooling effect (Kalny et al., 2017).

Streamflow temperature has been assessed at the national scale for Switzerland (Michel et al., 2020). The study showed a general increase in annual water temperature of 0.33/0.37°C per decade over a long-term (40 years)/recent short-term (20 years) period. An increase was reported for all seasons, with trends being most pronounced in summer and less pronounced in winter. On an annual scale, air temperature was found to be the main driver of water temperature. Trends are more pronounced at lower elevations than in alpine streams, where snow and glacier melt temporarily compensate for warming trends in air temperature. For Austria, the assessment is still fragmented, but the results are generally consistent with those for Switzerland. For alpine rivers in western Austria a substantial warming effect of mountain rivers with significant month-specific warming

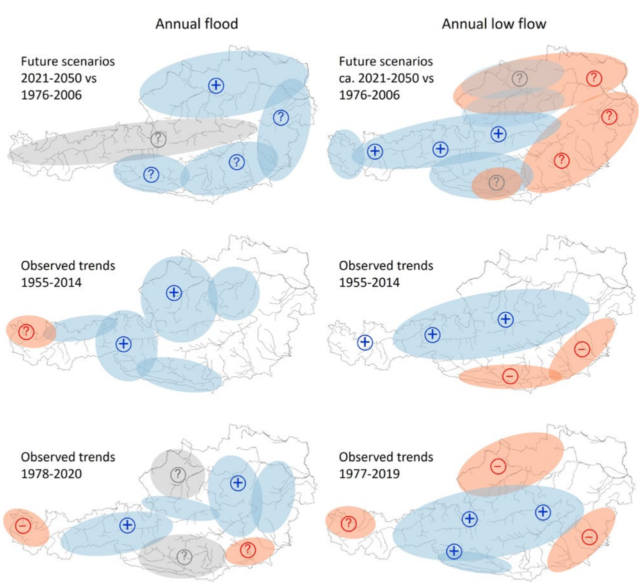



**Figure 1.12** Generalized changes in annual maximum floods (left) and Q95 low flows (right) from scenario analyses (top); long-term trends in annual values for the 1955–2014 series (middle), and more recent trends for 1978–2020 (floods) and 1977–2019 (low flows) (bottom). Blue colors indicate regions with increasing discharges, red colors indicate regions with decreasing discharges, and gray colors indicate regions with no clear trend. Future scenarios are derived from a synopsis of ÖKS15 RCP4.5 and RCP8.5 and expert scenarios focusing on mechanisms and cause-effect relationships. Based on Figures 3.21 and 5.21 of Blöschl et al. (2017) and Laaha et al. (2025).

rates was shown (Niedrist, 2023), with river size dependent rates of +0.24 and +0.44°C per decade at the annual scale. Here, the warming trends were found for all seasons and for the whole temperature range including minimum and maximum temperatures.

## 1.4.2. Lakes

Lakes are particularly vulnerable to climate change, they have been warming worldwide since the 1980s (Adrian et al., 2009; O'Reilly et al., 2015) with concurrent impacts on greenhouse gas emissions (Walter et al., 2006), nutrient cycling (Trochine et al., 2011; Michelutti et al., 2015), and changing biodiversity (Heino et al., 2021). In Austria, there are about 25,000 lentic aquatic ecosystems, including lakes, ponds, gravel pit lakes, and reservoirs. Together they cover 613 $km^2$ or 0.7 % of the Austrian territory[4]. Although these are relatively small ecosystems, they contain high levels of biodiversity and provide many ecosystem services.

The largest and one of the shallowest lakes in Austria, Lake Neusiedl (320 $km^2$), is currently at risk of drying up (see Chapter Box 1.3), while the deepest lakes, Traunsee (191 m) and Attersee (171 m), also contain the largest volumes of water (2,189 million $m^3$ and 3,890 million $m^3$, respectively). Lakes in Austria >0.5 $km^2$ range from alpine lakes, the highest being Vilsalpsee (1,165 m a.s.l.), to lowland lakes, the lowest being Lake Neusiedl (115 m a.s.l.).

### Lake temperatures

The surface temperature of monitored lakes with long-term data series in Austria has increased on average between 2.0°C (since the 1980s) and 1.5°C (since the beginning of this century) in parallel with increasing air temperature (*high confidence*). According to Kainz et al. (2017), the surface water temperature of the subalpine Lunzer See (608 m, 68 ha, 34 m depth) increased by 0.8°C in the period 1920–2015, with the strongest increase in spring and summer months (~1–2°C) and less in fall (~0.3°C). Since 1980, however, lake surface temperatures have increased more rapidly by ~1.5°C, with the lowest mean surface temperature recorded in 1980 (10.6°C) and the highest in 2015 (14.3°C, Figure 1.13a, Figure 1.13b; *high confidence*). Similarly, the lake surface temperature in the southernmost province, Carinthia, increased

[4] info.bml.gv.at/themen/wasser/wasser-oesterreich/zahlen/fluesse_seen_zahlen.html

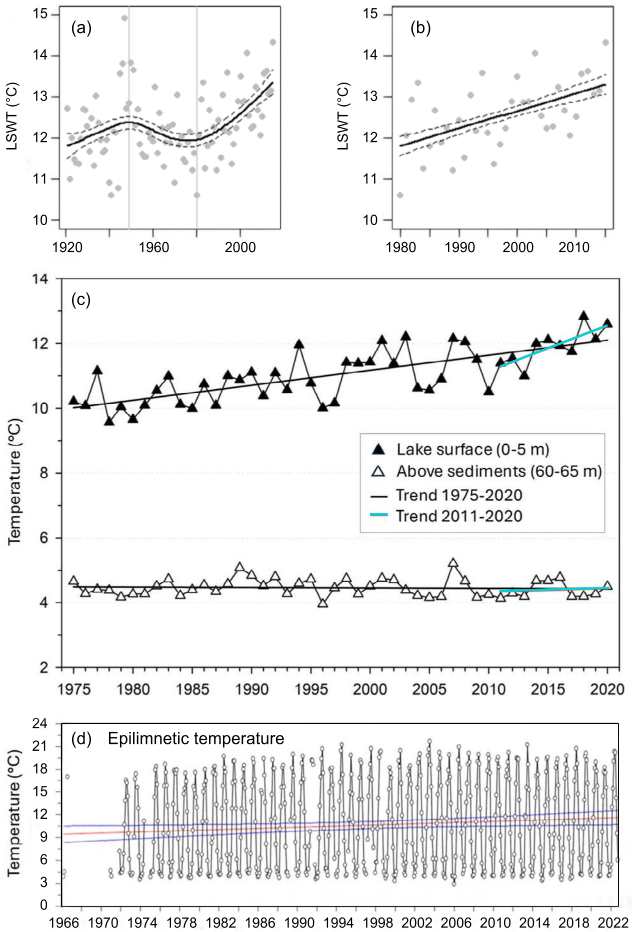



Figure 1.13 Annual mean lake surface water temperature (LSWT; °C) during the ice-free periods of (a) Lunzer See (1920–2015), (b) Lunzer See (1980–2015, Kainz et al., 2017), (c) Mondsee (Luger et al., 2021), (d) Piburgersee (Sommaruga et al., 2023).

between 1.2°C (Faaker See) and 2.5°C (Klopeiner See)[5] over a period of 16 years (2007–2022), and the current report on the environment in Styria[6] concludes that Grundlsee (732 m a.s.l.) also significantly increased its lake surface water temperature by an average of 0.5°C to 3.5°C (in 2018) over the period 2007–2021, compared to the mean lake surface temperatures of an earlier reference period (2000–2006). Mondsee (Upper Austria) also increased its surface water temperature consistently by ~2°C from 1975–2020, while the mean annual temperatures at the bottom (60–65 m depth) remained stable at ~4.5°C (Luger et al., 2021) (Figure 1.13c). Piburgersee (Tyrol, 913 m a.s.l.) also increased its lake surface water temperature by ~2°C, from 9 to 11°C, between 1966 and 2022 (Sommaruga et al., 2023) (*high confidence*) (Figure 1.13d).

Changes in water temperatures below the lake surface are lake-specific and cannot be generalized to all lakes. For example, there is *robust evidence* that the subsurface temperature (0–5 m below the water-air interface) of Grundlsee has increased from 0°C (2011) to 2°C (2013) relative to the mean water temperature profile of the reference period (2000–2006). The higher surface temperature of the lake in winter is a tipping point. If the surface temperature does not fall below 4°C (highest water density), convective mixing does not occur and the water column remains stratified, resulting in reduced oxygen supply to the hypolimnion.

## Lake ice

There is no consistent data record on the duration of lake ice on Austrian lakes. Since 1905, full lake ice cover at Lunzer See has decreased dramatically from 93 days (1905–1915) to 35 days in the last decade (2010–2020). In 2007 and 2014, Lunzer See had no ice cover at all (Kainz et al., 2017) (Figure 1.14a). While Piburger See (Tyrol) was fully ice-covered for 119 days in 1966, the duration of full ice cover decreased steadily to 84 days in 2023 (Sommaruga et al., 2023) (Figure 1.14b). In general, lake ice-on occurs later in the season and lake ice-off occurs earlier (*medium confidence*). The observed decrease in annual lake ice duration is comparable to other lakes in the Northern Hemisphere, where ice duration has become 28 days shorter on average over the past 150 years (Woolway et al., 2022).

## Nutrients and oxygen dynamics

Temporal nutrient dynamics, in contrast to consistently increasing lake water surface temperatures, are lake and probably catchment-specific (*high confidence*). Mondsee strongly decreased its total phosphorus (TP) concentrations above the sediment-water interface from ~350 µg $L^{-1}$ (1975) to ~20 µg $L^{-1}$ (1990s), after which [TP] increased again to ~100 µg $L^{-1}$ by 2023 (Luger et al., 2021). A similar pattern was observed for ammonium concentrations. This temporal nutrient pattern coincided with changes in dissolved oxygen ($dissO_2$) concentrations. At Mondsee, $dissO_2$ concentrations increased from 1975 until the 1990s and then decreased until 2023. Low $dissO_2$ concentrations in the hypolimnion remobilize phosphorus from the sediment-water interface back into the lake water. The concurrent low $dissO_2$ and increasing

5 data.gv.at/katalog/dataset/8f554c0a-fd7b-4d66-bfdb-dc2237318a52#resources

6 app.luis.steiermark.at/berichte/Download/Umweltschutzberichte/Umweltbericht_20-21_Gesamt.pdf

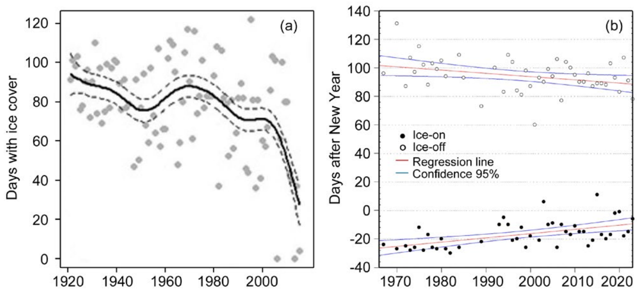



**Figure 1.14** Changes in full ice cover of (a) Lunzer See in days from 1921 to 2015 (Kainz et al., 2017), and (b) Piburgersee ('Eislegung': ice-on and 'Eisbruch': ice-off) from 1966 to 2023 (Sommaruga et al., 2023).

phosphorus concentrations result in restricted habitats for fish and other oxygen-demanding animals, but may result in higher algal biomass enabled by the re-mobilized phosphorus in the photic zone of the lakes, and may eventually lead to re-eutrophication of certain lakes. Similar patterns, but much lower [TP], have been reported for Piburgersee, where [TP] decreased from ~35 μg $L^{-1}$ (1975) to ~20 μg $L^{-1}$ by 2000, and then increased again to ~30 μg $L^{-1}$ by 2023 (Sommaruga et al., 2023). The decreasing diss$O_2$ concentrations of Austrian lakes are very consistent with observed decreases in diss$O_2$ levels of lakes worldwide, which are reported to be 3–9 times greater than in the world's oceans (Jane et al., 2021). There is *robust evidence* that declining diss$O_2$ levels have the potential to dramatically shift species habitats and threaten lake ecosystem services (Schindler, 2017).

Overall, the most important changes relate to temperature, stratification, diss$O_2$ and TP content: all four parameters are very closely related or dependent on each other. Therefore, particularly careful management of avoidable nutrient loads remains important. Steadily increasing [TP], as currently measured in these lakes at the reduced diss$O_2$ hypolimnion, is a clear indication of internal fertilization.

## 1.4.3. Groundwater and soil water

The vadose zone is the variably saturated zone between the ground surface and the permanent water table of groundwater (Stumpp and Kammerer, 2022). The vadose zone and groundwater are important parts of the water cycle (Aquilina et al., 2023), storing more than 10,000 times the amount of water held by rivers worldwide (Oki and Kanae, 2006). In Austria, groundwater, including spring water, is the most important water resource, accounting for 100 % of the drinking water supply (Vogel, 2001; BMLRT, 2021). For the sustainable management of water resources, and thus for the protection of groundwater resources in terms of quantity and quality, it is important to understand the impacts of climate change on subsurface water fluxes and storage.

### Observed trends

In the last Austrian Assessment Report (APCC, 2014), Nachtnebel et al. (2014) summarized that, based on different emission scenarios and regional climate models (ARPEGE-ALADIN, ECHAM5-RegCM3, REMO-UBA), only small variations in groundwater recharge rates can be expected for the future; exceptions are individual, drier regions with decreasing precipitation rates and unfavorable hydrogeological situations. However, in the agricultural areas of eastern and southeastern Austria, more groundwater was expected to be needed for irrigation due to increasing crop water demand.

These past results are mainly confirmed by recent studies that provide additional information on quantities and uncertainties. An analysis of past groundwater recharge in Austria found a west-east gradient, with generally higher groundwater recharge in the western part of Austria compared to the eastern or southeastern part (BMLRT, 2021; Schübl et al., 2023) (*high confidence*). The ratio of groundwater recharge to precipitation (GWR/P) is strongly correlated with the amount of precipitation, and higher recharge rates and lower actual evapotranspiration are correlated with a higher percentage of sand in soils (Schübl et al., 2023). Groundwater recharge rates are seasonally more variable (71–265 %; quantified as the coefficient of variation of the standard deviation between monthly sums and annual means) compared to precipitation (52–76 %) and actual evapotranspiration (64–76 %) for selected grassland sites in Austria (Schübl et al., 2023). More detailed studies of groundwater recharge for forested or agricultural sites across Austria are lacking and would require a systematic analysis of monitoring data for representative sites.

Groundwater use and climate change can affect groundwater levels and thus subsurface water availability. Groundwater level trends for the period 1976–2000 show that 12 % and 18 % of the wells investigated showed a significantly increasing and decreasing groundwater level trend, respectively. 70 % showed no significant trend (Blaschke et al., 2011). Integrated results for Austria show overall decreasing trends in groundwater levels, with a pronounced decrease until 1985 and increasing trends until 2016; regional differences were found for the analysis from 1980–2018, with increasing trends in Lower Austria, Vienna, Vorarlberg, Burgenland and Upper Austria, mostly decreasing trends in Carinthia, and varying or no trends in Styria and Salzburg (Haas and Birk, 2019) (*medium confidence*). Changes in groundwater levels are directly related to climate change, especially during dry periods (Haas and Birk, 2017), but also indirectly due to increased water consumption and water management (see Sections 2.2.1 and 7.4.1) and proximity to surface water bodies. In general, the impact of hydrometeorological extreme events on groundwater depends on local hydrogeological conditions, particularly whether precipitation or stream-aquifer interaction is the primary driver of groundwater level changes (Haas and Birk, 2019). A nationwide analysis of groundwater level changes and groundwater droughts with more recent data is still lacking. It has to be emphasized that the concept of groundwater drought research is rather new and only limited index-based methods exist (Bloomfield and Marchant, 2013). Due to the lack of Austria-wide studies, no confident and reliable statement can be made for the current situation; such research should include the development of new methods based on time series analysis, similar to streamflow drought (Stahl et al., 2020).

It is not known whether declines in groundwater levels due to exploitation or reduced groundwater recharge can cause infrastructure-relevant subsidence in Austria, as has been observed in other – mainly densely populated – areas worldwide (Corti et al., 2009; Chaussard et al., 2021). However, it is expected to be highly uncertain given the groundwater level variability currently observed in Austria, as drastic water level declines in clay-rich sediments would have to persist over longer time scales (Collados-Lara et al., 2020).

Furthermore, little is known about the effects of climate change on future groundwater quality and ecology. For Austria, absolute groundwater temperature changes were observed that were even higher (+0.7±0.8°C) compared to air temperature changes for the period 1994–2013 (+0.5±0.3°C) (Benz et al., 2018). Therefore, these temperature increases are also expected to affect biogeochemical processes, similar to the potential impacts of geothermal energy use on groundwater quality and ecology (Griebler et al., 2016). As with climate change impacts on groundwater levels, the impacts on groundwater quality will depend on whether the main source is precipitation or also indirect recharge from streams.

### Future changes

Predictions of groundwater recharge rates (1981–2100) for grassland sites vary drastically between three ÖKS15 models (MOHC-HadGEM2-ES, ICHEC-EC-EARTH, IPSL-CM5A-MR) and two RCPs (4.5 and 8.5), especially for the summer months (Schübl, 2023) (see Figure 1.A.14). An increase in recharge is simulated mainly for winter and for western sites, due to higher temperatures with less snow accumulation and/or higher amounts of winter precipitation, followed by decreasing recharge rates in spring. If the scenarios show decreasing trends in annual groundwater recharge, they are more pronounced at western sites and at higher elevations, with longer droughts lasting until later in the calendar year. Uncertainty in recharge prediction is largely dominated by the difference in climate projections; only at the dry sites in the east and for shorter time periods, do uncertainties in soil hydraulic parameters play a role in predicting water fluxes. Significant increasing trends in recharge are projected for IPSL (RCP8.5) and decreasing trends for MOHC (RCP4.5) until the end of the 21st century (*limited evidence, medium agreement*). However, an increase in potential evapotranspiration for MOHC (RCP4.5) does not consistently lead to an increase in actual evapotranspiration rates, as the predicted dry conditions would not provide enough water to meet the atmospheric evaporative demand (Schübl, 2023). Such behavior is also predicted for other dry regions (Ng et al., 2010). Integrated over Austria, the available groundwater resources may decrease by up to 23 % by 2050, regionally by as much as 30 %, whereas the decrease in the east of Austria is small and groundwater resources may even increase with increasing winter precipitation (BMLRT, 2021; Schübl, 2023) (*medium confidence*). The resulting water fluxes from the use of different climate models and emission scenarios differ, highlighting the need for more accurate future scenarios for predicting water fluxes and availability with lower uncertainty. In addition, changes in water fluxes should not only be compared between climate scenarios, but also in relation to GWLs. It would also be necessary to consider the consequences of land use and land cover changes on subsurface water fluxes due to climate change, such as longer growing seasons, changes in plant diversity or human water consumption.

## 1.5. Pedosphere

The diversity of geology, landscape and climatic conditions in Austria results in a large variety of soils. Agricultural soils (cropland and grassland) are well documented.[7] For the ap-

[7] See bodenkarte.at

proximately 50 % of the Austrian land area that is not used for agriculture, the documentation is either coarse or limited to certain areas. Improved documentation of forest soils is currently being carried out. However, only a part of this data is yet available to the public.

Land use has influenced Austria's soils for millennia, depending on its intensity and soil type. Therefore, Austria's current 'soilscape' is as much a result of natural processes as it is of human intervention. The current driving forces shaping Austria's soils are management practices: Land use (cropland, grassland, forest), tillage, fertilization, crop rotation, crop residue management, water management, cutting practices, etc., as well as micro- and macroclimatic conditions. In combination, land use and climatic conditions produce additional changes, often within relatively short periods of time. As a result of these drivers, important impacts on both the abiotic and biotic environment can be expected, in particular changes in organic matter dynamics and erosion (including water and wind erosion, see also Section 1.4). Countermeasures against soil degradation should be specifically linked to management practices capable of preserving soil functions. First and foremost, the long-term stabilization or increase of soil organic carbon is an important aspect in countering the consequences of climate change. Carbon-rich soils have higher aggregate stability, higher water infiltration rates and water retention capacity (Amlinger and Geszti, 2001; Erhart and Hartl, 2010; Kolbe and Zimmer, 2015), making them more resilient to extreme events such as heavy rainfall and drought (Fliessbach et al., 2008; Petersen and Weigel, 2015), reduce the risk of erosion (Erhart and Hartl, 2010) and, above all, produce higher yields in the medium to long term (see Chapter 2) (Johnston et al., 2009; Kolbe and Zimmer, 2015). In specific cases, management changes may also be an option to maintain key soil functions. While the overall effects of management measures are well documented, detailed mechanisms remain to be elucidated. Furthermore, research is needed to foster the implementation of respective measures in the practical land management.

In general, the carbon sequestration potential of most Austrian soils is not large, with the notable exception of histosols (peat soils, see Section 2.1.1 and Table 2.1). First estimates for arable soils (Baumgarten et al., 2022) show a sequestration potential of max. 2.2 tC/ha, where the results show clear differences in different regions (from losses to moderate sequestration). Acceleration is possible both with respect to climate change (e.g., enhanced mineralization) and specific measures related to carbon farming practices (for more details, see Table 2.3 and Section 2.3.1). The effect of measures may also differ regionally (e.g., soil tillage, waterlogging).

As soil erosion is an important mechanism of soil degradation and affects soil organic matter (SOM) and water dynamics, it is discussed in more detail: Precipitation-induced soil erosion is strongly dependent on precipitation intensity. Common model approaches to estimate so-called precipitation erosivity are often closely coupled to the maximum half-hourly precipitation intensity (I30). Currently, however, most climate models do not provide sufficient temporal resolution to accurately estimate peak intensities in the intermediate and distant future. Cluster studies (Vasquez et al., 2023) show that especially convective precipitation types in summer, often of short duration and high peak intensity, dominate the erosivity behavior in Austria – even though the total precipitation amounts of highly erosive events can often be relatively lower than those of long-lasting stratiform types.

The clear trends towards temperature increase are accompanied by an increased tendency to convective events, and thus extreme precipitation erosivity. In particular, the southeastern foothills of the Alps in Carinthia and Styria have an increased risk of highly erosive events (Johannsen et al., 2022; Vasquez et al., 2023). Ultimate soil erosion, however, depends on factors other than precipitation erosivity, such as terrain, land use, vegetation cover, and soil infiltration and erodibility. Erosion plot studies by, e.g., Strohmeier et al. (2016) or Rab et al. (2023), have shown that the local context of precipitation erosivity and soil erodibility is critical to properly assess erosion behavior. The study by Strohmeier et al. (2016) showed that in Mistelbach (Lower Austria), for example, the long-term average soil erosion is dominated by the extreme events (i.e., >20 years recurrence interval), whereas in Pixendorf near Tulln (Lower Austria), about 50 km away, with slightly higher average annual precipitation, the large number of less erosive but much more frequent events (i.e., <<20 years recurrence interval) have the largest share in the total erosion events. Climate research to determine future precipitation intensities will be of central importance to properly assess erosion behavior and thus the sustainability of, e.g., agricultural ventures in context (*high confidence*).

In addition, higher temperatures may lead to higher mineralization rates of SOM if the water supply is still sufficient (Schindlbacher et al., 2015; Wiesmeier et al., 2016). This can be expected especially in the western regions of Austria with higher elevations. This loss of SOM may lead to an increase in GHG emissions (Wiesmeier et al., 2016), but may also have negative effects on soil structure (Jensen et al., 2019) (*high confidence*).

## 1.6. Biosphere

### 1.6.1. Wetlands

This section describes the characteristics of wetlands in Austria and assesses the threats that wetlands in Austria face from climate change and inappropriate land management, which ultimately lead to habitat degradation and changes in their specific animal and plant communities.

Wetlands can be categorized according to different guidelines. The IPCC classifies wetlands as a land use category (IPCC, 2014a), while other classifications define wetlands more broadly (Ramsar, 1971). Although this report takes a similar approach to the IPCC, it does not define wetlands according to the IPCC wetlands supplement (IPCC, 2014a). Here, both peat accumulating wetlands and wetlands that do not accumulate peat, such as some floodplains and soda pans, are included, but drained sites are not, as these are covered in Section 1.5.

Austria hosts a wide variety of mires. Due to the climatic and topographic diversity and varying degrees of land use intensity, many different types of mires still exist today. In the mountains, mires predominate, while in the lowlands, floodplains, riparian wetlands or soda pans occur.

The majority of wetlands in Austria are managed. Many mires and floodplains are dominated by grassland or forest. Management practices strongly influence the occurrence and abundance of species. For examples of management and its impact on biodiversity, see paragraph on anthropopogenic drivers of wetland degradation below and Section 1.6.4. Historically, and especially in the last 80 years, drainage to convert natural wetlands to agricultural or forest land has been the most important driver of wetland loss (*high confidence*). Although it is possible to restore wetlands, drainage can alter wetland characteristics to such an extent that they cannot be successfully restored in the medium term. Mires in particular experience severe changes in soil porosity and peat composition that may make restoration very difficult even in the long term (Loisel and Gallego-Sala, 2022) (*high confidence*).

Despite the often detrimental influence of land management on wetlands, wetland management is sometimes welcomed for the sake of species conservation. In Austria, many mires are extensively managed without strong drainage. Such sites are valued by conservationists as they host valuable biodiversity. Nevertheless, it must be emphasized that the survival of wetland species is impossible without intact wetlands, so wetland conservation is the highest management priority.

Wetlands have been lost to a greater extent than other ecosystem types (*high confidence*). 80 % of Europe's wetlands have been lost in the last 100 years (Verhoeven, 2014). They are highly threatened by climate change, as a positive water balance is a prerequisite for the existence of wetlands. The climatic drivers of wetland degradation are droughts, increased evapotranspiration, extreme precipitation and the resulting strong runoff, and a more incoherent water supply due to the disappearance of glaciers and reduced water storage in snow (*high confidence*) (see Section 1.2.2).

Of all ecosystems, peatlands store the most carbon per area. Covering 3 % of the Earth's land surface, they store one third of global soil carbon. When intact, they are persistent carbon sinks, but when drained, they become strong carbon sources. On a global scale, they are estimated to contribute 5 % of global greenhouse gas emissions (Leifeld and Menichetti, 2018). In Austria, this figure is unknown, but is likely to be around 1–2 % of national greenhouse gas emissions (BMLRT, 2022). The high carbon dioxide release associated with peatland drainage is itself a driver of climate change (see Section 2.2.2), creating a positive feedback loop by releasing greenhouse gases that in turn promote peatland drying-out in a warmer climate. Climate change has detrimental effects on most wetlands in Austria, although in some locations climate change is expected to foster the development of mires in the medium term (Essl et al., 2012). Overall, most wetlands – such as salt pans, floodplains and most mires – can be expected to be negatively affected by climate change (*high confidence*). In Austria, the effects of land use are immediate and more severe than those of climate change in the case of drainage, damming and diking of rivers, and the establishment of most agricultural crops or commercial trees (Gaube et al., 2024) (*high confidence*).

In addition to their value for biodiversity, the carbon cycle and greenhouse gas emissions, wetlands are important controls in the water cycle, slowing the runoff of excess water in rivers or on the soil surface. In the case of peatlands, they store water like a sponge and release it slowly under drier conditions (*high confidence*), alleviating water runoff problems in Austrian river valleys. Furthermore, wetlands provide local cooling due to their high evapotranspiration rates (Worrall et al., 2022). Thus, especially in Austria with its many valleys, rivers and small depressions, wetlands are an important insurance against extreme weather events and, more generally, against the effects of climate change. They are an important component of Austria's climate-resilient landscapes.

### 1.6.2. Forests

Forest ecosystems play an important role in global biogeochemical cycles, act as both sources and sinks of greenhouse gases, and thus have a significant influence on the Earth's climate. Here, we assess the current state and potential impacts of a changing climate on Austrian forests, as modulated by the tree population dynamics processes of growth, mortality and reproduction. How ecosystem services may be affected by a changing climate is discussed in Chapter 2.

According to the latest results of the Austrian National Forest Inventory (ÖWI 2016–21)[8], the forest area in Austria is 4.02 million ha (47.9 % of the land area). Of this, 14.7 % is classified as non-productive forest (not in yield), representing steep, inaccessible and unproductive forest areas. During the last decades, the forest area in Austria increased by 3,000–4,000 ha per year. Almost the entire forest area has been subject to land use (wood utilization, grazing, litter raking) with varying intensity for centuries.

According to a comprehensive study by Grabherr et al. (1998), 25 % are natural and semi-natural, 41 % are moderately modified and 34 % are heavily modified. Due to ongoing changes in species composition and deadwood accumulation, the proportion of moderately modified forests may have increased moderately. At present, 58.6 % of the accessible forest area is coniferous, 24.1 % is deciduous, 17.3 % is cleared and currently not stocked with timber species. *Picea abies* is the most common coniferous species with 46.2 % of the total area, the most common deciduous species is *Fagus sylvatica* (10.4 %).

Ownership is a key feature for understanding the current state of Austrian forests and drawing conclusions for future development paths. Small private owners (<200 ha) account for 53.5 % of the forest area, large private owners and communities for 35.7 %, and the state-owned share of 14.8 % is managed by the Austrian Federal Forests (ÖBf AG). The current average standing stock is 303 $m^3$/ha. The standing stock has been increasing for decades because the average annual harvest is lower than the annual gross growth. The relationship between growth and harvest varies between the different types of ownership. For small owners, it has been varying between 0.75 and 0.85, depending on timber prices and unplanned harvests due to disturbances. For large private owners and ÖBf AG, the balance between growth and harvest is approximately equal. The Environment Agency Austria (Umweltbundesamt, 2024) estimates that due to high damage caused by disturbances (storms, bark beetles) and reduced increment, timber removals exceeded growth in the years 2018 and 2019. This may occur more frequently in the future (*medium confidence*).

Climate change affects forest development by influencing the growth, reproduction and mortality processes of tree populations. These effects will vary depending on soil conditions, region and altitude. At higher elevations, temperature is currently a limiting factor for many tree species, especially broadleaf species. In a warmer climate, habitat for these species will increase in the mountains (*Fagus sylvatica, Acer pseudoplatanus*), while in the currently already warm and dry lowlands, drought-adapted tree species such as oaks will gain habitat and *Fagus sylvatica* will lose habitat (Augustine and Reinhardt, 2019; Buras et al., 2020; Kessler and Lexer, 2023). Productivity in mountain forests (>800 m a.s.l.) will increase by about 10–25 % by the end of the 21st century due to more favorable thermal conditions (Irauschek et al., 2017a; Albrich et al., 2020). At GWL 4.2°C, however, productivity in the lowlands (<800 m a.s.l.) will decrease by up to 50 %. Overall, temperature will be the dominant factor in the mountains and water limitation at low elevations (<800 m a.s.l.).

Disturbances lead to abrupt changes in forest structure and processes and are thus a key determinant in shaping the future composition and structure of forest ecosystems (Seidl et al., 2017; Patacca et al., 2023). The potential for natural regeneration (seed availability) and browsing pressure by ungulates (*Capreolus capreolus, Cervus elaphus, Rupicapra rupicapra*) will play an important role in shaping future species composition. In Austrian forests, the most relevant disturbance agents are wind, snow breakage, bark beetles and pathogenic fungi. Since about 1992, the amount of timber volume damaged by spruce bark beetles (mainly *Ips typographus* and *Pityogenes chalcographus*) has increased significantly from a mean annual damaged volume of about 250,000 $m^3$/year (1950–1990) to a mean damage volume of about 1.9 million $m^3$/year (2002–2012) to a mean damage volume of 2.8 million $m^3$/year (2010–2023). The main drivers are warmer temperatures, which favor the development of insect populations, and the increasing vulnerability of

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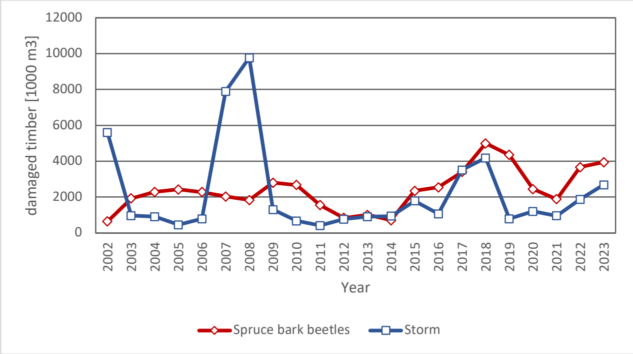


Figure 1.15 Damaged timber volume due to bark beetle and storm disturbances in Austrian forests (for a description of the approach, see Steyrer and Tomiczek, 2002).

the host species, Norway spruce, to water shortages (Figure 1.15). In mountainous regions, the high proportion of Norway spruce and warmer temperatures will increase the risk of intense bark beetle outbreaks, with significant negative impacts on the provision of ecosystem services such as protection against gravitational hazards (see Section 2.2.2, 7.4.2). New invasive pests, such as the fungus *Hymenoscyphus fraxineus* which caused the ash dieback in the 2000s, are a significant risk for the future (Halmschlager and Kirisits, 2008; Lapin et al., 2019).

The frequency of forest fires does not show a clear trend and varies between 150–300 fires per year. However, there appears to be an increasing trend in the frequency of fire events with area burnt >30 ha (Müller et al., 2020a). Expected increases in the intensity of droughts and heat waves, combined with more recreational activities, are likely to increase forest fire activity in the Alpine region (Müller et al., 2020b).

The long natural lifespan of trees and the long production cycles in managed temperate forests do not allow for rapid adaptation to environmental changes. This gap between adaptation needs and long lead times can seriously hamper the sustainable provision of ecosystem services from forests (Irauschek et al., 2017b; Sotirov et al., 2024) (see Chapter 2).

### 1.6.3. Grasslands

Grasslands are widespread in Austria. They cover about half of the cultivated land (excluding forestry) (Umweltbundesamt, 2020) and are mostly managed as pastures or meadows. Without management, a large part of these grasslands would develop into forests (or in some cases shrublands). Natural grasslands are limited to regions above the tree line and small areas that are either too dry or too wet for forests (Leuschner and Ellenberg, 2017). Semi-natural and intensively used grasslands are found in most parts of Austria, but are rare in the Pannonian region, where crop cultivation dominates. Grasslands provide a number of ecosystem services (ecosystem services are discussed in detail in Section 2.2). They provide forage for livestock and are important for carbon storage, tourism (see Sections 4.4.3 and 7.4.2), filtration of drinking water (e.g., Vienna's drinking water catchments), reduction of runoff and erosion control, especially in mountainous areas (Section 7.4.2). In addition, many extensively managed grasslands in Austria are located on peat soils and thus have a very specific species composition and high importance for soil carbon storage (see Sections 1.6.1 and 2.2.2).

The area of cultivated grasslands below the tree line has been decreasing for several decades, mainly because less productive and/or more difficult to cultivate areas have been abandoned and/or afforested (Pils, 1994; Umweltbundesamt, 2020). The use of the remaining grasslands was massively intensified in the second half of the 20th century, followed by a slight tendency towards de-intensification in recent decades. Currently, 30 % of Austria's cultivated grasslands are under organic farming regimes (BMNT, 2019). However, eutrophication and the high number and early timing of cuttings remain serious problems for many biota adapted to grassland ecosystems. As a result of the double pressure of abandonment and intensification, grassland specialists among plants and animals are high on national Red Lists (Schratt-Ehrendorfer et al., 2022; Umweltbundesamt, 2023), and at the habitat level, traditionally used, nutrient-poor to moderately nutrient-rich hay meadows with one or two mowings per year have become habitats of conservation concern and are listed in Annex I of the European Union's Habitat Directive (Types 6510 and 6520: lowland and mountain hay meadows).

Thus, climate change is not yet a major threat to grassland ecosystems in Austria. However, increasing drought could reduce the economic value or make them dependent on irrigation, possibly triggering conversion to other types of use. Depending on the type, some grasslands are quite resistant to drought in terms of species composition and also productivity (Deléglise et al., 2015). On average, however, grassland productivity is reduced under drier or even drought conditions, especially in the already dry areas of Austria (*high confidence*). Prolonged droughts can also lead to a shift in species composition (Stampfli and Zeiter, 2004). The high biodiversity of natural and low-intensity grasslands may act as a buffer against the effects of drought and increase the resilience of grasslands (Kreyling et al., 2017), but research on these topics in Austrian grasslands is lacking.

In high-alpine areas, the current shrinkage of grasslands is a consequence of the rise of the tree line and the densification of forests, which is primarily caused by the regionally varying abandonment of summer pastures (Gehrig-Fasel et al., 2007). Climate impacts on high alpine grasslands are likely to be slow to manifest (Dullinger et al., 2004; Tasser et al., 2017), but potentially massive (*medium confidence*). Areas above the tree line could shrink by >50 % in the European Alps even under moderate warming (Nagy and Grabherr, 2009), with severe consequences for tourism (Section 7.4.2) and biodiversity (see Section 1.6.4).

Natural or semi-natural grasslands below the tree line are either wetlands or dry grasslands. While the former are likely to decrease under climate warming (Essl et al., 2012; Baatar et al., 2019) (*medium evidence, high agreement*) (see Section 1.6.1), the latter may even benefit, as many of their biota are adapted to warm and dry conditions (Baatar et al., 2019). However, actual expansion will depend on whether concurrent land use provides the necessary space. Where grasslands are managed, use may intensify in the future to keep productivity high despite drier conditions, offsetting potential positive effects of climate change on warm or drought-adapted species.

### 1.6.4. Biodiversity

In Austria, climate change affects flora and fauna that are already under severe pressure from other stressors, such as agricultural intensification, changes in the composition and structure of pristine forest tree species, abandonment of traditional low-intensity land use, land consumption, pollution, or changes in water flow regimes (*high confidence*). Depending on the species group, between 25–65 % of the species occurring in Austria are listed as critically endangered, endangered or vulnerable in groups such as mammals, birds, amphibians, reptiles, fish, a number of invertebrate species or vascular plants, with only a minority so far citing climate change as the main reason for the threat (Schratt-Ehrendorfer et al., 2022; Umweltbundesamt, 2023). Nevertheless, the effects of climate change have already been observed in numerous species and are increasingly contributing to the pressure on biodiversity. This occurs both directly – through changes in temperature or drought conditions that exceed tolerance limits (Dorts et al., 2012; Borgwardt et al., 2020; Reiner et al., 2021) – and indirectly through adverse effects on non-climatic environmental conditions (Thom et al., 2017) or biotic interactions (Gilgen et al., 2010; Temperli et al., 2013; Alexander et al., 2015; Jakoby et al., 2019; Rehnus et al., 2020). Depending on the level of future warming and the local or regional effects, predictive models suggest that the contribution of climate change to the pressure on biodiversity will increase and may even exceed that of further land-use changes in certain taxonomic groups, habitats and regions (Dullinger et al., 2020; Barras et al., 2021a; Neff et al., 2022) (*medium confidence*).

Austria is a mountainous country, and mountains are the environment where climate impacts on species have been most clearly documented. In particular, the warming of recent decades has begun to affect the spatial distribution of mountain biota (*high confidence*) (see Chapter 7 for more details). Reports on upslope species shifts in Austria or neighboring countries are available for different taxonomic groups, e.g., mammals (Schai-Braun et al., 2021), birds (Popy et al., 2009; Knaus, 2018; Bani et al., 2019; Schai-Braun et al., 2021; Teufelbauer et al., 2024), butterflies (Bonelli et al., 2021; Kerner et al., 2023), bees and bumblebees (Biella et al., 2017; Maihoff et al., 2023; Scharnhorst et al., 2023), grasshoppers (Illich and Zuna-Kratky, 2022), snails (Baur and Baur, 2013), millipedes (Gilgado et al., 2022), vascular plants (e.g., Küchler et al., 2015; Lamprecht et al., 2018; Rumpf et al., 2018) and bryophytes (Bergamini et al., 2009). A recent meta-analysis from Switzerland – with results likely applicable to Austria – documents rates of shift of elevational optima and upper limits of up to 36 m per decade since 1970, albeit with strong variation among taxonomic groups and species (Vitasse et al., 2021). In vascular plants, a parallel regression of range limits has been demonstrated, implying that local populations of many species have become extinct at former lower range limits (Rumpf et al., 2018) (see Figure 1.16). Similarly, between 1981–1985 and 2013–2018, Austrian mountain birds showed both a contraction of the breeding range and a significant upward shift in elevation (Teufelbauer et al., 2024). The relative contribution of climate and land use change to these range shifts could not be quantified. In any case, upslope shifts of most species lag behind warming trends (Chen et al., 2011; Rumpf et al., 2019; Vitasse et al., 2021) (*high confidence*). Variation in these lag times among species may disrupt biotic interactions, such as those between faster-moving insects (Maihoff et al., 2023) and slower-moving host plants (Kerner et al., 2023). As a special case, it has been reported that non-native species, which are currently still rare at higher elevations, move upward considerably faster than native species (Dainese et al., 2017), with potential risks for populations of competitively inferior native species. In the Alps, continued upward shift will inevitably lead to shrinking populations of high-elevation specialists (Revermann et al., 2012; Lamprecht et al., 2018; Rehnus et al., 2018; Brambilla et al., 2022) (*high confidence*), as a consequence of conical mountain shapes, limited summit elevations, and concurrent tree line shifts induced by both summer pasture abandonment and climate warming (Dullinger et al., 2004; Gehrig-Fasel et al., 2007; Ferrarini et al., 2017; Bani et al., 2019). Microclimatic variation may mitigate extinction risks to some extent (Scherrer and Körner, 2011; Ohler et al., 2020), but declining populations will become increasingly vulnerable to all kinds of hazards, including habitat destruction from the expansion of infrastructure such as ski slopes (Imperio et al., 2013). The magnitude of population decline will depend strongly on the level of warming, and could be as high as ≥80 % for many alpine species under severe warming (Engler et al., 2011). The decline will be even more pronounced and/or reach comparable levels already at moderate levels of warming in the endemic flora and fauna of high altitudes in Austria, which includes many immobile species restricted to marginal alpine mountain ranges at rather low elevations (Dirnböck et al., 2011; Semenchuk et al., 2021) (*medium evidence, high agreement*).

Apart from elevational shifts, warm-demanding species, especially those with a (sub-)Mediterranean range center, have expanded their geographic distribution northward and increased their population sizes in Central Europe in recent decades, while cold habitat specialists have tended to decrease in population size, occupancy or population performance (*high confidence*). Corresponding reports, also from comparable neighboring regions such as northern Italy, Bavaria, Switzerland or the Czech Republic, exist for plants (Loacker et al., 2007; Lamprecht et al., 2018; Reich et al., 2018; Rumpf et al., 2018), various insect taxa (e.g., grasshoppers, dragonflies and butterflies; Kenyeres et al., 2019; Engelhardt et al., 2022; Neff et al., 2022), birds (Lemoine et al., 2007; Hušek and Adamík, 2008; Reif et al., 2008; Stiels et al., 2021), and some mammals such as alpine chamois (Chirichella et al., 2021), marmot (Tafani et al., 2013) and mountain hare (Rehnus et al., 2018). Species that are expanding in response to climate change include several forest and agricultural pests that have increased in distribution, population size and/or voltinism (= number of generations per year) – or are predicted to do so under further warming – such as the bark beetle (*Ips typographus*) (Seidl et al., 2009; Marini et al., 2012; Temperli et al., 2013), pine processionary moth (*Thaumetopoea pityocampa*) (Battisti et al., 2005), European corn borer (*Ostrinia nubilalis*) (Trnka et al., 2007) or codling moth (*Cydia pomonella*, (Stoeckli et al., 2012). Among the potential 'winners' of climate change are also a number of neobiota native to regions with warmer climates (Walther et al., 2007; Dullinger et al., 2017) (*medium evidence, high agreement*). Detailed studies of several invasive species of ecological, economic and/or health concern have confirmed that climate change has already triggered or facilitated their spread, or will do so in the future, e.g., *Ambrosia artemisiifolia* (Storkey et al., 2014; Mang et al., 2018), *Robinia pseudacacia* (Kleinbauer et al., 2010), *Vespa velutina* (Barbet-Massin et al., 2013), *Aedes albopictus* (Caminade et al., 2012; Kraemer et al., 2019; Bakran-Lebl et al., 2022). With continued warming, additional non-native pests and pathogens may establish and expand in Austria (Seidl et al., 2018).

The proximate causes of population declines under a changing climate are likely to vary among species and are only partially understood. Several studies suggest that an increased frequency and intensity of extreme events, such as periods of drought and heat or intense summer precipitation, may often be more important than warmer average temperatures (*medium confidence*). Corresponding results from Austria and neighboring countries are available for shrubs at the tree line (summer drought and heat: Francon et al., 2020), insects in Switzerland (high rainfall in summer: Neff et al., 2022), soil insects in acid oak forests (drought: Xu et al., 2012) or dry grasslands (prolonged drought: Flórián et al., 2019), truffles (hot and dry summers: Steidinger et al., 2022), and bats (high summer rainfall: Lučan et al., 2013). Intense summer droughts are also the main climatic driver of the widespread growth decline of spruce, the most important Austrian forest tree (Bosela et al., 2021), and may be involved in the population decline of high-elevation specialists among vascular plants (Lamprecht et al., 2018). In addition to extreme events, climate impacts on biota may also be mediated by the timing of snowmelt. Earlier melt-out advances phenology, with possible negative consequences due to increased frost risk (e.g., *Rana temporaria*) (Bison et al., 2021). Moreover, the changing climate affects species by decoupling biotic interactions in both space and time (*medium evidence, high agreement*). In space, different rates and directions of climate-driven migration between interaction partners may lead to reduced opportunities for range adaptation, e.g., of specialized herbivores such as certain butterfly species (Descombes et al., 2016; Kerner et al., 2023), or may intensify or relax pressure on hosts (e.g., spruce and bark beetle, larch and larch budmoth (*Zeiraphera griesea-*

*na*) (Johnson et al., 2010; Temperli et al., 2013; Jakoby et al., 2019; Büntgen et al., 2020). Over time, different responses of partners to climate change may disrupt the evolved co-timing of phenophases, e.g., between predators and prey (dormice and burrowing birds: Adamík and Král (2008); birds and larval tipulids: Schano et al. (2021); ring ouzel feeding habitat: Barras et al. (2020, 2021a, 2021b)) or plants and herbivores (chamois breeding and vegetation development: Chirichella et al., 2021). The cuckoo is a prominent example of such a temporal mismatch resulting from differences between its own migratory phenology and that of other species it parasitizes (Saino et al., 2009). In general, a shift of spring phenology to earlier dates is a widespread effect of climate change on biota in seasonally cold climates such as Austria (*high confidence*). A comprehensive review for Switzerland (Vitasse et al., 2021) demonstrates such shifts for the activity of vertebrates (amphibians, reptiles, birds), invertebrates (e.g. butterflies) and plants, with average rates of shift varying between 1–6 days per decade over the last 40 years. The data also show the idiosyncratic nature of these shifts and thus the potential for further temporal mismatches of biotic interaction partners.

In freshwater ecosystems, climate-driven distribution shifts are less commonly reported (Vitasse et al., 2021). However, upward elevational shifts have been documented for some wetland bird species in Austria (Teufelbauer et al., 2024). Similarly, elevational shifts of fish along mountain streams have been observed (Comte and Grenouillet, 2013), and some detailed studies suggest negative effects of warmer water on the physiology and reproduction of several fish species, such as brown trout (*Salmo trutta*; Borgwardt et al., 2020), European grayling (*Thymallus thymallus*) (Wedekind and Küng, 2010) or European bullhead (*Cottius gobio*) (Dorts et al., 2012). Opposite shifts in population size and occupancy of warm- and cold-adapted species have also been reported for freshwater-bound invertebrates such as dragonflies in Switzerland and Bavaria (Engelhardt et al., 2022; Neff et al., 2022), and this turnover is predicted to accelerate under further climate warming and to also affect all pond-associated fauna (Rosset et al., 2010). In both streams and alpine lakes, warming water (see Sections 1.4.1 and 1.4.2) has also triggered changes in the composition of invertebrate (Haase et al., 2019) and phytoplankton (Weckström et al., 2017) communities. The warmer climate and longer droughts will also increase the number of intermittently dry streams, which may also lead to strong turnover of their fauna (Crabot et al., 2021). Lakes that are currently fed by glacial meltwater but will become hydrologically disconnected as glaciers continue to retreat are expected to be particularly affected. Such a change in hydrological regime is likely to result in possibly richer but profoundly different communities and food webs, and unique species and processes of glacier-fed lakes will be lost (Tiberti et al., 2020; Kleinteich et al., 2022) (*medium evidence, high agreement*).

At the local scale of individual communities, global meta-analyses have highlighted considerable turnover in species composition despite relatively stable (average) species richness over the last decades (Vellend et al., 2017; Blowes et al., 2019), with a general trend towards homogenization through the replacement of specialist by generalist species (Jandt et al., 2022; Staude et al., 2022). While these changes are often due to land use, climate change may have similar homogenizing effects in both terrestrial and freshwater ecosystems of Austria/Central Europe (vascular plats in alpine grasslands, Jurasinski and Kreyling, 2007; Liberati et al., 2019; ant communities in grasslands, Gallé, 2017; cyanobacterial communities in lakes, Monchamp et al., 2017; and butterflies in alpine valleys, Bonelli et al., 2021) (*medium confidence*). However, climate effects on the richness and composition of individual communities are and are likely to be highly idiosyncratic, depending on taxonomic group, habitat type, and geographic location (Rosbakh et al., 2014; Thom et al., 2017; Liberati et al., 2019; Geppert et al., 2021; Kleinteich et al., 2022) (*high confidence*). At the regional scale of all of Austria, calculations of climate-induced changes in species numbers have not yet been published, either for the climate of recent decades or for future scenarios. Given the vulnerability of many narrowly distributed and dispersal-limited endemics to a warming climate, Austria's contribution to the global species pool is likely to shrink (Dirnböck et al., 2011; Semenchuk et al., 2021) (*medium evidence, high agreement*).

Both the positive and negative impacts of climate change on species and habitats are modified by other pressures on biodiversity. Reduced land-use pressure may stabilize populations and facilitate climate-driven range shifts to some extent, at least under moderate levels of climate change (Thomas et al., 2012; Wessely et al., 2017) (*medium evidence, high agreement*). Similarly, bird species adapted to a warmer climate appear to have benefited from recent warming only when cropland is not the primary habitat, as persistent adverse farming practices hinder their population growth (Nemeth et al., 2016). In freshwater ecosystems, flow regulation (Bruno et al., 2019), eutrophication (Monchamp et al., 2017) and pollution exacerbate climate effects on biota. As a consequence, the rapid and thorough implementation of recent international agreements on protected areas and ecosystem restoration (such as the Kunming-Montreal Global biodiversity framework of the Convention on Biological Diversity (CBD/COP/DEC/15/4, UNEP (2022), or the European Green Deal and the associated EU's biodiversity strategy for 2030 (European Commission Directorate General for Environment, 2021)) in Austria would also contribute to the capacity of biota to adapt to climate change (*medium evidence, high agreement*).

The vulnerability of biodiversity to land-use changes also sets sustainability limits for climate mitigation measures such as land-based $CO_2$-removal (CDR, see Section 2.3 and Cross-Chapter Box 6) or the expansion of renewable energy. In Austria, biodiversity conservation often implies the maintenance or restoration of traditional low-intensity land use, as many species of Austrian flora and fauna depend on the habitats created by this type of use (*high confidence*). Allocating such economically marginal areas to CDR measures such as afforestation or bioenergy capture and storage (BEECS, see Section 4.6 and Cross-Chapter Box 6 is therefore inconsistent with international commitments to halt biodiversity loss and with national biodiversity targets (Kerschbaumer, 2022). In contrast, 'nature-based' CDR, which includes the restoration of degraded ecosystems such as mires or the replacement of tree monocultures with near-natural mixed forests as well as other adaptive forest management strategies such as longer forest rotation cycles and associated higher deadwood volumes (Kropik et al., 2021; Jandl et al., 2024), could provide a double benefit for the intertwined biodiversity and climate crises (Deprez et al., 2024) (see Sections 2.3.2 and 2.3.3). Similar considerations apply to the expansion of renewable energy. The costs of irreversible biodiversity loss associated with energy decarbonization can be reduced or avoided if renewable energy infrastructure (see Section 4.5) does not overlap with protected areas or habitats important for biodiversity (Rehbein et al., 2020), if siting takes into account animal behavior (Gauld et al., 2022; Reusch et al., 2023; Salguero et al., 2023), and if their management thrives on harnessing synergies (Blaydes et al., 2021; Giuntoli et al., 2022). Thus, a comprehensive national strategy and careful spatial planning for land-based CDR that balances decarbonization benefits and biodiversity costs will be necessary to simultaneously meet international climate mitigation and biodiversity conservation commitments. A more detailed discussion of different CDR measures and their side-effects on biodiversity, among others, can be found in Sections 2.3 and 2.4.

In summary, climate warming has begun to reshuffle the distribution of biota in Austria (*high confidence*). The dominant trend in many taxonomic groups and habitats is a decline of cold-adapted and drought-sensitive species and an expansion of warm-adapted and/or drought-resistant species. As many Austrian (sub-) endemics belong to the former group, climate warming threatens Austria's unique contribution to biodiversity. In contrast, species that are detrimental to society, such as various invasive pests and pathogens, appear to benefit from climate change. In general, however, climate effects on biodiversity in Austria are unsystematically and insufficiently documented, despite a considerable body of literature. To improve our knowledge, a systematic, nationwide, long-term monitoring program with a broad coverage of taxa and habitats, including both terrestrial and freshwater habitats, and a design that disentangles climate effects from those of other drivers would be foremost required. Inclusion of the understudied soil (micro-)biota in this scheme is mandatory, as they are crucial for ecosystem functioning. Ideally, monitoring should also capture effects

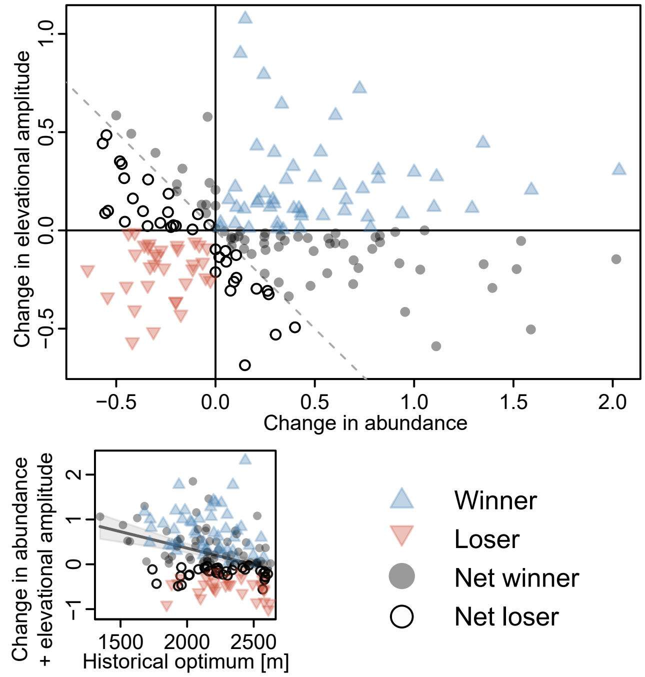


Figure 1.16 Proportional changes in abundance and elevational amplitude of 183 mountain plants of the Eastern Alps between the period before 1970 and the years 2013/14, based on a sample of 1576 vegetation plots (complete plant species lists with cover-abundance data, upper panel). Upper blue triangles symbolize 'winners' (both abundance and elevational range size have increased), lower red triangles 'losers' (a loss in both dimensions). Species symbolized by dots combine gain in one dimension with loss in the other. Among these, the dashed diagonal separates those for which the gain in one feature is less than the loss in the other (to the right of the diagonal) from those for which the opposite is true (to the left of the diagonal). The lower panel relates the sum of changes in the two features per species to its optimum elevation prior to 1970 (figure adapted from Rumpf et al., 2018).

at the intra-specific level, as changes in genetic make-up and diversity are considered important for the adaptive capacity of biota, but are poorly documented and understood.

## 1.7. Lithosphere

This section presents an assessment of the impact of climate change on geological and geomorphological processes of the Earth's lithosphere. Since endogenous processes such as earthquake activity (Hainzl et al., 2006; Husen et al., 2007) or volcanism are not or only marginally affected by climate change, the focus is on exogenous processes, in particular on landslides of different types relevant for the Alpine region of Austria. Surface settlements caused by groundwater lowering or permafrost degradation are addressed, but phenomena related to natural caves in limestone, collapsible soils, peat, evaporites and mining are out of scope.

### 1.7.1. Theoretical background

Endogenic processes are the driving force for the mountain landscape of Austria on geological time scales, causing a diverse temporally and spatially variable distribution of different rocks. Exogenic processes, including weathering, erosion and all transport processes of geological material, shape the landscape and lead to the characteristic geological and topographic situation (Dietrich and Krautblatter, 2017). This results in the great topographic and climatic diversity in Austria, which is prone to different types of natural hazards. Surface processes are expected to be affected by climate change on different time scales. Weathering and denudation, transport and deposition of sediments are dominated by fluvial, glacial, gravitational and aeolian processes. Landslides are one of the most relevant natural hazards that frequently affect the Austrian terrain, and climate change will negatively influence the magnitude-frequency relationship (Huggel et al., 2012b; Gariano and Guzzetti, 2016) as well as the seasonality and spatial occurrence, especially in dependence on elevation (Stoffel et al., 2014a).

Landslides can result from a variety of causes, including geological, morphological, physical and human, but often have only one trigger (Cruden and Varnes, 1996). A trigger is an external stimulus, such as a rainfall or snowmelt event, that causes a landslide to form almost immediately (Wieczorek, 1996). Preconditioning factors such as high antecedent moisture, degradation of mechanical stability, or changes in land cover can modify the trigger magnitude required to initiate a landslide (e.g., Chiarle et al., 2021). In many cases, however, no obvious attributable trigger can be identified, making it difficult to establish a clear cause-effect relationship between climate change variables and landslide occurrence (Wieczorek, 1996). Identifying and quantifying the impact of climate change on landslides is therefore challenging due to (i) the lack of long-term and comprehensive event records for conclusive statistical analysis, (ii) the difficulty of identifying causes and triggers, as well as their combination, interaction and delimitation, and (iii) the occurrence of cascading or compound processes.

A globally accepted classification system for landslides, based on the material involved and the type of movement, has been proposed by Cruden and Varnes (1996) and applied here to consider the various climate change-related influencing factors in a process-oriented manner. This classification distinguishes between rock and fine- and coarse-grained soils, referred to here as earth and debris. While rock is a solid aggregate of minerals that form a hard and solid mass, soil is an aggregate of mineral and rock particles resulting from sedimentation processes. Earth is a fine-grained soil in which 80 % or more of the particles or grains are less than 2 mm in size. Debris contains a substantial amount of coarse-grained soil in which 20–80 % of the particles are larger than 2 mm, which is above the upper limit of sand particle size.

To capture the natural variability of movement mechanisms, Cruden and Varnes (1996) defined five main types, including falling, toppling, sliding, flowing and spreading (Figure 1.17). Taking into account the different geological materials, (i) rock falls, (ii) rock slides, (iii) debris/earth slides, (iv) rock spreads, and (v) flow-like landslides such as debris/earth flows and rock flows (avalanches) are identified as primarily relevant for Austria and are assessed for the influence of climate change.

### 1.7.2. Climate change impact on landslides

Climate change will affect landslide causes and trigger factors in a variety of ways, and the response of landslides to climate change depends on movement type, volume, material, and whether there is first failure or reactivation/acceleration of pre-existing landslides (Crozier, 2010; Gariano and Guzzetti, 2016; IPCC, 2021a). The climate-sensitive causes and triggers relevant for landslide occurrence in Austria include (i) extreme precipitation in terms of intensity and duration (see Section 1.2.2), (ii) rapid and intense snowmelt, (iii) rising groundwater levels or rapid drawdown (see

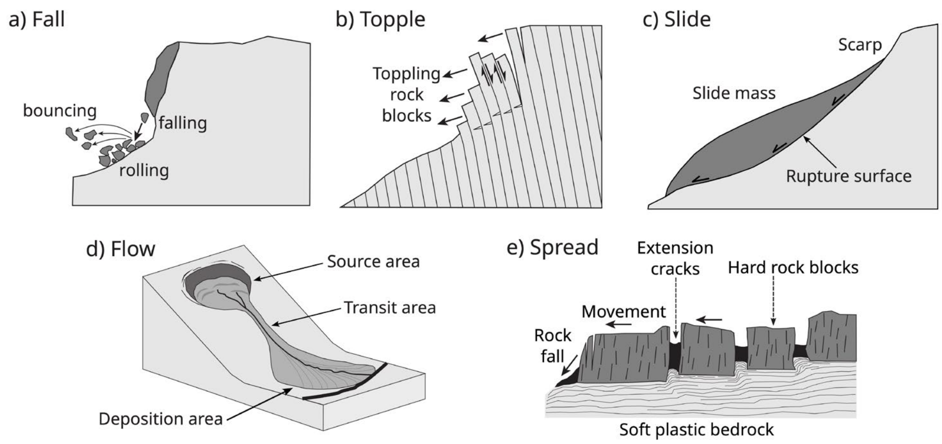


Figure 1.17 Landslide classification based on the main movement type: a) fall, b) topple, c) slide, d) flow and e) spread (modified after Cruden and Varnes, 1996; Zangerl et al., 2008).

Section 1.4.3), (iv) flooding accompanied by fluvial erosion of the slope base (see Section 1.4.1), (v) freeze-thaw cycles or shrink-swell weathering, (vi) permafrost thawing or degradation (see Section 1.3.3), (vii) glacier retreat and glacier discharge (see Section 1.3.2), (viii) glacier lake outburst floods (see Section 1.3.2), (ix) fluvioglacial processes, and (x) vegetation removal by forest fire or drought (Glade, 2020; Jacquemart et al., 2024) (see Section 1.6.2).

### 1.7.3. Observed trends and future changes

Recent case study reports of **rock fall** activity in glacial and periglacial regions in the Alps provide evidence that increased activity is associated with high temperatures, heavy precipitation, permafrost thawing, and/or glacier retreat (e.g., Ravanel et al., 2017; Paranunzio et al., 2019). A study of the rock fall database in Austria from 1900 to 2010, which primarily includes events below the permafrost line, does not support the hypothesis of increased activity during periods of higher temperatures (Sass and Oberlechner, 2012). However, case study specific data suggest an increase in rock fall activity in permafrost and glaciated regions of Austria (Hartmeyer et al., 2020a, 2020b). Due to limited data for larger regions, the evidence for the trend of climate change impacts on rock falls in high alpine regions can be considered medium, in other regions limited (Table 1.A.4).

**Rock slides** are usually deep-seated landslides that can reach volumes of several hundred million $m^3$ and velocities of a few mm/yr to several m/s. Fragmentation of the sliding mass into slabs with the potential for acceleration phases is often observed. Recent studies report first failures (mostly slabs) or reactivation/acceleration due to climate change-related causes and triggers, including (i) glacier retreat and permafrost degradation (Kellerer-Pirklbauer et al., 2012a; Zangerl et al., 2019; Rechberger and Zangerl, 2022), (ii) slope base erosion due to flooding in combination with heavy rainfall (Eder et al., 2006), (iii) intensive snowmelt (Hofmann and Sausgruber, 2017), and/or (iv) extreme precipitation that raises the water table (Brückl et al., 2013; Pfeiffer et al., 2021; Zieher et al., 2023). Most of the studies are based on single-case investigations, highlighting the need to identify the relevant causes and triggers on a case-by-case basis. In glacier retreat zones and permafrost-affected high mountains, a trend towards an increased occurrence of rock slides can be assumed. However, due to a lack of data and regional statistical analyses, there is *medium evidence* that the frequency has increased over the past half century. The assessment of the influence of climate change on rock slides at elevations below permafrost and glacier retreat areas is even less clear. Theoretical considerations suggest that initial failures or reactivation/acceleration phases will increase, but there is *limited evidence* for this trend.

Although there is a strong theoretical basis for an increase in **shallow earth and debris slides** activity due to climate change (e.g., Crozier, 2010), there is *limited* statistical *evidence* of changes in recent occurrence due to the lack of a homogeneous database, including the exact location and timing of the event. Case studies have been conducted for several locations worldwide (Gariano and Guzzetti, 2016), and the number of detailed studies for Austria has increased in recent years. Changes in initiation conditions for shallow earth/debris slides are expected in sensitive regions such as the Bregenzer Wald, the Karawanken and the Northern Alps (Lexer, 2019). A scenario-based predictive study showed an increase in shallow earth/debris slide susceptibility in two forested watersheds in Tyrol, with forest disturbances and forest management practices having the potential to partially compensate for negative effects of a future climate on slope stability (Scheidl et al., 2020). Analysis of the 2009 landslide events in the district of Feldbach, Styria, shows that about 10 % of the slides can be attributed to climate change (Mishra et al., 2023) and that the affected area could increase by up to 45 % in a future climate (Maraun et al., 2022). In particular, the uncertainty associated with landslide triggering models can be higher than the uncertainty of climate model variability (Knevels et al., 2023). As these initial results for Austria are supported by other studies (see review by Gariano and Guzzetti, 2016), a trend towards increased shallow slide activity in the future is assumed, but with *medium evidence*.

The response of deep-seated **earth or debris slides** to climate change is controlled by changes in seasonal or annual rainfall (Gariano and Guzzetti, 2016). Case studies in Italy and the USA, predict a slowdown by the end of the 21st century (Coe, 2012; Rianna et al., 2014), while increased activity may be observed in regions with increased annual rainfall (Gariano and Guzzetti, 2016). Based on a modeling study, Schmidt and Dikau (2004) find that local geomorphological and geological settings are more relevant for deep-seated slides in different soils than variations in groundwater in a changing climate. In contrast, a case study for a deep-seated earth/debris slide in Tyrol shows a temporal relationship between reactivation and intensive snowmelt (Dai et al., 2023), and another case study demonstrates the influence of increased pore water pressure in the subsoil on movement behavior (Jaritz and Soranzo, 2014). Thus, the influence of groundwater on slope movement can be demonstrated for selected case studies, although no general statements can be made. A constant or slightly increasing trend is assumed, but with *limited evidence*.

In Austria **rock spreading** is mainly located in the Northern Calcareous Alps and occurs when a large slab of limestone or dolomite overlies a ductile substratum (e.g., marls, limestone/marl interbeds, clays, evaporites) (Rohn et al., 2004, 2005). Lateral extension occurs due to plastic behavior and when a basal shear zone is absent or poorly defined. Secondary processes such as rock falls and rock flows originating from the margin zones are common. Recent studies focusing on the influence of climate change variables, in particular the role of groundwater on rock slope spreading, are not available and therefore projected changes are unreliable, resulting in *limited evidence* of the trend.

Past **debris flow** activity in the European Alps has been investigated on a case study basis (e.g., Huggel et al., 2012a; Kiefer et al., 2021) and on a regional basis (e.g., Jomelli et al., 2004, 2007; Stoffel et al., 2014b). There is a general expectation of an increase in potential rainfall trigger events (Berg et al., 2013) and an increase in sediment availability in high alpine regions, mostly related to changes in the cryosphere and changes in weathering processes (Beniston et al., 2018; Jacquemart et al., 2024). This may not be the case in regions with limited sediment availability (Hirschberg et al., 2021). A database study for the Austrian Alps found an increasing trend in triggering rainfall indices in recent decades, but no corresponding signal for debris flow activity (Schlögl et al., 2021). A predictive study reports regional and seasonal changes in hydrometeorological trigger conditions for debris flows, including a trend toward critical conditions earlier in the year (Kaitna et al., 2023). Due to limited data on the complex interplay between short-term trigger conditions and long-term geomorphologic susceptibility, there is *medium evidence* for the proposed trend.

**Earth flows** characterized by low to moderate velocities occur on low-inclined slopes, typically in plastic, clay-rich soils. Reactivation or acceleration can occur when the earth flow is destabilized, usually by a temporary increase in pore pressure, often associated with undrained loading mechanisms (Sausgruber et al., 2004; Poisel et al., 2012; Hungr et al., 2014). Studies focusing on climate change variables affecting earth flows are not available for Austria (Glade, 2020). Based on the sensitivity of earth flows to water, it is likely that changing precipitation conditions will have an impact in the future, although there is *limited evidence* for this trend.

**Rock flows or rock avalanches** with volumes of up to several hundred million $m^3$ occurred continuously in the Austrian Alps during the Holocene, although two clusters, one at 10,000–9,000 and one at 4,200–3,000 cal. BP were found (Prager et al., 2008; Ostermann et al., 2017). In many cases, the triggers for these extreme events are not clearly verifiable, but for some events a temporal relationship between failure time and seismic activity can be demonstrated (e.g., Lenhardt, 2007; Oswald et al., 2021). Smaller events with volumes in the range of several 10,000 to 1,000,000 $m^3$ are more frequent in the Austrian Alps and are often, but not exclusively, related to the high alpine environment affected by permafrost degradation and glacier retreat (Krautblatter et al., 2024). Data from the European Alps show a trend of increasing frequency in recent decades (Huggel et al., 2010, 2012a), and this trend is expected to continue for the high alpine area in Austria, suggesting *medium evidence* for this trend. It is still difficult to assess the effects of climate change on steep rock slopes at lower elevations, where there is no influence from glacier retreat and permafrost degradation, because data and studies are scarce. However, from a rock mechanics perspective, it is expected that (i) thermo-mechanical forcing due to larger temperature variations (Gischig et al., 2011a, 2011b; Luethi et al., 2015), (ii) increase in frost-thaw cycles, and (iii) extreme precipitation events will amplify and accelerate the rock strength weakening process (e.g., Atkinson and Meredith, 1987). It is assumed that the number of events will remain the same or increase only slightly, although the *evidence* for this trend is *limited*.

**Surface settlement** due to climate change is caused by permafrost thaw (Harris et al., 2001) and/or rock glacier creep, and by lowering of groundwater levels due to reduced recharge rates (see Sections 1.3.2 and 1.3.3). Studies on permafrost-driven surface settlement processes are related to infrastructure damage (Duvillard et al., 2019), creep phenomena of rock glaciers (Avian et al., 2009; Fey and Krainer, 2020), and in fractured rock masses (Klug et al., 2017). It is likely that permafrost-induced subsidence will become more common as temperatures continue to rise (see Section 1.3.3).

Surface settlements due to groundwater drawdown receive little attention in Austria because the adverse effects are generally small (Bedini, 2021). The assessment of projected settlement magnitudes is based on scenarios of natural groundwater drawdown due to reduced recharge rates (Glade, 2020). However, the expected magnitudes may be small compared to settlements caused by anthropogenic factors (e.g., excessive groundwater pumping, see Section 1.4.3). Due to the lack of data on both permafrost and groundwater drawdown related settlement, there is *limited evidence* for this trend.

## 1.8. Cross-cutting topic: Natural hazards

According to IPCC (2021a), hazards define the potential for the occurrence of a natural or human-induced physical event or physical impact that may cause loss of life, injury or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, services, ecosystems and environmental resources. In this section, the term hazard primarily refers to processes and events related to the different earth spheres, usually called natural hazards.

Table 1.A.4 lists and summarizes selected natural hazard processes that are susceptible to climate change in Austria, grouped into the categories atmosphere, cryosphere, hydrosphere, biosphere, and lithosphere (see Sections 1.2–1.7). Only individual, i.e., single hazards and/or climate impact drivers (Ruane et al., 2022) are presented here in fine resolution, with a brief description of the type, the affected region, proposed indicators, and how climate change affects the natural hazard process in Austria (Fuchs et al., 2022). Information on future trends is included by providing an assessment of the evidence and agreement of trends (Mastrandrea et al., 2010). Irrespective of single hazards, there is often the potential for multi-hazards to occur, which can lead to much more severe damage to settlements and infrastructure and, in the worst case, cause fatalities (Kappes et al., 2012). A number of studies on this topic have been published in the last decade to clarify ambiguities in terminology, but most importantly to demonstrate the need to consider spatial, temporal, and causal dependencies of hazard processes, with a general distinction between cascading and compound processes (Cutter, 2018; Mani et al., 2023). In the context of this assessment, numerous cascading or compound processes can be identified for Austria in the past, some of which led to major damage and high financial losses. A selection of the hazard types identified in this assessment as particularly relevant for Austria and their expected trends is shown in Figure 1.18. The concept and identification of key risks for Austria is presented in Cross-Chapter Box 1.

Extreme rainfall over large areas has triggered debris flow events in headwater catchments, which deliver large amounts of sediment to mountain rivers in very short time scales (Hübl et al., 2005; Pfurtscheller, 2014), leading to river damming and subsequent flooding. Riverbank erosion triggered or reactivated deep-seated rock slides by undercutting the base of the slope during the 2005 flood event in Tyrol (Eder et al., 2006).

A recent temporally multi-hazard event in Austria occurred in 2021 in the Pinzgau region. Due to a succession of rainstorm events on August 14, 15, and 16, debris flows from several torrent catchments, including three from the same catchment, devastated settlements and infrastructure in the Salzach valley floor (Hübl et al., 2022).

A weather situation characterized by a warm and wet winter, such as in January 2018 and 2019, caused multiple hazard events over large areas, including snow avalanches at high elevations and a combination of local floods, debris flows, and earth/debris slides at lower elevations due to a sequence of rain-on-snow events (Stoffel and Corona, 2018).

Drought affects all water resources and can lead to extensive damage and high economic losses (Laimighofer and Laaha, 2022; Haslinger et al., 2023; Tallaksen and Van Lanen, 2023). Drought hazards in Austria typically occur in

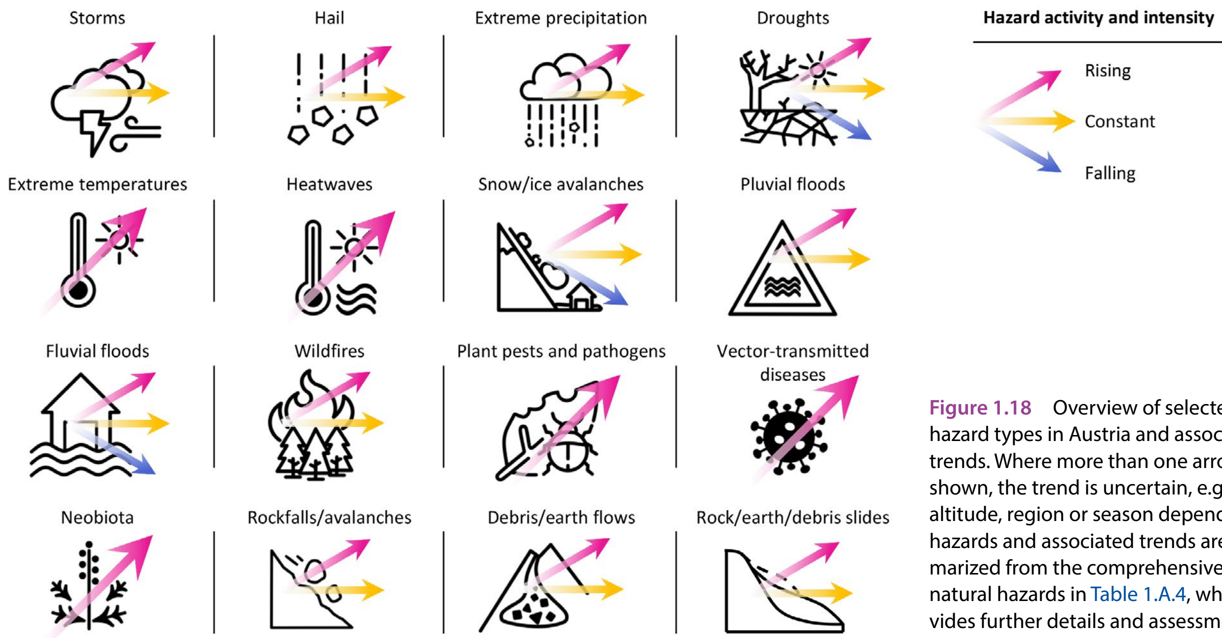


**Figure 1.18** Overview of selected natural hazard types in Austria and associated trends. Where more than one arrow is shown, the trend is uncertain, e.g., due to altitude, region or season dependency. The hazards and associated trends are summarized from the comprehensive table of natural hazards in Table 1.A.4, which provides further details and assessments.

summer, when a prolonged dry spell leads to a precipitation deficit (meteorological drought), which propagates through the hydrological cycle and can lead to droughts in the entire hydrological system (soil moisture, streamflow and groundwater drought). Socio-economic sectors are differently vulnerable to different types of droughts, so each sector is affected differently depending on the specific genesis of the event and the timing and region affected (Van Lanen et al., 2016; Kramsall, 2018). Meteorological droughts are often associated with heat waves that cause health hazards and mortality. They increase the risk of wildfires, which in turn can trigger deforestation and increase the risk of avalanches or rock falls. On the other hand, wildfires lead to soil degradation and erosion processes, triggering debris flows, landslides, rock falls and other natural hazard cascades.

Soil moisture droughts affect plant growth and, depending on the season, cause losses to agriculture (agricultural drought) or biological systems. Droughts and heat waves can lead to reduced tree vitality, which favors the growth of pathogens (fungi) and insects (bark beetles), thereby triggering snow avalanches, erosion and rock fall. Other hazard chains triggered by drought and heat waves include tree damage leading to bark beetle infestations and deforestation promoting snow avalanches.

Streamflow droughts manifest themselves as low-flow events and can, among other things, threaten water quality, restrict navigation, and reduce hydropower production (Laaha and Blöschl, 2007). In particular, the combination of low flows and high water temperatures can lead to fish mortality, plant damage, and ecosystem degradation. Finally, groundwater droughts can limit the supply of water for drinking and irrigation, increasing the risk of agricultural drought. The damage caused by droughts has been shown to exceed that caused by major floods, as the 2003 event demonstrated not only for Europe but also for water-rich Austria.

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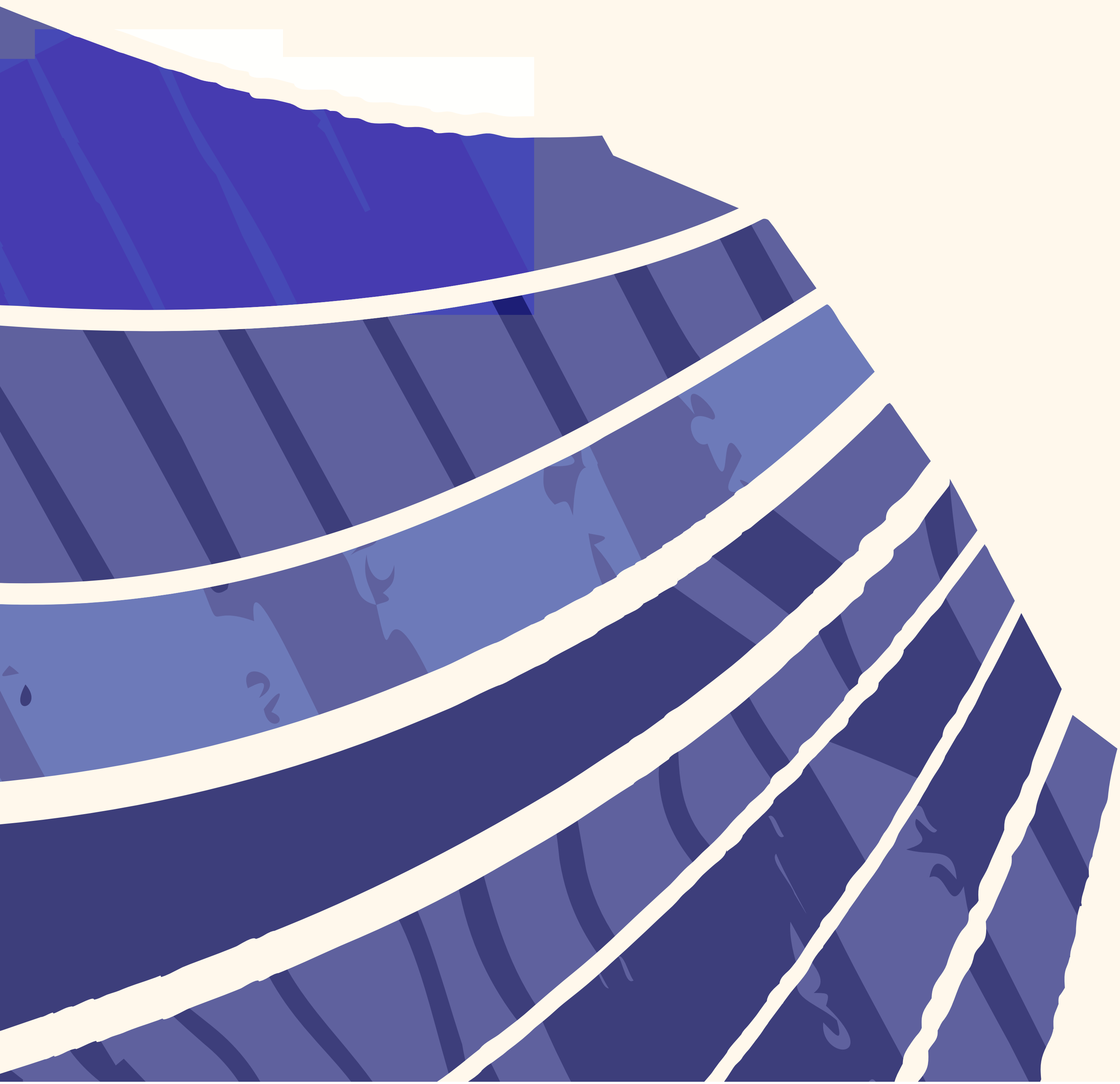
# Chapter 2

# Climate change, land use, ecosystem services and health



## Second Austrian Assessment Report on Climate Change | AAR2

# Chapter 2
# Climate change, land use, ecosystem services and health

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## EXECUTIVE SUMMARY

**Land-related human activities that benefit from multiple ecosystem services constitute an important element of Austria's greenhouse gas (GHG) budget (*high confidence*).** Agricultural activities, which are essential for food production, contributed 9.9 % to Austria's total GHG emissions during the most recent available 5-year average (2019–2023), dominated by $CH_4$ and $N_2O$ (*high confidence*). For the same period, the sector land use, land use change and forestry, contributed 2.3 % of Austria's GHG emissions (*medium confidence*). This sector represented in the past a strong carbon sink, which decreased since the early 2000's and turned into a source around 2020, characterized by large year-to-year variations. {2.1.1}

**The use of land for human livelihoods alters biogeochemical cycles and ecological patterns and processes, affecting the climate system, biodiversity and ecosystem services (*high confidence*).** There are multiple trade-offs between different ecosystem services, mostly because the (global) land surface is limited. Rapid reductions in anthropogenic greenhouse gas (GHG) emissions that limit warming to 'well-below' 2°C would greatly alleviate, while warming above 2°C will exacerbate existing trade-offs. {Chapter 2}

**The future provision of agricultural crops for feed, food, fiber and fuel will be compromised by climate change, particularly regarding water availability (*medium confidence*).** Among the wide range of temperature, precipitation and adaptation scenarios, impacts of climate change on agricultural yields show a high variance from negative to positive (*high confidence*). Impacts of extreme weather events, other disturbance factors (e.g., pests), the role and effect of $CO_2$ fertilization, adaptation measures (e.g., new crop types, plant breeding) still represent knowledge gaps. {2.2.1}

**Forest-related disturbance regimes (drought, fire, windthrow, snow and ice breakage, bark beetle) are projected to increase with climate change, negatively affecting some important ecosystem services (*high confidence*).** However, the extent of the resulting damage to forests and impacts on ecosystem services cannot yet be reliably quantified and assessed. Impacts on the protection function of forests against gravitational natural hazards and on the protection of drinking water resources can be assessed with *high confidence*, while impacts on the provision of wood for timber and energy or on carbon storage are difficult to quantify. {2.2.1, 2.2.2, Chapter Box 2.2}

**Climate change threatens the extent and quality of services provided by ecosystems (*medium confidence*).** In addition to provisioning and regulating services in agriculture and forestry, cultural ecosystem services are also affected. This includes impacts on certain recreational activities through reduced snow fall, increased rock fall, and reduced water quality. However, warmer temperatures also create opportunities, e.g., for bathing activities or summer tourism. {2.2.2, 2.2.3}

**In limited situations, climate change improves ecosystem productivity due to increasing temperatures extending growing seasons (*medium confidence*).** In both forestry and agriculture, observations show that a warmer climate increases plant productivity. These opportunities are jeopardized by the speed of change – in forestry, challenges are related to the long rotation periods in forest management, which limit the rapid adaption of tree species to take advantage of a different climate, while in agriculture, infrastructure changes are needed to allow for handling extreme weather situations (droughts, cold spells, heat waves). {2.2}

**Irrigation needs will require new perspectives on water availability (*medium evidence, high agreement*).** Provisioning of drinking water will be impaired in certain regions of northern and eastern Austria, whereas the increased need for agricultural irrigation will impact water resource planning significantly across Austria during drought events. {2.2.1}

**Ongoing climate change will have regionally diverse impacts on the provision of ecosystem services due to complex biophysical conditions (*high confidence*).** Notably, (1) a general decrease of all ecosystem services, particularly provisioning ecosystem services, is expected in the northern Alpine foothills and highlands, in the southern Alps with the Klagenfurt Basin and in the central Alps (*medium confidence*); (2) a spatial shift of dominant ecosystem services towards higher elevations will occur for regulating ecosystem services and towards low and peripheral areas for provisioning ecosystem services, depending on water availability and plant stress profiles (*medium confidence*). {2.2}

**Some of Austria's international supply chains will become more vulnerable (*medium confidence*).** Austria is a net importer of biomass, importing mainly raw materials and exporting mainly highly processed and manufactured final products. About 16 % of Austria's imports of food and feed and 5 % of Austria's imported wood products originate from regions that are moderately to highly vulnerable to climate change and do not yet appear to be ready to adapt, especially tropical and Mediterranean regions. {Chapter Box 2.1}

**Technical and management measures in agriculture and forestry can reduce greenhouse gas emissions and increase sinks but their mitigation potential is limited (*high confidence*).** Compared to a reference scenario, measures in agricultural management (e.g., increasing soil organic carbon, reducing emissions from agricultural inputs, optimizing livestock farming) show mitigation potentials of 0.4 to 2.5 $MtCO_2eq/yr$ (*medium confidence*). Adaptive forest management like changing tree species shows a mitigation potential up to 1.9 $MtCO_2eq/yr$ (*low confidence*), calculated over 2020–2150. This potential materializes only under a high global warming level (GWL; between GWL 4.0°C and GWL 5.0°C) and primarily beyond 2080. {2.3.1}

**Tapping far-reaching mitigation potentials in agriculture and forestry requires structural measures reducing the use of biomass and changing current economic practices and consumption patterns (*high confidence*).** Ambitious mitigation will require far-reaching measures with substantial costs, involving trade-offs and structural disruptions, such as loss of livelihoods for farmers or the need to deal with spillover effects (*high confidence*). Shifting towards healthy, plant-based diets shows mitigation potentials of 5.0 to 15.4 $MtCO_2eq/yr$, when agricultural production can be restructured to reduce agricultural emissions and increase sinks through afforestation on freed agricultural land (*medium confidence*). Halving food waste may reduce emissions by 2.1 to 4.7 $MtCO_2eq/yr$ (*medium confidence*). Prioritizing long-lived harvested wood products over energy show mitigation potentials of 0.1 to 0.5 $MtCO_2eq/yr$ (*low confidence*). In the currently only available set of model results for Austria, contrasting two scenarios shows that annual average wood harvest of 25 million Vfm/yr (15 million Efm/yr) compared to wood harvest levels of 30 million Vfm/yr (25 million Efm/yr) will yield a mitigation potential of 7 to 8.4 $MtCO_2eq/yr$ until 2150. Current harvest levels (2016–2022) are 25 million Vfm/yr (20 million Efm/yr). To which extent the realization of all these potentials is constrained by climate change induced disturbances (e.g., increases in windthrows, insect infestations, vegetation fires) remains a research gap. {2.3.2, 2.3.3, Chapter Box 2.2}

**Implementing mitigation measures along the entire value chain, including production, processing, trade and consumption, is crucial to avoid leakage or spillovers (*high confidence*).** Shifting emissions and environmental pressures to other regions through increased imports and exports negates any climate benefit, but trade measures can mitigate leakage. Research gaps exist for mitigation strategies that consider the total food system, encompassing more than just emissions from agricultural production. {2.1.1, 2.3.3, 2.A.9, 2.A.11}

**Various land users compete for the resources, services and benefits they derive from land, inducing conflicts of objectives and interests (*high confidence*).** A major conflict exists between biomass extraction on the one hand and carbon storage, biodiversity and nature conservation (with their associated social benefits and costs) on the other hand. There are also potential conflicts between agricultural uses and renewable energy, e.g., in the case of agriphotovoltaics, wind and water energy. Ambitious mitigation measures entail important challenges and conflicts. Transparent and democratic negotiation of trade-offs between values and stakeholders is essential to overcome barriers to the transformations of the land use system, counteracting path dependencies and unequal power relations among actors, while supporting vulnerable land users. {2.4}

**A fundamental conflict unfolds between economic growth and environmental conservation (*high confidence*).** Economic growth, in its current form, drives increased production and consumption and thus land demand, making it a key driver of climate change and biodiversity loss, e.g., due to land-use intensification and land-conversions. Technological improvements that increase yields partly offset land demand, but rebound effects in the land system often annihilate the efficiency gains. {2.4}

**Adverse effects on the health of the Austrian population due to climate change are visible already, and these effects are expected to increase, as climate change continues (*high confidence*).** In particular, extreme weather events such as heat waves pose serious health threats including premature death, but also non-fatal disease, reduced well-being and productivity. These impacts affect different population groups in different ways, raising the issue of environmental justice. The poor, elderly and chronically ill, those with physically or mentally demanding jobs, and members of ethnic minorities are and will be most affected. Geographical differences must also be considered, both at the small (e.g., urban heat island, poor neighborhoods) and larger scale (e.g., mountain regions). {Cross-Chapter Box 2}

**Local mitigation measures, while benefiting the climate globally, can also exert remarkable beneficial effects on public health locally, e.g., regarding healthy diets or sustainable (pollution-free) modes of transport (*high confidence*).** Nevertheless, poor implementation of measures (both mitigation and adaptation) could also have negative effects on health. Evaluating measures from a health perspective (health in all policies concept) allows to avoid such implementation failures. {Cross-Chapter Box 2}

**The health care system contributes to climate change with its own carbon footprint (*limited evidence, high agreement*)** and could also contribute substantially to the mitigation efforts. {Cross-Chapter Box 2}

**Human health is highly dependent on functioning provisioning systems, which include global supply systems, local infrastructure and many ecosystem services. These are threatened by ongoing climate change (*medium evidence, high agreement*).** Both ongoing long-term changes and acute extreme events can have long-lasting negative consequences for physical and mental health and social well-being. Pressures from climate change elsewhere in the world could affect health and the health care system in Austria. Chronic effects, especially on mental health, of extreme events and climate change have been documented elsewhere but are still heavily understudied in Austria. The interplay between ecosystems and human health, together with animal health, is an important aspect of One Health. {2.2, 2.3, Cross-Chapter Box 2}

## 2.1. Chapter Introduction

The impact of climate change on life is far-reaching. Rising temperatures, altered precipitation patterns, and different wind exposure influence the way land is used by humans and covered by vegetation. Changes in land use and vegetation also influence animal husbandry as well as wildlife. Human livelihood and health are affected by climate, climate change and the ecosystems around them.

Land ecosystems provide a wide range of essential, partly irreplaceable services to human society (*high confidence*). They support production of crops and livestock serving as food to nourish our global population (IPCC, 2019a). Ecosystems also produce fibers and energy resources, contributing to various industries and ensuring our energy needs are met, and they are hosts to biodiversity (IPBES, 2019). Freshwater, an essential resource, is regulated by land ecosystems through processes such as filtration and groundwater recharge (Reid et al., 2005; IPCC, 2019a), securing a vital supply for drinking, agriculture, and industry. Moreover, these ecosystems actively participate in climate regulation by sequestering carbon, mitigating climate change, and influencing local weather patterns (IPCC, 2019b; Erb et al., 2023a).

This chapter assesses the current state of scientific knowledge for Austria on the interlinkages between climate change, ecosystems, and the services they provide to human society, including human health (see also Cross-Chapter Box 2). Here we use the concept of ecosystem services as a classification scheme that describes the benefits humans

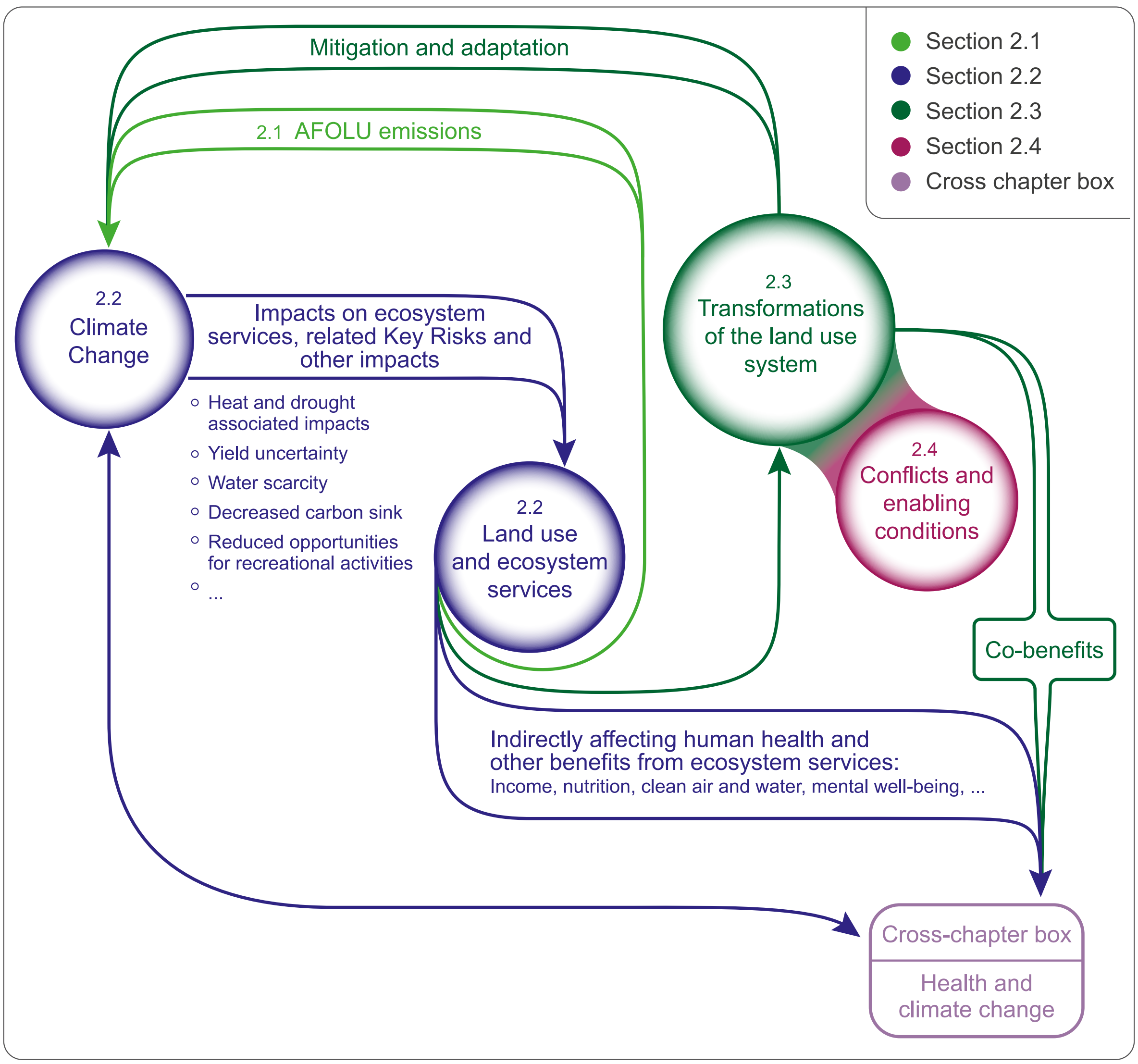



Figure 2.1 Chapter structure and overview of topics.

derive from ecosystem functioning (see 2.A.1). These services are closely linked to human land use. As land is a finite resource, land use in many cases involves land competition, i.e., the use of land for only one of several possible purposes (Haberl, 2015; Meyfroidt et al., 2022; Erb et al., 2024). Certain land uses may specifically affect the adaptation to and mitigation of climate change, in particular by inducing greenhouse gas emissions, depleting carbon stocks, or altering the resilience of ecosystems to climate change. However, ecosystem functions can also be employed to remove and sequester carbon from the atmosphere by increasing carbon pools in ecosystems (Griscom et al., 2017; Bossio et al., 2020), an essential but not sufficient strategy to combat global warming (Boysen et al., 2017; IPCC, 2019a). Moreover, ecosystems can also contribute to mitigating the impacts of climate change, especially through their regulating capacity.

In agreement with the concept of ecosystem services, the approach taken here is deliberately anthropocentric. This does not mean that we ignore or undervalue the ethical intrinsic values of all living beings and ecosystems (Vilkka, 2021), but it is consistent with the basic objectives of the assessment report. These are (i) to identify societal strategies to adapt to unavoidable climate change, (ii) to contribute to the design and implementation of such strategies, and (iii) to devise pathways for human activities (including production and consumption) and their land use impacts that are consistent with the goal of keeping global warming well below 2°C above pre-industrial levels. Thus, we describe activities and changes in human practices to adapt to or reduce the impacts of climate change. Since natural or near-natural ecosystems cover a relatively small part of the Austrian landscape and have already been covered in Section 1.6, this chapter will focus mainly on human land use.

Key input to this chapter was taken from science performed in Austria and about Austria. Relevant compilations are available as the recently completed Special Reports to the Austrian Assessment Report (in German language), specifically on Land Use and Climate Change (Jandl et al., 2024c), on Health, Demography and Climate Change (APCC, 2018), and on Structures for a Climate-Friendly Living (Aigner et al., 2022). The discussions that these reports were able to provide in much detail inform the views arrived at in this chapter.

The chapter covers the following elements (see Figure 2.1): Section 2.1 summarizes the state of current land use in Austria, associated resources, greenhouse gas emissions and ecological carbon stocks. Section 2.2 assesses the impacts of climate change on a range of ecosystems services are discussed and if possible quantified. Here, the Common International Classification of Ecosystem Services (CICES) is used to classify impacts – see 2.A.2 (Haines-Young and Potschin, 2018). Where traceable, indirect impacts of climate change (as on human health) are also assessed. Given the high dependence of the Austrian supply systems of land-based products from global value chains, special attention is paid to the assessment of the linkages between Austrian land use and global ecosystems (Chapter Box 2.1). Based on various national (Allianz Nachhaltige Universitäten in Österreich, 2021; Aigner et al., 2022) and international classifications (Roe et al., 2019), Section 2.3 discusses possible land-based activities and transformations to achieve climate change adaptation and mitigation and assesses their potentials (including health impacts). The resulting challenges related to potential land-use conflicts and opportunities to overcome them conclude the analysis (Section 2.4). Direct land-use considerations for human health are discussed throughout the chapter, while other health-related issues are addressed separately in Cross-Chapter Box 2, with interrelated concepts described in 2.A.3. The notion of considering ecosystems and their services as a foundation of human well-being (Reid et al., 2005) serves as the overarching concept.

### 2.1.1. Resource use and greenhouse gas emissions from Austria's land system

#### Biomass flows from ecosystems to consumption

Most land use and associated greenhouse gas emissions are related to the provision of biomass. Biomass can be used for the provision of food, feed, fibers and fuel. Figure 2.2 shows an approximation of biophysical biomass flows through the Austrian economic system (Kalt, 2015; Eisenmenger et al., 2016; Jacobi et al., 2018; Strimitzer et al., 2022), but following simple approaches (see 2.A.14). In total, the biomass input to the economy is about 24.5 MtC/yr (year 2020). The Austrian economy is deeply interconnected with global markets and heavily dependent on both imports and exports (*high confidence*). In terms of carbon units, biomass imports represent more than one third of the biomass input to Austria's economy. Exports are about half the size of imports (note that due to data limitations, exports of paper and highly processed wood products are not included). Agriculture production and wood harvest contribute about equally to domestic biomass extraction.

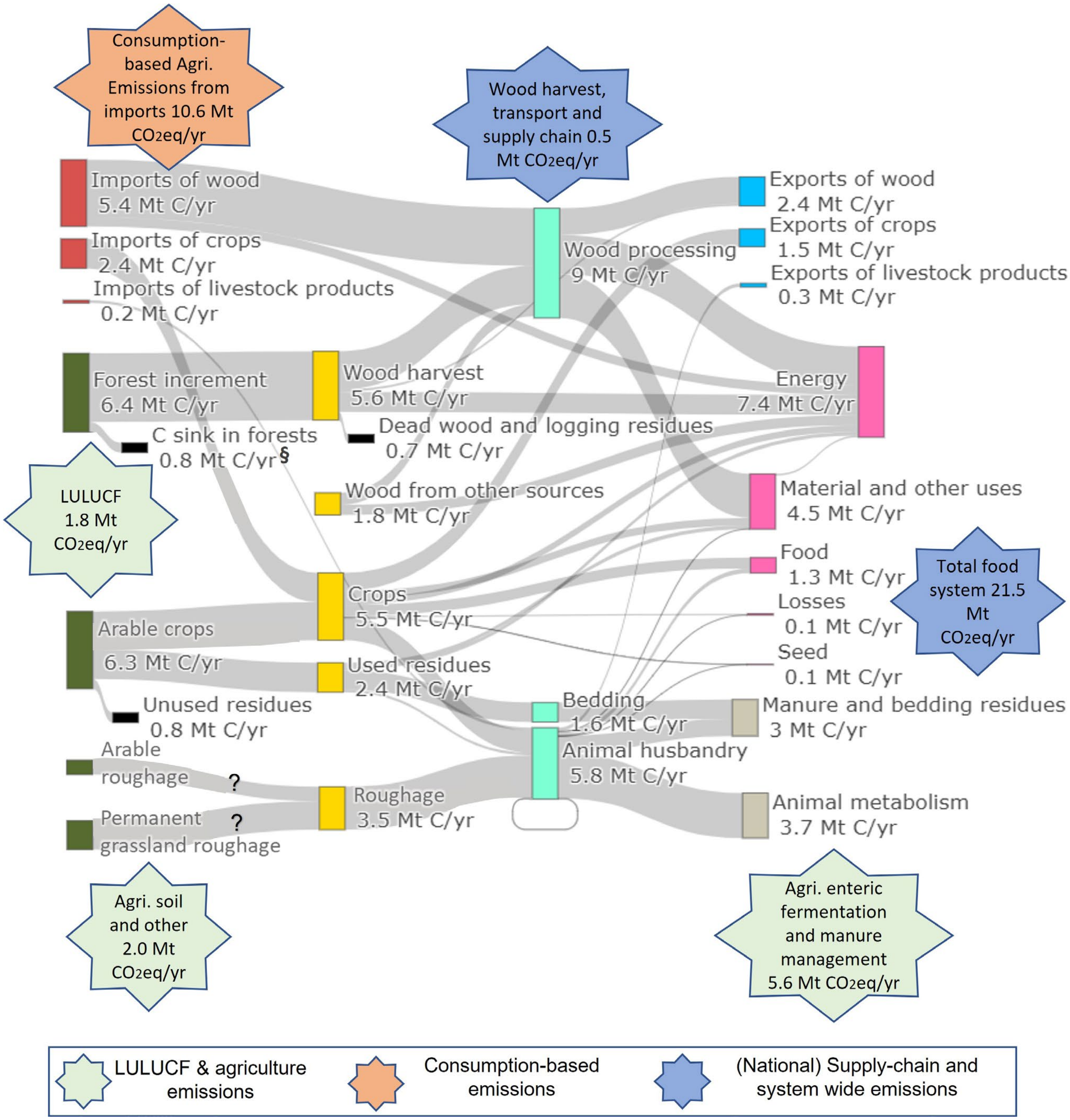



Figure 2.2 Approximation of biomass flows in Austria's socioeconomic system in MtC/yr and related GHG emissions. Biomass flows (year 2020) (Kalt, 2015; BMK, 2022; Erb et al., 2023a; Roux et al., 2023, updated as explained in 2.A.14). LULUCF and agriculture emissions are from Umweltbundesamt (2025a), on average for 2019–2023. These emissions are displayed in detail and for several years in Table 2.A.2 in 2.A.5. Consumption-based emissions are from Frey and Bruckner (2021) for the year 2013. Food system emissions are from Crippa et al. (2021) for the year 2015, and wood supply chain emissions are from Kühmaier et al. (2022) for the year 2018. Wood flows in [m³] have been converted to [tC] using a crude factor of carbon density [500 t dry matter/m³], dry matter biomass flows were converted to carbon fluxes applying a carbon content factor of 50 %. Note that foreign trade of manufactured wood products (millwork, furniture, paper, etc.) is missing in this scheme. § Forests acted as carbon sinks in 2020 (grey arrows), but are a source of $CO_2$ in the five-year average (colored stars). Color coding is used to indicate similarity of components (imports, domestic extraction, processing stages, exports, final consumption, etc.). The loop below animal husbandry represents animal products used as feed (especially milk and whey). Data are subject to various uncertainties, including statistical discrepancies (e.g., between forest increment, forest sink and wood harvest).

The largest processing nodes in Austria's economy are the wood processing industries and the energetic use of biomass (9 and 7.4 MtC/yr, respectively). The latter is associated with corresponding C-emissions to the atmosphere. At the production side, biomass provision is sustained by a flux of carbon from the atmosphere to the land ecosystems. For the quantification and balance of these flows (see Section 2.1.1). Also, an important node is the livestock sector, with feed input of about 5.8 MtC/yr and 1.6 MtC/yr of bedding, yielding 0.8 Mt of animal products and ca. 3 Mt of manure and bedding residues, while the rest is metabolized and exhaled by animals as $CO_2$ and $CH_4$.

The wood sector is particularly important in biophysical terms with a total domestic material input (DMI; domestic extraction plus imports) of 11.8 MtC/yr in 2020. Imports of wood and wood products exceeded the production of wood from domestic forests by 11 %. Exports reported in the Austrian wood flow diagram (roundwood, sawn wood and sawmill-byproducts) are about half of the import volume, however, foreign trade with millwork and paper is not included in the wood flow diagram and Figure 2.2, resulting in an underestimation of wood exports (see below). The domestic wood harvest averaged 89 % of annual stem wood increment in the last inventory period (2016–2021) and showed an increasing trend over the last decade, leaving only little room for enhancing domestic wood provision under sustainability criteria and with current management practices (European Environment Agency, 2017; Beck-O'Brien et al., 2022; Kirchmeir et al., 2022; Erb et al., 2023a). The amount of woody biomass used for energy purposes, at 6.4 MtC/yr, is almost equal to the total amount of wood harvested domestically from forest and non-forest ecosystems with woody vegetation in Austria. Overall, the energy use of wood biomass covers about 17 % of the gross domestic consumption of energy (BMK, 2023). 38 % of the energy use of wood derives directly from domestic harvest, which is directly used for energy, and 12 % comes from direct imports (firewood, sawmill by-products and pellets). The remainder (50 %) are residual materials from processing, including black liquor from paper production, which are of mixed domestic and imported origin. On average, the average share of imports in the energy use of wood biomass is 39 % (Erb et al., 2023a).

The agricultural sector shows a DMI of 12.4 MtC/yr with a dominance of domestic extraction. 1.3 MtC/yr are consumed as food (11 % of the DMI), while material and energy uses of agricultural biomass are significantly smaller. Animal husbandry, including bedding straws represent 64 % of the agriculture DMI and leads to an output of 0.8 MtC/yr in the form of animal products (meat, milk, eggs, including hatching eggs and animal products fed to other animals). The remainder consists of manure, bedding residues, emissions and waste and represents a key component of AFOLU emissions (see below).

### Current ecosystem carbon stocks and greenhouse gas emissions from agriculture, forestry and other land uses

Available data on C stocks are essential for estimating stock changes and hence greenhouse gas emissions or sinks in ecosystems. Land use related C stocks occur as soil organic carbon (SOC) and biomass carbon stock (often separated into above and below ground biomass). Land use is a key determinant of these carbon pools, interacting with other factors (e.g., organic soils show considerably higher SOC contents than mineral soils). The total C-stock in vegetation and soils is 1273 (±341) MtC (Table 2.1), of which about one third is in biomass and two thirds in the form of soil organic carbon (SOC). Conceding regional differences due to biophysical conditions, including soil types and local climatic conditions, changing land use will lead to a gradual adjustment of SOC in soil over decades (Baumgarten et al., 2021). Forests contribute more than 60 % to the total ecosystem carbon stock of Austria, followed by unmanaged/ unsurveyed land, while all other categories play a smaller role.

On average over the last five years with data (2019–2023), the total sum of emissions from the UNFCCC-sectors 'Agriculture' and 'Land use, land-use change and forestry' (LULUCF) fluxes was a net source of greenhouse gases (flux from the biosphere to the atmosphere), of about 9.4 $MtCO_2$/yr (Figure 2.3 and Table 2.A.2), or about 12.3 % of the total GHG emissions in Austria (19.8 % in the year 2023). In the five-year average, the total carbon flux in agriculture and LULUCF reached a maximum sink strength of >13 $MtCO_2$eq/yr around 2000, which decreased continuously (by approximately 1 $MtCO_2$/yr) to turn from a sink to a source after 2014 (Figure 2.3A). Here and elsewhere in this chapter, total GHG emissions include also those of LULUCF.

Agricultural emissions are dominated by $CH_4$ emissions from enteric fermentation, i.e., ruminant livestock production, whereas soil $N_2O$ emissions (direct and indirect) play a much smaller role, followed by manure management (see also Lauk et al., 2024). In total and on average between 2019 and 2023, emissions from agriculture, excluding direct and

Table 2.1 Area of land use and carbon stocks in Austria, 2020 (from Umweltbundesamt, 2023a; Baumgarten et al., 2021; [a] Seeber et al., 2022; [b] Tappeiner et al., 2008; [c] Tasser et al., 2020). Note that a fraction of grazing land is subsumed under unsurveyed land in this table.

| | Area | Average carbon stock in biomass per area (above and below ground) | Average soil organic carbon per area in the layer 0–30 cm | Range of carbon stocks§ |
|---|---|---|---|---|
| **Land use** | **[1,000 ha]** | **[tC/ha]** | **[tC/ha]** | **[MtC]** |
| Cropland | 1,283 | 6.7±4.1b | 62.5±19.9* | 63–115 |
| Mountain grassland | 12 | 8.3±2.3a | 108.73±41.9 | 1–2 |
| Extensively used grassland | 323 | 7.9±2.2a | 122.2±58.1 | 23–61 |
| Intensively used grasslands | 459 | 6.1±1.9a | 95.3±15.0 | 40–53 |
| Vineyards / orchards | 40 | 25.4±6.9c | 49.1±15.6* | 2–4 |
| ForestΩ | 4,015 | 106.5±10.0 | 115.3±46.0 | 702–1,080 |
| Peatland** | 21 | 41.3±14.5b | 220.0±70.0* | 4–7 |
| Settlements | 568 | 2±0.6b | 39.6±12.6* | 16–31 |
| Unmanaged land/unsurveyed land | 1,667 | 9.6±2.5a | 146.8±25.5 | 218–303 |
| **Total** | **8,389** | **54.9±4.9** | **107.5±22.9** | **1,165–1,559** |

* Range estimate unavailable, the average of all ranges (±32 %) was taken.
** Natural peatland area only
Ω Per-area C-stock data from the year 2020 FAO/FRA. Data do not contain deadwood.
§ For ranges, error margins of individual components were combined assuming error propagation of a normal distribution for independent data. Error margins of total were derived using the same logics. Hence also the range of the total is smaller than the difference between sums of low and high estimates.

indirect technical emissions (e.g., machinery, mineral fertilizer production) amounted to 9.9 % of total GHG emissions (10 % for the year 2023) (*medium evidence, high agreement*).

On average between 2019–2023, the sector LULUCF contributed +2.3 % to Austria's total GHG emissions (in the year 2023: 9.9 %). The LULUCF inventory shows strong annual fluctuations, particularly in the forest compartment (stock increases and decreases in existing forests, not so much in area expansion), which makes the interpretation of individual time cuts intricate. Figure 2.3A shows the total GHG fluxes between 1990 and 2023 according to the 2025 GHG inventory (Umweltbundesamt, 2025a). The data represent a major update of the calculation methodology, see 2.A.4 for a comparison with the previous inventory version. Changes in forest (forest remaining forest and new forest land) account for 0.3 % of total emissions in the five-year average (7.1 % in the year 2023). In 2018, and especially in 2019 and 2023, forests decreased in carbon stocks so that the aggregated agriculture and LULUCF sectors acted as strong net source of GHG emissions (*medium confidence*). In all years before 2018, forests had acted as carbon sinks and compensated for a considerable share of Austria's GHG emissions, especially around the year 2000. Changes in other land-use types (i.e., excluding forests), account for about 3.6 % of the total emissions on average (3.7 % in 2023) and harvested wood products represent a sink of −1.6 % on the five-year average (-0.9 % in 2023).

While emissions from agriculture slightly decreased over the same period, mainly due to a decreasing livestock herd (FAOSTAT), the overall development is mainly driven by forest dynamics (Figure 2.3B). Increment increased from 2.8 $m^3$/ha/yr in 1954 and 5.7 $m^3$/ha/yr in 1961–70, to 9.4 $m^3$/ha/yr for the 1981–1985 inventory, and decreased since then, reaching 9.3 $m^3$/ha/yr in the period 1986–1990 and 8.2 $m^3$/ha/yr in the period 2007–2009 to 2016 (Austrian National Forest Inventory, accessed in 2024). In the meantime, the inventory method has changed and might influence those findings. Schieler (1997) proved that the increments based on the 1961–1980 method are comparable with those since 1981. On the other hand, annual wood harvest increased from 3.4 $m^3$/ha/yr in 1954 to 7.8 $m^3$/ha/yr in the period 2000–2002 to 2007–2009 and was 7.4 $m^3$/ha/yr in 2007–2009 to 2016–2021. Taking the total wood harvest from census statistics (BMLF, 2024b), the share of wood harvest triggered by wind, snow or bark beetle damage in Austria was on average 26 % between 1990 and 2021 (28 % in the last decade), and showed strong variations, with a minimum in 2001 (9 %) and a maximum in 2008 (55 %). Note that harvest estimates from the annual census statistics (HEM) are significantly lower than harvest estimates from

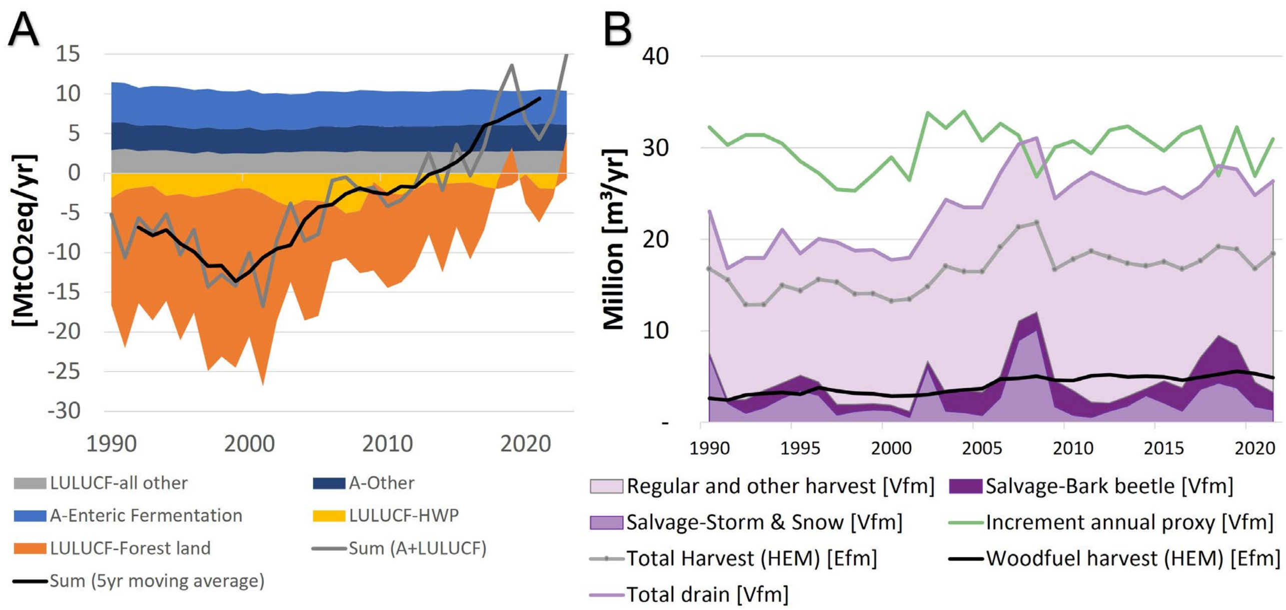



Figure 2.3 Austrian GHG inventory 1990–2023, version 2025 (Umweltbundesamt, 2025a). Panel (A) Total GHG-fluxes of the two compartments Agriculture (A), and Land use, Land-use change and Forestry (LULUCF). The agricultural flux is split into $CH_4$ from enteric fermentation (ruminant livestock; A-enteric fermentation) and other agricultural emissions (A-other), mainly $N_2O$ from soils and manure management. The LULUCF flux is separated in three components, Forest land (LULUCF-Forest land), harvested wood products (LULUCF-HWP) and the sum of all other fluxes (LULUCF-all other). The gray line in panel (A) indicates the resulting annual net-flow, the black line the 5-year moving average. Not all years prior to 2005 were available in tabular format in the 2025 version; missing values were extracted from a figure published by Umweltbundesamt (2025b). Panel (B) Forest and forestry dynamics 1990–2021: Areas refer to harvest volumes, disaggregated into salvage logging for storm and snow and bark beetle as well as regular and other wood harvests according to BFW (Steyrer, 2020) and Umweltbundesamt (2023a). The gray and black lines indicate the total wood harvest and wood fuel harvest, respectively, according to the 'Holzeinschlagsmeldung' (HEM) that reports annual 'harvestable volumes' (not solid volumes) without bark and without natural losses ('Erntefestmeter' – Efm). HEM results are thus significantly smaller than the harvest volumes according to the Forest Inventories (FIs), which are, however, only appraised in inventory periods. The annual proxy for increment is based on Forest Inventory data disaggregated to annual fluxes using HEM information (Umweltbundesamt, 2023a). Note that the difference between increment and harvest in panel (B) basically determines the net C flux of forests in panel (A).

the forest inventory, even when differences in methodology and definitions are taken into account (Gschwantner, 2019). The harvest of wood fuel (including primary wood, thinning wood and harvest residues) increased exceptionally strongly, by a factor of 1.9 between 1990 and 2019, from 16 % to 28 % of the total harvest (excluding bark and natural losses; FAOSTAT).

## National upstream or downstream emissions (land-related)

Land systems integrate various processes from production to consumption. In addition to the emissions subsumed in the emission accounts described above, these processes are associated with further emissions, that are accounted for in other sectors in the national GHG inventory (for details and further information, see 2.A.5). These emissions derive from on-farm energy use, from processing and retailing of agricultural products (downstream emissions), and the embodied emissions of materials used in farming such as fertilizers and pesticides (upstream emissions), excluding the provision of infrastructure and machinery.

Globally, Crippa et al. (2021) estimate that food systems account for 34 % of total GHG emissions. About 71 % of these are related to agriculture and land use/land use change with the remainder resulting from processing, transport, storage, or disposal. For Austria, Crippa et al. (2021) estimate total food system emissions at 21.5 $MtCO_2eq$ (based on GWP-100) in 2015, which is substantially higher than the agricultural emissions reported in the national GHG inventory (see above).

The current supply chain of wood biomass involves fossil energy inputs and thus generates emissions in addition to the land-use emissions that are included in the AFOLU sector. Life cycle assessments (LCA) have been conducted since the early 1990s to analyze the environmental impacts of various forest products and processes, but consistent results are lacking due to different boundary conditions (e.g., processes included in the accounts, assumptions about productivity rates, or fuel consumption of machineries). A meta-study showed large differences in greenhouse gas emission estimates of wood products, ranging from 2.4–59.6 $kgCO_2eq/m^3$ over bark calculated from site preparation to forest road, and from 6.3–67.1 $kgCO_2eq/m^3$ over bark from site preparation to reaching a plant gate or consumer (Klein et al., 2015). In 2018, 492 $ktCO_2eq$ were emitted for harvesting and transporting of 19.2 million°$m^3$ of timber, which corresponded to 25.63 $kgCO_2eq/m^3$. Transport accounted for the largest share of emissions (77 %) within the supply chain, extraction accounted for 14 % of emissions, felling and processing 5 %, and chipping 4 %. Emissions from felling, delimbing, and crosscutting were much lower when using a chainsaw compared to a harvester (Kühmaier et al., 2022). However, chainsaw operations are associated with higher work-related accident rates (SVS, 2024).

## Across-border impacts of Austrian consumption of agricultural and forestry products

There is *high confidence* that the consumption of forestry and agricultural products in Austria drives land use related pressures on ecosystems and greenhouse gas emissions in other countries (for an assessment, see Jandl et al., 2024c, pp. 147–152). Biomass use and processing in Austria is embedded in international trade networks, with imports exceeding exports. In terms of primary biomass equivalents, about half (45 % on average in 2010–2013) (Kalt et al., 2021) of the food, feed, fiber and biofuels consumed in Austria relies on imports (Schaffartzik et al., 2014; Kalt et al., 2021). Frey and Bruckner (2021) estimate that greenhouse gas emissions embodied in Austria's consumption of agricultural products reached 16.5 $MtCO_2eq$ in 2013, with food products accounting for 12.7 $MtCO_2eq$. Almost two thirds of the greenhouse gas emissions embodied in the Austrian consumption of agricultural products occur outside of Austria, especially in other European countries (22 %), Asia (19 %) and Latin America (14 %) (Frey and Bruckner, 2021). This account includes emissions from agricultural activities and land use change, typically deforestation. Leather is the most important non-food agricultural product causing emissions (only beef, milk and dairy, and pork cause higher emissions), of which only 0.7 % occur domestically, while 25 % occur in India and 15 % in Australia.

Austria's dependence on bioenergy imports is higher than indicated by national energy statistics on direct wood energy imports, as part of the wood processing residues used for energy come from imported sources (see above), questioning claims that bioenergy represents a self-sufficient energy source (Anca-Couce et al., 2021). This is because a large share of imports – Austria is the world's second largest importer of roundwood after China (FAOSTAT) – is processed in Austria, while final products are exported, and residues are used for paper production and energy purposes. Total roundwood imports amounted to 4.6 million $m^3$ in 1990, 8.6 million $m^3$ in 2000, 8.7 million $m^3$ in 2010, 12.5 million $m^3$ in 2020 and 8.7 million $m^3$ in 2022 while the sawn wood exports show a similar pattern of 4.2 million $m^3$ (1990), 6.4 million $m^3$ (2000), 6.1 million $m^3$ (2010), 6.1 million $m^3$ (2020) and 5.9 million $m^3$ (2022) (FAOSTAT). An older study calculated that taking embodied imports in the Austrian use of bioenergy from wood and agricultural products into account, reduced the domestic share from 84 to 67 % (Kalt and Kranzl, 2012). An analysis of wood flows in Austria reveals that in 2020, on average, 39 % of all wood and wood products used for energetic purposes in Austria originated from imports (BMK, 2023; Erb et al., 2023a). There is *high confidence* that biomass imports are associated with considerable direct and indirect embodied emissions (Marques et al., 2019; Pendrill et al., 2019; Peng et al., 2023), which have not yet been quantified for Austria's trade of wood.

Such impacts are operationalized with, e.g., concepts such as 'imported deforestation' risk, which in the Austrian case has declined from 3,000–5,000 ha/yr to 1,000–4,000 ha/yr, representing a 20–60 % reduction of deforestation related $CO_2$ emissions (Pendrill et al., 2022). However, in some countries, better governance of deforestation has shifted export driven agricultural expansion frontiers to non-forest ecosystems (Dou et al., 2018). Decreasing rates of deforestation embodied in Austrian consumption are laudable but need to be interpreted with caution as such spillover effects on non-forest ecosystems are often overlooked and may offset reductions in carbon emissions and biodiversity loss associated with decreasing rates of deforestation (Searchinger et al., 2015; Dou et al., 2018). The degradation of non-forest ecosystems embodied in Austrian imports remains largely unquantified. Agricultural imports have increased rapidly in recent decades. The share of imports in total agricultural area embodied in Austria's consumption increased by 130 % since the late 1980s (data from Roux et al., 2023). Depending on the specific indicator chosen, the methods used and system boundaries, studies find diverging trends associated to the environmental impacts of Austrian biomass imports (Gingrich et al., 2024). While pressures on ecosystems, mea-

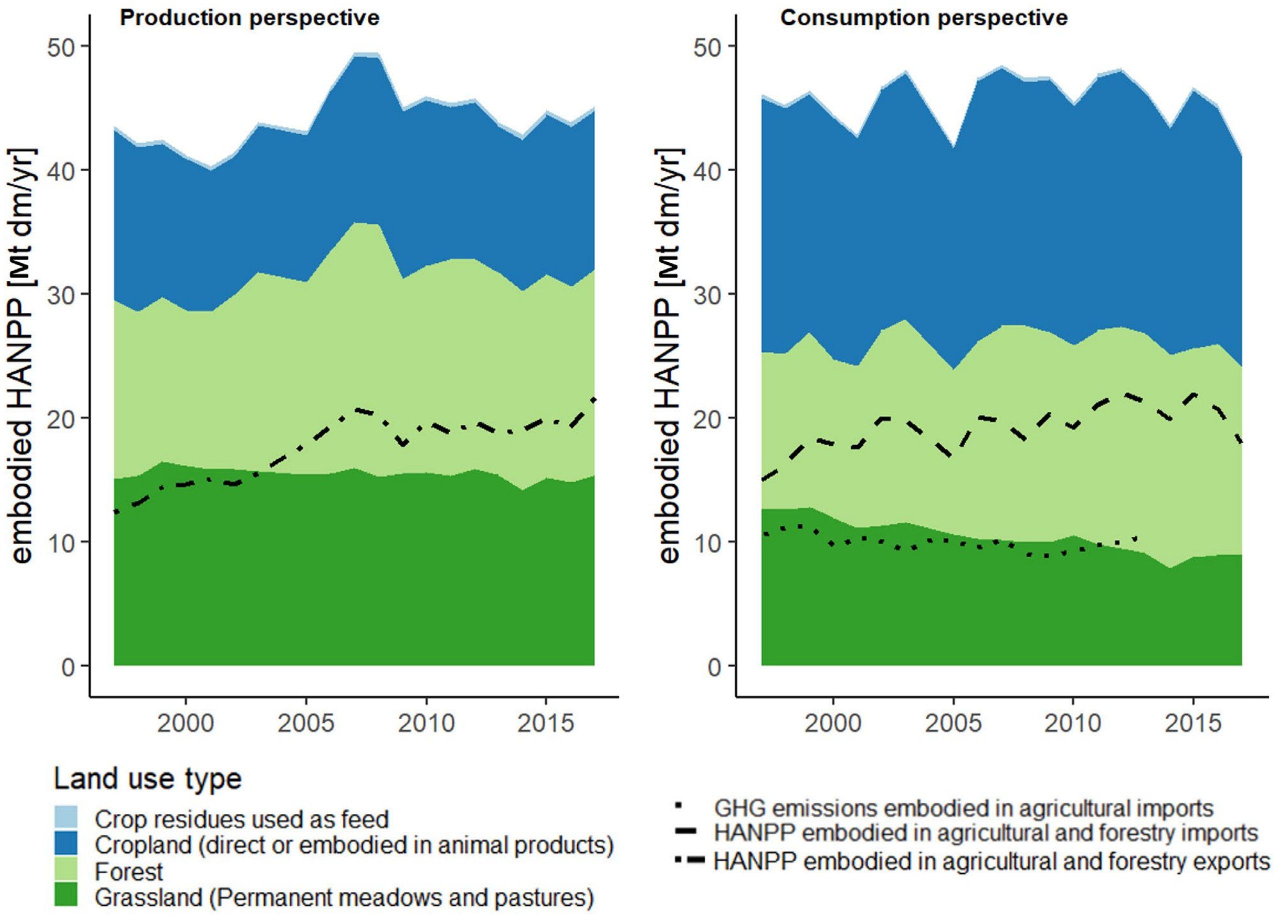



Figure 2.4 Human Appropriation of Net Primary Production (HANPP) embodied in Austria's production and consumption of agricultural and forestry products, by land use types (data from Roux et al., 2023, updated) (see 2.A.15). HANPP is an indicator for land use and pressures on ecosystems, accounting for the extent and intensity of land use (Haberl et al., 2014). Greenhouse gas emissions embodied in imports of agricultural products (dotted line) are from Frey and Bruckner (2021). Imports and exports are corrected for re-exports.

sured in Human Appropriation of Net Primary Production (HANPP) embodied in Austria's consumption of agriculture and forestry products decreased, the HANPP embodied in imports and exports increased since 1990 (Figure 2.4). HANPP embodied in biomass imports and exports are of similar magnitude.

## 2.2. Terrestrial ecosystem services under the influence of climate change

This section assesses the impacts of climate change on ecosystem services and their benefits, especially human health and economic income. Austria's ecosystems have been influenced by long-term management practices, affecting their resilience or vulnerability to climate change. Although it is difficult to disentangle the effect of management from those of climate effects, we attempt to do so in the following subchapters. The section is structured following the Common International Classification of Ecosystem Services (CICES), to ensure the comprehensiveness of the assessment. Where possible, the assessment is made under different Global Warming Levels (GWL; see Chapter 1), and also considers changes in precipitation. The quantification of impacts is sometimes done based on ÖKS15 Scenarios. Note that, as explained in Section 1.2.2, these scenarios are subject to a time lag or 'cold bias': The impacts of climate change appear to occur earlier than modeled by ÖKS15. There is *high confidence* that climate change has an overall negative impact on ecosystem services in Austria, but that the impacts differ by region and ecosystem service considered. Table 2.2 provides an overview of the magnitude of the impacts of temperature and precipitation changes on the ecosystem services assessed in this chapter. See 2.A.6 for detailed quantifications and Figure TS.7 for a cartographic representation.

Table 2.2 Mean potential impacts of climate change on Ecosystem Services (E.S.) under GWL 3.0°C and GWL 5.0°C, differentiated by three major biogeographical regions and classified into qualitative impact levels (Schirpke and Tasser, 2024). Impacts were derived by identifying potential impacts on multiple indicators, used to quantify the potential ecosystem service supply, based on current literature. The indicators were multiplied by the potential impacts and spatially weighted with projections of temperature and precipitation under the two GWLs. For methodological details, see Schirpke and Tasser (2024). A strong negative impact is indicated by '-3', a medium negative by '-2', a low negative by '-1', and a low positive by '1'. Values are averaged across regions. The regions encompass several ecosystems. E.S. not covered by Schirpke and Tasser were estimated by expert judgement (blue font). If supported by literature levels of confidence are given (*/**/*** = low/medium/high).

| Values from publication (Schirpke and Tasser, 2024) attributed to ecosystem services from this chapter and reclassified into qualitative impact levels | Chapter section | GWL 3.0°C | | | Confidence | GWL 5.0°C | | | Confidence |
|---|---|---|---|---|---|---|---|---|---|
| | | North-eastern plains, Alpine foothills and highlands | Northern and Central Alps | Southern lowlands and Alps | | North-eastern plains, Alpine foothills and highlands | Northern and Central Alps | Southern lowlands and Alps | |
| ***Provisioning ecosystem services*** | | | | | | | | | |
| **P1) Food and feed from arable crops** | 2.2.1 | -1/+1 | -1/+1 | -1/+1 | ** | -1 | -1 | -1 | * |
| **P1) Food and feed from permanent crops** | 2.2.1 | Research gap | | | | | | | |
| **P2) Livestock products** | 2.2.1 | 1 | 1 | 1 | ** | 1 | 1 | -1/+1 | ** |
| **P3) Products from hunting and wild animals** | 2.2.1 | -1 | -2 | -1 | ** | -1* | -3* | -1* | * |
| **P4) Products from aquaculture** | 2.2.1 | 1 | 1 | 1 | ** | 1* | 1* | 1* | * |
| **P5) Fiber, bio-based energy** | 2.2.1 | -1 | -1/+1 | -1 | ** | -1 | -2 | -2 | * |
| **P6) Water** | 2.2.1 | -1 | -1 | -1 | ** | -1/-2 | -2 | -2 | ** |
| ***Regulating ecosystem services*** | | | | | | | | | |
| **R1) Climate regulation/ carbon sinks** | 2.2.2 | -1 | -1 | -1 | ** | -1 | -1 | -2 | * |
| **R2) Biochemical cycles** | 2.2.2 | -1 | -1 | -1 | Research gap | -1 | -1 | -1 | Research gap |
| **R3) Mass movement and erosion control** | 2.2.2 | -1 | -1 | -1 | * | -1 | -1 | -1 | ** |
| **Wind and fire protection** | 2.2.2 | Research gap | | | | | | | |
| **Water flow regulation and flood control** | 2.2.2 | Research gap | | | | | | | |
| **R6) Pollination** | 2.2.2 | 1 | 1 | -1 | ** | -1 | 1 | -1 | ** |
| **R7) Pest control and invasive species** | 2.2.2 | 1 | 1 | 1 | *** | 1 | 1 | 1 | *** |
| ***Cultural ecosystem services*** | | | | | | | | | |
| **C1) Recreation** | 2.2.3 | -1 | -1 | -1 | *** | -2 | -2 | -2 | ** |
| **C2) Cultural heritage** | 2.2.3 | -1 | -1 | -1 | ** | -1 | -1 | -1 | * |
| **C3) Aesthetic value** | 2.2.3 | -1 | -1 | -1 | *** | -2 | -2 | -2 | ** |
| **C4) Symbolic value** | 2.2.3 | -1 | -1 | -1 | ** | -1 | -1 | -1 | * |

### 2.2.1. Impacts of climate change on provisioning ecosystem services and related benefits and limitations

#### Impacts of climate change on the provision of food and feed from arable crops

Austria's arable crop production for food and feedstock covers an area of about 1.3 million ha. The largest arable production areas are planted with wheat, maize/corn, barley and soybeans. Cereals, produced on about 58 % of arable land, are the most important crop group, followed by feedstocks (18 %) and oilseeds (12 %) (Statistik Austria, 2023a). On average, the production of arable crops incl. feedstocks generates 30–38 % of the production value of the entire agricultural sector (BMLF, 2023a).

There is *medium evidence* and *high agreement* that the effects of climate change described in Section 1.2.2, such as increased temperatures, altered vegetation periods and enhanced $CO_2$ fertilization will affect crop yields and product quality. Thereby, predicted yield deviations vary strongly. The variance depends on the GWL, the climatic region and the time period considered. In particular, the characterization of precipitation patterns as well as regional variables such as soil quality, soil water storage capacity, crop types and management practices (e.g., irrigation) play a role (Schönhart et al., 2014, 2016; Kirchner et al., 2015; Thaler, 2021). With *medium confidence*, for scenarios close to GWL 2.0°C, Austrian studies, all considering $CO_2$ fertilization effects and comparing to yields around the beginning of 2000, present yield changes spanning from -10 to +10 %, with regional disparities (Thaler et al., 2012; Eitzinger et al., 2013; Schönhart et al., 2014; Mitter et al., 2015a). Heterogeneity is observed between humid western and semi-arid eastern regions (Schönhart et al., 2014, 2018; Mitter et al., 2015a, 2015b; Kirchner et al., 2016; Thaler, 2021). With more pronounced climate change, one study predicts yield increases of 3–23 % for winter wheat and spring barley under close to GWL 4.0°C scenarios, but strong yield reductions of >-20 % for maize (Thaler, 2021). With *high confidence*, $CO_2$ effects on $C_3$ crops exceed those on $C_4$ crops (Ebrahimi et al., 2016; Ainsworth and Long, 2020; Thaler, 2021). However, the effects of $CO_2$ fertilization remain uncertain, and the effects of technical advancements (plant breeding, digitalization and other improvements in crop management) call for further research. In terms of product quality, wheat protein concentration could increase in scenarios with the largest yield reductions (Ebrahimi et al., 2016).

In addition to general yield trends, specific climate change phenomena as described in Section 1.2.2 – with *medium confidence* – will also increase the uncertainty of crop yields. Indirectly, trends such as elevated temperatures and altered precipitation patterns will affect the dynamics of weeds, pests and diseases (Eitzinger et al., 2013; Deutsch et al., 2018; Juroszek et al., 2020; Lehmann et al., 2020). Directly, the increasing occurrence of weather extremes such as thunderstorms, heavy rainfall (Mitter et al., 2015b; Naumann et al., 2015; Rajczak and Schär, 2017; Lehmann et al., 2018; Mäkinen et al., 2018), heat spells (Trnka et al., 2014; Mitter et al., 2015b; Mäkinen et al., 2018; Lorenz et al., 2019b; Bönecke et al., 2020), hail, and especially increased frequency and severity of droughts (Mitter et al., 2015a; Naumann et al., 2015; Hochrainer-Stigler et al., 2019) can lead to remarkable production losses. One study covering two Austrian drought scenarios up to the year 2040, models annual yield decreases of winter crops of up to 27 % on national average, causing annual production value losses of the most important crops of $EUR_{2023}$ 78–191 million, depending on the scenario (Mitter et al., 2015a). The highest drought-related yield vulnerabilities of >20 % (maize) are modeled for the Pannonian zone in Burgenland and Lower Austria (Hochrainer-Stigler et al., 2019).

The impacts of climate change on arable crop production vary between the different production areas in Austria. While adaptation of management (irrigation, soil management, adaptation of crop rotations and choice of crop species) will be necessary to counteract negative impacts, productive cropping areas may also emerge in the western part of the country (Kirchner et al., 2016).

#### Impacts of climate change on the provision of food from permanent crops

In 2021, the two major branches of Austrian permanent crop production, namely wine and fruit production, covered an area of 46,634 ha (vineyards) and 15,760 ha (orchards). In 2022 wine and fruit production generated a value of $EUR_{2023}$ 740 million and $EUR_{2023}$ 447 million, respectively, representing 10 % of the agricultural sector (Statistik Austria, 2023b). The main fruits are apples and pears, apricots (and strawberries), and the major production areas are located in Styria (64 % of area), Lower Austria, Upper Austria, Burgenland (Statistik Austria, 2023b). Major wine production areas are located in Lower Austria, Vienna, Burgenland and Styria (BMLF, 2023a).

Literature quantifying yield reductions in permanent crops under different GWLs is not available for Austria and represents a major research and knowledge gap. However, there is *limited evidence* but *high agreement* that climate change will provoke changes in the risk of crop failure and product quality of permanent crops. The literature agrees that yields and product quality in Austrian wine and fruit production will be impacted mostly by elevated average temperatures and the related increase in the length of vegetation periods. In fruits, increasing spring temperatures lead to changes in phenology, and thereby especially to the earlier timing of bud break (Unterberger et al., 2018, for Styria; Haokip et al., 2020), potentially causing a phenological decoupling of plant-pollinator mutualism (Settele et al., 2016, for Europe) and strongly increasing the risk of severe damage up to total yield losses and quality losses due to the occurrence of late frosts (Unterberger et al., 2018; Dalhaus et al., 2020). For example, in 2023, late frost caused a total loss of apricot harvests in Wachau/Lower Austria (BMLF, 2024a), and in the years 2023, 2021 and 2020 production losses in all fruits of 10 to 14 % compared to the 10-year average (BMLF, 2023a, 2024a). In addition to late frosts, extreme weather events (heavy rain, thunderstorms, hail) directly endanger crops. Prolonged periods of heat and short-term extreme droughts can affect yields and product quality and require irrigation measures and investments in management systems such as cooling, shading, and smart irrigation (Hannah et al., 2013, international scale). In wine production, earlier ripening and higher temperatures during ripening alter quality parameters (Vršič and Vodovnik, 2012, for northeast Slovenia; Vršič et al., 2014). Production of high-quality wine grapes in regions at the margins of their climatic limits will become more difficult, while elevated temperatures could make some regions more favorable to produce current or new varieties (Moriondo et al., 2010, for Tuscany; Eitzinger et al., 2013; Santillán et al., 2020, for northern Italy). In Austria, the entire Waldviertel and Mühlviertel regions will potentially be suitable for viticulture by the end of the century (Formayer and Goler, 2013). Migration of production areas to higher altitudes is also possible (Eccel et al., 2016, for Trentino; Egarter Vigl et al., 2018, for South Tyrol; Alikadic et al., 2019, for Trento). Threats from climate change-induced changes in pest and disease dynamics are expected to increase (Salinari et al., 2006, for northwestern Italy; Caffarra et al., 2012, for northern Italy; Lehmann et al., 2020). For Austria, both fungal and insect dynamics are expected to be impacted by climatic parameters, with mixed results depending on climatic variations (Legler et al., 2012; Zaller et al., 2013; Redl et al., 2021; Möth et al., 2023).

## Impacts of climate change on the provision of livestock products

In 2021, livestock production in Austria produced a value of $EUR_{2023}$ 4,417 million, representing 44 % of the agricultural sector, using large areas of cropland and grassland (Table 2.1). Animal production is, in economic terms, dominated by dairy products (40 % of the commercial value), beef production including veal (23 %), pork (20 %) and poultry and eggs.

Climate change will impact Austrian livestock production through the effect of heat stress on animals (Hempel et al., 2019; Mikovits et al., 2019) on the one hand, and through impacts on feed supply chains (see Section 2.2.1 for more detail) (Haslmayr et al., 2018) on the other hand (*medium evidence, high agreement*). However, estimates for Austria indicate rather low heat stress related losses in milk sales revenue of 0.6 % (0.1–2.5 %) even under a GWL 3.6°C (Schönhart and Nadeem, 2015). In addition to productivity losses, impaired welfare due to the increased frequency and intensity of heat stress occurrence may increase skepticism among societal groups towards animal farming. This emphasizes the urgency of mitigation strategies from an animal welfare perspective (Shields and Orme-Evans, 2015).

There is *medium evidence* and *high agreement* that, depending on the severity of climate change, grassland productivity can be expected to be maintained or even enhanced in large parts of western and central Austria, which are dominated by grassland (Haslmayr et al., 2018) (see Section 1.6.3). Water availability and rainfall distribution are the main factors for the expected development of grassland yields, with an increasing probability of yield depression of individual cuts (*high confidence*), thereby putting at risk a constant feed supply for ruminant livestock (Finger et al., 2010; Neuwirth and Hofer, 2013; Bahn et al., 2023). In alpine grasslands, severe climate change, represented by a reduced water supply of the order of 40–50 %, together with droughts of several weeks and partially an increased ambient temperature, induces shifts in vegetation and soil microbes, leading to enhanced water use efficiency (under GWL 1°C: 2018; no increased temperature: Tello-García et al., 2020, 2023) (*medium confidence*). Regions focused on the production of important feed crops (maize, cereal and legume grains, oilseeds) for all livestock species will be stronger affected by climate change (see above). The impact on feed supply will be considerably variable across regions (see above).

In addition, securing the water supply for livestock has become an increasingly important issue for livestock farmers in certain parts of Austria in recent years (*limited evidence, medium agreement*). The livestock farming sector currently requires about 55 million m³ of water. An increase of 46 % is expected by 2050 (BMLRT, 2021b). Most likely, the situation will vary regionally, mainly depending on precipitation patterns and the type of water source (groundwater vs. spring discharge; for details see below). Given the high drinking water requirement of livestock, roughly three times the daily dry matter intake (Schlink et al., 2010), securing a continuous water supply is a critical issue for livestock farms, which will become even more challenging due to increasing conflicts of use (BAFU, 2014).

Animal health in a narrow sense (i.e., occurrence of health disorders as a consequence of climate change) is perceived as a potential challenge, but has not yet been researched in depth for the specific conditions in Austria. The infection pressure by certain vector-borne pathogens is expected to increase because of climate change (Gale et al., 2010). Bluetongue disease in ruminants, which has also appeared in Austria in the last one and a half decades (Pinior et al., 2018), is an example for vector-borne diseases, where in particular the interactions between vector and host are still poorly understood (Baylis, 2013). This poses a challenge for the development of specific preventive actions.

### Impacts of climate change on the provision of products from hunting and wild animals

There is *high confidence* that climate change leads to elevational shifts in the distribution of habitats for many plants and animals of about 140–180 m per degree of temperature increase (Zu et al., 2021; Rubenstein et al., 2023). Since the 1970s, there has been an elevation migration of 36 m/decade (see Section 1.6.4). Especially in the peripheral Alps, but also in the lower elevations of the Central Alps, the subalpine and lower alpine, forest-free habitats are colonized by forests and shrubs and have thus largely disappeared (Chamberlain et al., 2013; Tasser et al., 2017). The distribution of most forest and shrub game species (especially ungulates) has remained stable or increased in response to the expansion of suitable habitats (Reimoser and Reimoser, 2016; Tasser et al., 2023). However, there is *high confidence* that the distribution of alpine habitat specialists could decline sharply as open grassland areas disappear (Chamberlain et al., 2013; Imperio et al., 2013; Rehnus et al., 2018) (see also Section 1.6.4). These results confirm that the conservation of alpine game species such as the rock ptarmigan (Revermann et al., 2012) and the marmot (Tafani et al., 2013), but also chamois (Chirichella et al., 2021), will become problematic in the future, but this can be reduced by management strategies to preserve summer pasture areas (Chamberlain et al., 2013; Tasser et al., 2024).

### Impacts of climate change on the provision of products from aquaculture

There is *high confidence* that climate change increases the temperature of freshwater bodies (Niedrist, 2023), causing a deterioration of water quality, e.g., due to a reduced dissolved oxygen and increased algal blooms and toxicity of pollutants (Ficke et al., 2007; Orság et al., 2023) (see also Section 1.4.3 and below). For fisheries and aquaculture in Austria, this also means increased stress for fish and an increase in associated diseases and parasite infestations, as well as lower feeding and growth performance (Handisyde et al., 2006; Schindler, 2017; Casas-Mulet et al., 2021).

Austrian fish farming focuses mainly on salmonids, carp and African catfish (3,599 t salmonids, especially rainbow, brown and brook trout, 617 t carp and 494 t catfish) (Statistik Austria, 2022a). Furthermore, 32.9 million spawning fish and 25 million stocking fish are produced. Since salmonids are generally cold-water fish (average preferred temperature of 11–15°C in summer), while carp and catfish are cold- to warm-water fish (>21°C), climate warming will lead to a shift of breeding populations from salmonids to cyprinids, pike and catfish (Meisner et al., 1987; Reist et al., 2006) (*high confidence*). At the same time, salmonid species are expected to be displaced upstream in Alpine rivers, but warm-water species such as carp and some invasive species such as exotic rainbow trout, grass carp and sunfish will become established (Matulla et al., 2007; Rabitsch et al., 2013; Pletterbauer et al., 2015).

### Impacts of climate change on health aspects related to food provision

Looking at food-related health issues, climate change certainly affects food safety (Duchenne-Moutien and Neetoo, 2021). Although food safety issues are not of major concern in Austria compared to lower- and middle-income countries (Cissé, 2019; Seitner et al., 2022), Austria is dependent on global supply chains (Leidwein et al., 2014) (see Chapter

Box 2.1) and also in Western European countries, an association between ambient temperature and number of salmonella infections has been demonstrated, even after controlling for seasonal effects (Kovats et al., 2004). Behavioral changes (e.g., more outdoor preparation of food) contribute to these increasing risks. However, it should be noted that climate effects on food safety and food-borne diseases in Austria are understudied. In addition to food quality and security, the effects of climate change on food quantity will also directly impact human health. Springmann et al. (2016) in their global modeling study also provide estimates for Austria under GWL 2.0°C–GWL 3.0°C (main scenarios) for 2050 accounting for (i) reduced calorie intake (mostly beneficial), (ii) reduced red meat intake (beneficial), and (iii) reduced fruit and vegetable intake (detrimental). All factors combined they estimate 220 (95 % confidence interval: 70–360) additional deaths annually due to these changes (compared to a 'no climate change' reference scenario).

## Impacts of climate change on the provision of fiber

For Austria, fiber production from agriculture (fiber plants: Hemp, flax; animal fibers: Sheep wool) is minimal and hence not covered. In contrast, the use of wood fiber includes most wood products (timber, paper, cellulose) and therefore, the provision of fibers is mostly dependent on the forestry sector.

Forest ecosystems and forest management will be impacted not only by changes in climate trends, but also by increased variability and intensity of extreme weather events, such as drought, storms and floods (*high confidence*) (see also Chapter 1). In particular, mountain forests will experience higher temperatures (see also Chapter 7), which will lead to higher production rates and an expansion of the forest area at higher elevations in sites that are currently limited by temperature (Lindner et al., 2010). The disturbance regime will also be influenced by the changing climatic conditions, leading to more frequent and intense bark beetle infestations, wind throws and forest fires (Senf and Seidl, 2021). Climate change is and will continue to impact the tree species composition, productivity, and ultimately wood supply. At local warming levels above 2°C, especially conifer-dominated landscapes in mountain areas of Austria characterized by large trees, might shift to a landscape dominated by smaller, predominantly broadleaved trees (Albrich et al., 2020). Higher growth rates can be expected in higher elevation mountain areas due to longer vegetation periods and warmer temperatures, and generally, the provision of timber might be influenced by increased disturbances and droughts (Obojes et al., 2018, 2020, 2022). Businesses will therefore face a potential scarcity of wood availability for certain assortments or species as forest management adapts to the changing climate. The results of the Austrian Forest Inventory 2016/21 of the Federal Research Centre for Forests (BFW) show a clear trend towards more broadleaved forests. Pure conifer stands have decreased by 6 % over the last decade, while mixed hardwood stands have increased by the same percentage. Due to climate change, spruce has already lost parts of its distribution between 600 and 800 m a.s.l (BMLF, 2023b).

Despite Austria's forests having lost their property of being a carbon sink (see Figure 2.3) large quantities of $CO_2$ are taken up in forest ecosystems. The current increment of Austria's forests (i.e., before harvest and mortality, as opposed to stock changes) is 24.7 $MtCO_2$/yr. However, scenarios show a decrease to 21.1 $MtCO_2$/yr if local temperatures increase by 3°C. In addition, if precipitation decreases by 30 %, capacity drops further to 19.0 $MtCO_2$/yr. The distribution of changes is heterogeneous (Figure 2.5), with higher altitudes experiencing increased productivity and lower altitudes experiencing decreased productivity, especially when accompanied by increased temperature. The probability of a single 'bad year' increases with increasing temperature and can lead to the destruction of large forest areas and the gradual release of previously stored $CO_2$. Furthermore, Kindermann (2021) points out that the $CO_2$ uptake becomes smaller than the $CO_2$ release, turning a forest from a sink to a source. Increased mortality results in an increased mass of deadwood in the forest, which may either remain in the forest or be harvested and used for fiber production. However, lower carbon uptake by forests means that, to keep the carbon stock constant, harvest of deadwood must also be proportionally reduced. On the other hand, forest biodiversity benefits greatly from structural diversity and the abundance of deadwood in forests (Oettel and Lapin, 2021; Rigo et al., 2024).

The distribution of forests showed an accumulation of ages with high rates of productivity rates in 1990. 30 years later, forests have matured and the age peak has flattened, leading to a decrease in productivity from 9.3 $m^3$/ha/yr in 1990 to 8.2 $m^3$/ha/yr in 2020. This trend of decreasing productivity is estimated to continue by the forest growth models EFDM, Caldis (Kindermann and Ledermann, 2023), G4M and EFISCEN (Böttcher et al., 2011). In the coming decades, this trend can be reversed, by harvesting old and overmature forests with low increments and regenerating

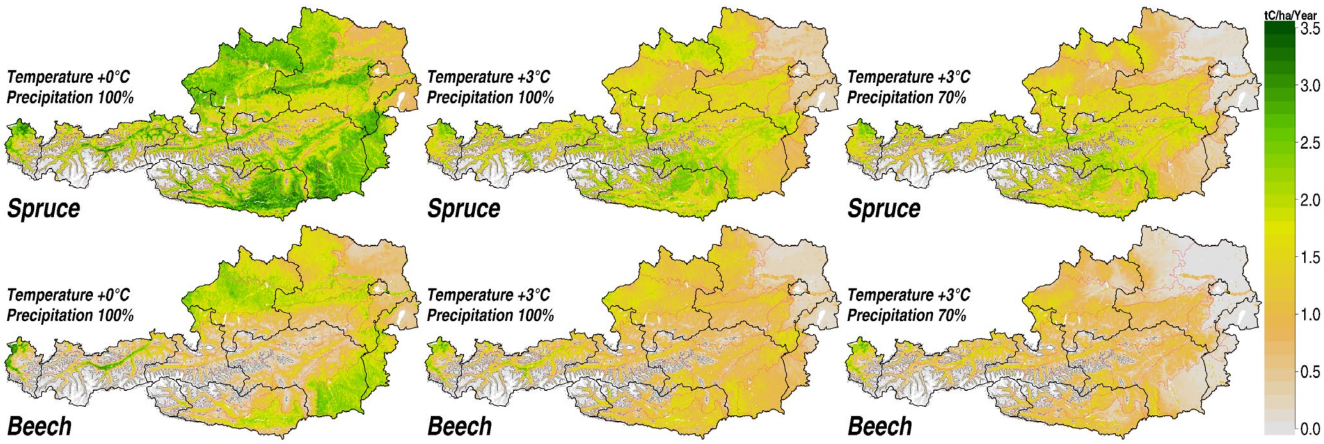



**Figure 2.5** Estimated average productivity in tC/ha/yr of spruce (*Picea abies L.*) and beech (*Fagus sylvatica L.*) for (i) current climatic conditions; (ii) increased local temperature (+3°C); and (iii) increased local temperature (+3°C) and reduced precipitation (70 % of current climatic conditions) (Kindermann, 2021). Effects on other tree species can be found in Figure 2.A.2 for (i) current climatic conditions; (ii) increased local temperature (+3°C); and (iii) increased local temperature (+3°C) and reduced precipitation (70 % of current climatic conditions) (Kindermann, 2021).

them to younger forest stands with higher growth rates (see Section 2.3.1 for related effects on climate change mitigation). Overall, the growth of the same species in the same location was higher in the following stand generation (Rössler, 2014). In addition to climate, other factors such as nitrogen deposition can influence forest growth. Spiecker et al. (1996) have shown this trend of increasing growth for Europe. A recent study by Chakraborty et al. (2024) expects that growth will decline in the future.

In any case, the expected high amount of salvage wood will affect the market price of timber and can cause losses of income for forest owners due to limited opportunities to sell high quality sawn timber, rather than industrial round wood with lower quality. Based on the analysis of a past storm event in Italy, a 40 % drop in timber prices was observed (Udali et al., 2021).

## Impacts of climate change on the provision of bio-based energy

Cropland-based biomass is insignificant for Austria's overall energy supply. Despite the negligible role of yield quality and therefore climate-induced changes in yield quality, the impacts of climate change on crops grown for energy uses are similar to the impacts on crops grown for food, feed, and other industrial purposes (see above). The two major cropland-based energy sources, bio-based liquid fuels and biogas, respectively account for only 4.4 % and 0.8 % of total renewable energy demand in 2020 (Biermayr, 2022). About 11 % of cereal consumption in Austria was used for bio-ethanol production (AMA, 2022). Biogas feedstock was produced on 15,800 ha cropland, 7,000 ha grassland and cropland with second harvests or crop residues. Livestock manure and residues from the food industry and sewage systems are also included.

About 26.9 million m³ of the timber being harvested domestically, imported or coming from other sources (e.g., waste wood, groves) are used annually for energy supply in Austria, accounting for 55 % of the total energy supply from renewable resources (see Section 4.5). The material originates from harvested industrial roundwood or firewood, processes and by-products in the sawmill, pulp and paper industries (e.g., cross-cut ends, barks, products from further wood processing, wood chips, pellets), which has been argued to be $CO_2$ neutral by Jandl et al. (2024) but not in other sources (Norton et al., 2019; Erb et al., 2022; Peng et al., 2023) (for a discussion on carbon neutrality of biomass use, see 2.A.5 and Box 1.1 in Jandl et al, 2024c). The impacts of climate change on the provision of forest fuels are similar to those for fiber, although there is *limited evidence* and *medium agreement* that climate change will increase the amount of salvage wood harvested from the increasing number of disturbances (see above). This will probably increase the supply for renewable energy and other material uses in the future (Sohngen and Sedjo, 2005; Lantz et al., 2022).

## Impacts of climate change on the provision of water

The provision of ecosystem services and related benefits of water bodies (surface- and groundwater) is manifold (Keeler et al., 2012; Hallouin et al., 2018; Lupi et al., 2023). In addition to supplying drinking water, healthy waters are rich in biodiversity, provide fishing grounds and recreational areas including bathing, and are essential landscape elements. They are also indispensable elements of water and food supply for neighboring ecosystems (e.g., wetlands). Reduced water availability and deteriorating water quality endanger these services.

There is *high confidence* that changes in rainfall patterns, drought duration and intensity can significantly impact pollutant transport, dilution and, together with increasing water temperature, related water quality. Therefore, climate change has the potential to counteract efforts to improve water quality and may lead to further deterioration. See 2.A.7 and Section 1.4 for a discussion of climate impacts on water fluxes and related substance transport, or indirect impacts due to climate change adaptation measures.

There is a *high confidence* that phosphorus pollution is responsible for 21.1 %, of Austrian surface water bodies failing good ecological status as defined in the EU Water Framework Directive (WFD). For conditions similar to GWL 2.0°C and increasing precipitation trends, Schönhart et al. (2018) estimate an increase in median total phosphorus river loads of about 20 % and, for decreasing precipitation trends, an increase in the of rivers orthophosphate environmental quality standards (EQS) by a factor of about 1.2 (*medium confidence*). Nitrate is responsible for 9 % of groundwater monitoring stations exceeding the WFD threshold (*high confidence*). Mehdi-Schulz et al. (2024) estimate a heterogeneous pattern across Austria with an increase of up to 10–15 % for N concentrations in some rivers in northeastern and southeastern Austria for a GWL 2.0°C and decreasing precipitation trends (*medium confidence*). Nitrate in groundwater can be assumed to follow a similar pattern. These impacts may affect current efforts to reduce nitrate levels below EQS by environmental programs in agriculture (e.g., Österreichisches Programm für umweltgerechte Landwirtschaft, ÖPUL) (*high confidence*).

In addition, pollution with priority substances deteriorates the chemical status of surface waters, with 100 % failing to achieve good status if either of the ubiquitous substances mercury and polybrominated diphenyl ethers (PBDE) are considered, while only 17 % are at risk of failing good status if these substances are neglected (BMLRT, 2022). While the vulnerability of water bodies with decreasing flow under climatic stress continues to increase, this could become even more critical if the European Commission adjusts/lowers the thresholds for priority substances (European Commission, 2022; Brielmann et al., 2023; Clara and Müller-Rechberger, 2023) (*high confidence*).

There is *medium evidence* and *high agreement* that impacts of climate change on the provision of water will manifest locally and seasonally, with areas in northeastern and eastern Austria being most at risk of facing water scarcity (Mitter and Schmid, 2019; ZAMG, 2020; BMLRT, 2021a; Hanger-Kopp et al., 2024). Drinking water demand across Austria will rise until 2050 under GWL 2.0°C, particularly in western and Alpine regions with a high share of tourism, where water demand in some hotspots may increase by 50 % under GWL 2.0–3.0°C (BMLRT, 2021a). In a dry scenario, agricultural water demand may double by 2050 (GWL 2.0–3.0°C), whereas other material water uses, such as for industrial purposes, are not predicted to change significantly (BMLRT, 2021a). Usage intensity across Austria will largely remain within sustainable boundaries; however, in a very dry scenario, regions with intense usage in Eastern Austria exceed the available groundwater resources (GWL 2.0–3.0°C). Demand for drinking water will rise by approximately 15 % by 2050 under a very dry scenario – GWL 2.0–3.0°C, with about 10 % of these 15 % being due to population growth, and 5 % due to climate change (BMLRT, 2021a).

Water demand for agricultural irrigation will rise, particularly in northern, eastern, and southeastern Austria (*medium evidence, high agreement*). Across Austria, the total irrigable land area has increased by 30,349 ha (from 91,998 to 122,347 ha) between 2010 and 2020 (Statistik Austria, 2022b), representing 4.7 % of the total used agricultural area (Statistik Austria, 2024). About 85 % of the irrigated areas in Austria are concentrated in Lower Austria and Burgenland (Statistik Austria, 2022b). Very dry scenarios (GWL 2.0°C) show an increase in irrigable land in these federal provinces, as well as in Upper Austria and Styria, by 2050 (BMLRT, 2021a). In the same regions, scenarios considering severe multi-annual dry spells show increases in irrigated areas by a factor of 5.6 compared to a reference scenario (GWL 1.5°C), where increases further depend on the level of risk aversion of farmers (Mitter and Schmid, 2019). Currently, there is no monitoring of actual water use for irrigation. Such data would significantly improve the accuracy of predictions and thus adaptation decisions (BMLRT, 2021b; Hanger-Kopp et al., 2024).

### Chapter Box 2.1. Impacts of climate change on Austria's global supply chains of food and other biomass products

There is *medium evidence* but *high agreement* that Austria's supply of food, feed, fiber, and bioenergy is increasingly dependent on global supply chains, and that imports from tropical and Mediterranean regions are more vulnerable to climate change than Austria's domestic supply. Due to the increasing reliance on imports, the supply of agricultural products to Austria is vulnerable to climate change not only in Austria, but also in countries exporting to Austria (Davis et al., 2021; Hedlund et al., 2022). Nonetheless, about two-thirds of Austria's imports of biomass originate from neighboring countries (Kalt, 2021), which, except for Mediterranean region, may largely face similar risks as Austrian production (ESPON, 2012; Knox et al., 2016; Hasegawa et al., 2022). On the other hand, the provision of tropical products (e.g., coffee, cocoa, palm oil, soybeans) is more vulnerable due to the concentration of production in a limited number of countries and their vulnerability to climate change (European Environment Agency, 2021). 16 % of Austria's imports of food and feed, in raw biomass equivalent, originate from regions that are moderately to highly vulnerable and do not yet appear to be ready to adapt to climate change (trade data from Roux et al. (2023), updated as explained in 2.A.15, vulnerability from Kan et al. (2023)). The supply of wood in Austria is slightly vulnerable to climate change, as about 5 % of Austria's imported raw material input (RMI) of wood originate from regions that are moderately to highly vulnerable and do not yet appear ready to adapt to climate change (Kan et al., 2023; Roux et al., 2023). However, for certain wood products, the share of imports from vulnerable regions can be substantially higher. Diversifying origins and reducing the overall demand for vulnerable products decreases the vulnerability of supply in Austria, while at the same time decreasing environmental pressures on global ecosystems.

Demand for European agricultural exports is also expected to increase in response to climate change, as a response to reduced yields in other regions of the world (Janssens et al., 2020). This increased demand could potentially increase land demand and pressure on ecosystems in Austria (*limited evidence, high agreement*).

## 2.2.2. Impacts of climate change on regulating ecosystem services and related benefits

### Impacts of climate change on carbon sinks in ecosystems

The impacts of climate change on forests and other ecosystems are described in Chapter 1. Here, we build on Chapter 1, by describing the consequences for carbon sinks in forests and other ecosystems. The simulation under a strong warming scenario (GWL 2.0°C–GWL 3.0°C by 2050 and close to GWL 4.0°C by 2100) showed an increase in soil organic carbon (SOC) when conifers are replaced by deciduous tree species (Jandl et al., 2021). In the 150-year simulation, the majority of forest sites become suitable for deciduous forests. The build-up of a large soil organic carbon stock is driven by the harvesting pressure on the remaining coniferous forests. Deciduous forests were less in demand and developed under a regime of light forest intervention. However, towards the end of the century, when the temperature level is far above present levels, soil organic carbon stocks declined (Jandl et al., 2021). Highly intensive production of wood biomass will decrease the carbon stock in forest soils by 3 % in 80 years (Repo et al., 2015).

Impacts of climate change on the carbon sink function of wetlands are outlined in Section 1.6.1. Peat accumulating wetlands are the ecosystems that store the most carbon per area. The effect of land use-related drivers of carbon loss on peat accumulating wetlands, namely drainage and agricultural and forestry management are estimated to be more severe than the effects of climate change. For German peatland sites, there is *high confidence* that drainage and drying out turns peatlands from a carbon sink to a large source of greenhouse gases with emissions averaging 25 $tCO_2eq/ha/yr$, with peaks up to >60 $tCO_2eq/ha/yr$ (Tiemeyer et al., 2016; BMLRT, 2022). For Austria, the actual amount and location of agriculturally used drained peatland areas are understudied (Hogl et al., 2023). The Austrian NIR 2023 estimates 13,000 ha of grassland on organic soils, while arable land on organic soils is not listed. In contrast, a recent study estimates 31,000 ha of peatland area under mostly intensive agricultural grassland or cropland management (Hogl et al., 2023). For Austria quantitative modeling studies on the impact of climate change on drained, agriculturally used peat soils and the carbon sinks remain a research gap.

### Impacts of climate change on the regulation of urban micro-climate

Climate change affects regulating ecosystem services in urban areas. Rising temperatures, long lasting drought periods and altered precipitation patterns as observed in Austria (Chimani et al., 2016; Haslinger et al., 2022), can make trees more susceptible to diseases and can affect the ability of vegetation and green spaces in cities to filter pollutants, reduce the heat island effect, and regulate local temperatures, leading to increased energy demand for cooling, reduced air quality, and heat-related health issues. These impacts hamper the resilience of cities to environmental changes (Lafortezza and Sanesi, 2019). Urban forests, parks, or simply tree-lined streets – urban greens in general – are known to facilitate adaptation to climate change in terms of regulating temperature and water budget. This improves the public health and well-being of urban populations and contributes to sustainable living in terms of positive effects on humans, microclimate, soil and biodiversity (*high confidence*). More details on heat in urban areas can be found in below, in Cross-Chapter Box 2 and in Chapter 3.

### Impacts of climate change on biochemical cycles

Ecosystem processes regulating the exchange of nutrients (including mineralization) and soil formation may be hampered by climate change, especially as altered soil humidity and temperatures will also affect soil biota. Results for Austria also take advantage of the specific sites established under the Long-Term Ecological Research network (Mirtl et al., 2015). Investigations for alpine grassland (Seeber et al., 2022) demonstrate that climate change influences the way carbon (C) and nitrogen (N) pools increase as a consequence of extensified grassland management. This effect is primarily driven by rising temperatures, as precipitation is not considered a limiting factor in this context. In forest soils, Kengdo et al. (2023) demonstrate increased carbon inputs due to increased fine root turnover. These cases provide proof that climate change would help to alleviate temperature limitations on many biological processes that support regulating services. However, warming of forest soils also decreases microbial carbon and nitrogen use efficiencies (Tian et al., 2023), thereby reducing regulation – an observation that is in line with microbial biomass accumulation observed with soil cooling (Schnecker et al., 2023). More research is needed to establish the effect of additional stressors on biological systems, such as droughts (especially in areas already now experiencing water scarcity) or ozone damage to vegetation, given that the presence of ozone has been observed to reduce drought stress in oak trees (Peron et al., 2021). Similarly, the effects of drought on microbial communities that had been exposed to elevated temperatures and $CO_2$ concentrations in a treatment experiment were strongly alleviated (Metze et al., 2023). All these results come from experiments at Austrian sites or with Austrian substrates and demonstrate a high level of scientific activity, especially in recent years, but will only gradually allow conclusions to be drawn about climate change impacts on ecosystems and their ability to regulate nutrient flows, especially as the observations demonstrate that combinations of ecosystem stressors do in several instances not add up, but rather cancel each other out.

### Impacts of climate change on mass movement and erosion control

Climate change will affect the frequency and intensity of gravitational processes through changes in precipitation amounts, duration and snow cover, or frost dynamics (*limited evidence, high agreement*). Permafrost dynamics in alpine environments influence rock–slope stability through shear stresses and reduced shear resistance of rock masses (Krautblatter et al., 2013; Mamot et al., 2021). Warmer temperatures and longer growing seasons lead to improved tree growth, but longer dry periods also mean additional stress (Schuldt et al., 2020). As tree species have different tolerances to stress situations, new competitive conditions will arise and the tree species composition will alter the protective effect of mountain forests. In addition, the protective effect of forests will be reduced by intensified disturbance regimes caused by temperature driven agents, such as increased bark beetle infestations in Norway spruce dominated forests at higher altitudes (Maroschek et al., 2015), and a higher chance for stand replacing forest fires due to longer drought periods (Müller et al., 2020) or more wind throws caused by extreme wind events (Costa et al., 2021). Protective functions against landslides and snow avalanches are negatively impacted by the stochastic creation of small gaps under warming scenarios with an increase in mean annual temperature up to 4°C across the Alps (Maroschek et al., 2015, 2024) (*limited evidence, high agreement*). The simulated shift of precipitation events from summer to winter and spring will promote wet snow avalanches in the mountains and the occurrence of flood-relevant snowmelt events, limiting the capacity of forests to control erosion control and reduce mass movements (Glade, 2020). Soil erosion could also increase in agricultural areas, which are usually not covered by vegetation in winter and spring (Glade, 2020). Forest vegetation can influence permanent or deep landslides through drainage in the catchment and directly on the landslide mass (Rickli et al., 2004), but the soil-stabilizing effect of tree roots is not strong in relation to the location of the sliding surfaces in the catchment area (Frehner et al., 2005; Bollinger et al., 2008; Losey and Wehrli, 2013). In general, forest vegetation will presumably exhibit a higher protection from precipitation events with longer duration but lower intensity than from to short-term-high-intensity events (Kleemayr et al., 2020). Direct effects of climate change might have a stronger influence on the future supply of erosion control than management or natural disturbances (Seidl et al., 2019). The impacts of avalanches are difficult to predict with simulation models (in terms of time, space and size) as the influencing factors vary greatly over a very small geographical area and the effect of forests is hardly understood (Studeregger et al., 2020) (see also Sections 1.6.2, 1.7 and 7.4.2).

### Impacts of climate change on wind and fire protection

Climate change affects the capacity of ecosystems to protect society from wind and fire as they act as natural barriers, reducing wind speed, regulate the local climate and prevent erosion. There is *high confidence* that climate change will increase the frequency and intensity of disturbances, which will affect the species composition, forest structure, forest cover and the amount of flammable material in the forest (Hlásny et al., 2021; Berčák et al., 2023). Windstorm damage in European forests has increased over the past century (Seidl et al., 2011; Schelhaas et al., 2015; Gregow et al., 2017; Patacca et al., 2023) and this trend is expected to continue (Ikonen et al., 2017; Seidl et al., 2017) especially due to the high vulnerability of flat-rooted Norway spruce dominated forests (Bourke et al., 2023). The combination of a high amount of salvage wood from wind disturbances and long drought periods (Senf et al., 2020) further increases the predisposition of these forests to bark beetle infestations (Hlásny et al., 2021) and wildfires (Müller et al., 2020). This will in particular reduce the capacity of the protection forests in Austria to secure the living environment as well as critical infrastructure and settlements in the wildland urban interface (see also Sections 1.2.2, 1.6.2 and 7.4.2).

### Impacts of climate change on the water flow regulation and flood control

Flood hazards are predicted to increase (Chapter 1, Table 1.A.3). Many ecosystems, particularly rivers and riparian forests, depend on floods to function. Ecosystems also regulate high and low flows in two major ways: They mitigate flood risk by providing retention space in the direct vicinity of rivers, and they prevent floods at the catchment scale through vegetation cover and soil type. In addition, drought in the catchment area may affect the water holding capacity of soils (Vári et al., 2022). Anthropogenic interventions such as land-use change, wetland drainage, and river regulation, have had major impacts on this regulating function in rivers and surrounding ecosystems (Jungwirth et al., 2002; Mergili and Duffy, 2022, for the river Lech). In comparison the direct impact of climate change on the capacity of ecosystems to regulate water flow and floods is probably small. Depending on the scenario and its assumptions about future precipitation, various effects can be expected, such as various types of ecosystem degradation due to increased heat and wildfires, or exceeding the ecosystem capacity to hold floods. However, there is little to no information for Austria.

### Impacts of climate change on pollination

There is *high confidence* that climate change leads to a shift in the range of species, resulting in reconfiguration of species communities and decoupling of community interactions (Zulka and Götzl, 2015; Rollin et al., 2022). In general, an increase in mean annual temperature has a negative effect on the abundance of wild pollinators (Vasiliev and Greenwood, 2021). Bumblebees and hoverflies are particularly affected (Minachilis et al., 2021), but the degree of ecological specialization of species is also negatively correlated with the risk of extinction (Roberts et al., 2011). As a result of global warming, higher temperature improves foraging by reducing the energy cost of maintaining optimal body temperature, which has been shown for example, for honey bees (Abou-Shaara et al., 2017; Usha et al., 2020) (*high confidence*). On the other hand, there is *high confidence* that nectar abundance and total sugar content in nectar are negatively correlated with heat and drought exposure of plants (Borghi et al., 2019) as well as pollen quality and quantity (Zinn et al., 2010). The associated effects are changes in the area and isolation of suitable habitat with appropriate forage plants and significant declines, especially in specialized pollinator species, but also in generalist species (Rollin et al., 2022).

Directly affected are related ecosystem services such as pollination services and pest control. The value of pollination alone is estimated near to $EUR_{2023}$ 442.5 million in Austria, or 9.9 % of the total value of agricultural crop products (Zulka and Götzl, 2015). However, these consequences of climate change can be buffered by targeted management measures and nature-based solutions, such as the development of near-natural elements or habitats with appropriate forage plants in agricultural landscapes (Roberts et al., 2011; Zulka and Götzl, 2015). More near-natural areas increase the possibility of plant and animal migration and thus also of pollinators, while fewer natural areas make this process more difficult.

Low air quality and climate change also increase allergies (Bergmann, 2016). Climate change (mostly due to temperature and $CO_2$ increase) will affect plant growth and pollen production. Plants will react to heat stress and ozone by producing more pollen or producing pollen more frequently, and the single pollen particles will often have more allergenic proteins on their surface (*medium confidence*). Climate change will also affect the introduction and wider spread of new and sometimes also highly allergenic plants (like *Ambrosia artemisiifolia*) (Cheng et al., 2023).

## Impacts of climate change on pest control, invasive species, vectors, and related health issues

There is *high confidence* that climate change increases risks to ecosystems, biodiversity, food security, and human and animal health (Cissé et al., 2022). Typical examples are neobiota species. Out of the 3,462 vascular plants occurring in Austria, 10.6 % are naturalized neophytes (Schratt-Ehrendorfer et al., 2022). If temporarily occurring species are included, a total of 1,463 non-native vascular plants have been recorded in Austria (Kalusová et al., 2024). Climate and global change are expected not only to open new pathways and territories for invasion, but also weaken the resilience of ecosystems and native species, thus facilitating the establishment of invasive species (IUCN, 2021). These species may have the same impact as natural hazards and are very costly to eradicate or contain (Turbelin et al., 2023). One example in forests is ash dieback caused by an alien fungal pathogen (Marçais et al., 2022). In agriculture, the main route of introduction of invasive plants has been through deliberate imports as ornamental or crop plants (*medium evidence, high agreement*). A small percentage of these are considered invasive (AGES, 2023a) such as common ragweed (*Ambrosia artemisiifolia*) and jimsonweed (*Datura stramonium*), which are rapidly spreading over Austria (Follak et al., 2017, 2023). These plants not only cause yield and quality losses, but also health burdens, such as increased allergenic load and prolonged allergy seasons (Ambrosia) or poisoning along the food chain (Datura).

There is *high confidence* that climate change also affects blood-sucking arthropods (mosquitoes, biting midges, ticks, etc.), which are vectors for several pathogens (viruses, bacteria, protozoa) that cause mainly zoonoses (Rocklöv and Dubrow, 2020; Thomson and Stanberry, 2022). A disease vector is an organism, most often an arthropod, that transports a pathogen (viruses, bacteria, protozoa) from one host organism to another. Hotter summers and warmer winters (see Section 1.2.2) lead to increasing vector densities (Sonnberger et al., 2020; Duscher et al., 2022), due to higher overwintering success or multiple generations per year, expansion of endemic areas (e.g., tick-borne encephalitis, bluetongue disease), accelerated replication rate of pathogens in vectors, and more frequent years with favorable conditions for the transmission cycle (e.g., Rubel, 2021).

In Austria, native arthropods are potential vectors of emerging pathogens, that have caused several disease outbreaks, such as West Nile virus (Aberle et al., 2018), Usutu virus (Brugger and Rubel, 2009) or bluetongue virus (Purse et al., 2005; Lebl et al., 2013; Brugger et al., 2016). In addition, invasive vector species are increasingly establishing themselves in Austria. Examples include mosquitoes of the genus *Aedes* or *Anopheles* (Lebl et al., 2013; Bakran-Lebl et al., 2022), tick species such as *Hyalomma marginiatum* (Duscher et al., 2022), and sandflies of the genus *Phlebotominae* (Poeppl et al., 2013). These species are potential vectors for tropical and subtropical diseases caused by Chikungunya virus, Dengue virus, yellow fever virus, Crimean-Congo haemorrhagic fever virus or Leishmania parasites.

## Cross-Chapter Box 2. Health and climate change

*Hans-Peter Hutter; Hanns Moshammer*

To gain a better understanding of how we might address the massive effects of climate change on human health in Austria, we look at the direct and indirect effects of climate change on human health, discuss beneficial and adverse health consequences of some mitigation (and adaptation) measures, and finally describe the carbon footprint of our health care system.

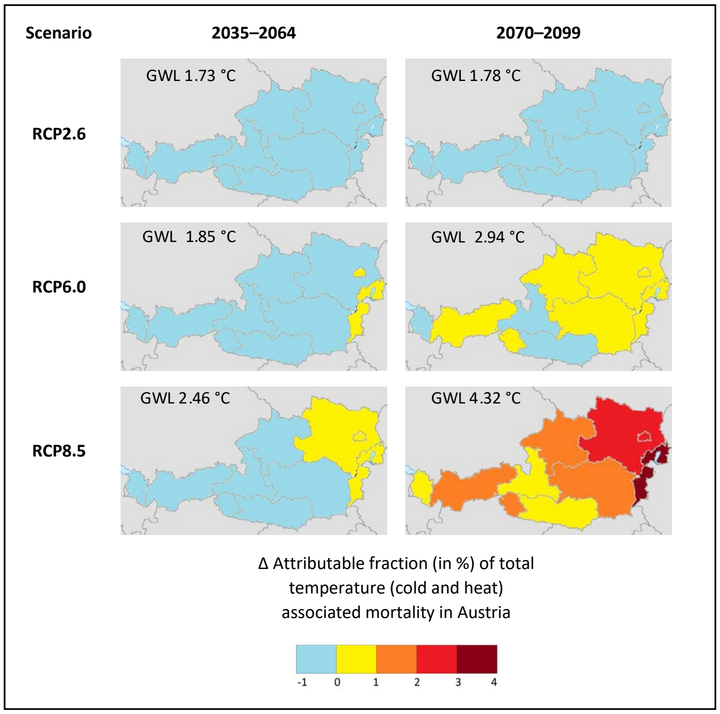
### The health impact of climate change

There are many ways in which climate change affects health (APCC, 2014, 2018; Weitensfelder et al., 2023). The media and the public are mostly aware of the direct health impact of heat waves. Indeed, extreme weather events such as heat waves, storms, heavy rains and droughts, are likely to increase due to climate change thus intensifying their direct impact on human health and well-being (see Section 1.1.2). From a medical point of view, the most important impact of climate change on health to date is through heat and heat waves (*high confidence*). In 2022, 419 (CI 109; 741) heat related deaths in Austria were estimated (Ballester et al., 2023). The most vulnerable to heat stress are the elderly, and even more so very old and chronically ill people. In addition, very young children and pregnant women are more vulnerable (Kuehn and McCormick, 2017; Chersich et al., 2020; Jiao et al., 2023). But outdoor workers, especially those with physically demanding jobs, also suffer from the heat (Cheung et al., 2016; Ferrari et al., 2023). Hot days and even more so, hot nights reduce regeneration and sleep quality. Therefore, general work performance suffers (*medium evidence, high agreement*). Other vulnerable groups are the socioeconomically disadvantaged with poor housing and lack of access to cool areas, health care, and urban green spaces. This also affects ethnic minorities (Gronlund, 2014; Ellena et al., 2020; De Schrijver et al., 2023).

Not only heat but also extreme cold is detrimental to health. Nowadays, more people die on cold days than on hot days (Gasparrini et al., 2017; Statistik Austria, 2022d; Masselot et al., 2023). As temperatures rise, heat-related deaths are predicted to increase and cold-related deaths to decrease (*high confidence*). According to Martínez-Solanas et al. (2021), heat-related deaths will exceed cold-related deaths in Austria by the end of the century and especially under high-emission scenarios (CCBox 2 Figure 1). However, estimates of cold-related deaths heavily depend on assumptions about effect-thresholds (Arbuthnott et al., 2018) and own data analyses demonstrate that increases in heat deaths already outweigh decreases in cold deaths in Austria (Moshammer, 2023).

The seasonal mortality pattern is first of all characterized by stronger prevalence of cardiovascular diseases, but also infectious diseases play a role (Madaniyazi et al., 2022; Statistik Austria, 2022d). Food-borne bacterial diseases peak in summer and viral respiratory infections in winter (*high confidence*). However, the relevance of temperature (high or low) is far from clear (Liu et al., 2020), making it difficult to assess the impact of a warming climate on these infectious diseases.

While the effects of temperature extremes on well-being, productivity, and physical health are already well understood, the long-term effects on mental health are still understudied in Austria (Weitensfelder et al., 2023). These mental health effects concern post-traumatic stress disorder (PTSD) after catastrophic weather events (Neria et al., 2008), increased suicide rates with increasing temperatures (Kim et al., 2019), but also climate anxiety (Clayton, 2020; Gago et al., 2024). Hickman et al. (2021) report surprisingly high numbers of climate anxiety among young adults, while no representative data are available for Austria. However, based on a convenience sample, Raile and Rieken (2021) report a high percentage of worries about climate change in Austria (81 %) with 41 % 'somewhat' and 16 % 'strongly' or 'very strongly' burdened by these worries. The societal polarization around climate change issues is also likely to reduce human well-being. There is evidence that climate change increases polarization (Wong-Parodi and Feygina, 2021), and that polarization in turn increases stress and anxiety (Fraser et al., 2022). In addition to the political polarization, many young people suffer from the impression that the elder generations and the government do not take care of them and do not take their worries seriously (Hickman, 2020; Hickman et al., 2021).




CCBox 2 Figure 1 Difference in the attributable fraction (in % of total deaths) of total temperature (cold and heat) associated mortality in Austria, compared to the reference period (1976–2005) according to (Martínez-Solanas et al., 2021). The authors reported the values for 3 representative concentration pathways and for 2 time slots, translated into global warming levels. See 2.A.17 for a monochromatic version of this figure.

Regarding mortality during heat waves, there are indications of ongoing adaptation: As average temperatures rise, the threshold above which an increase in daily mortality is observed also rises (Weitensfelder and Moshammer, 2020) (*limited evidence, high agreement*). Population-wide adaptation through a selection process may also contribute to the rising temperature threshold for daily mortality: Individuals most vulnerable to high temperatures have already died in previous heat waves, leaving the remaining population more resistant to upcoming heat waves (little evidence except for short-term mortality displacement up to several months, but high plausibility).

In addition to the short-term and long-term impacts of extreme weather events, there is a more complex relationship between human health and climate change associated with atmospheric transport and chemistry, soil and water ecosystems, forestry, agriculture, and human energy and transport infrastructure. Many of these changes will have repercussions on human health (APCC, 2018). A recent ARCP project examined the impacts of climate change on ozone concentration in Austria, including impacts on health (Rieder et al., 2023). With drier and hotter summers, average ozone concentrations will likely increase. However, regional ozone concentrations and especially the local peak of ozone concentrations are mainly affected by national emission scenarios: Lower local emissions of non-methane VOCs as well as nitrogen oxides will impact Austria's national ozone levels significantly more than global emission and climate trends. In the follow-up project Future_Capacity (Formayer et al., 2024a), interactions between ozone concentrations and high temperatures on mortality and morbidity were also examined in a systematic literature review (Wallner and Moshammer, 2023). A total of 45 relevant studies were identified, most of which examined short-term effects on mortality (*high confidence*). They examined either the effect of high ozone levels on the strength of the heat-mortality association or the effect of hot days on the ozone-mortality association. Only few directly examined multiplicative interactions. Most studies demonstrated a clear (over-additive) effect of ozone and heat.

Climate and meteorology affect air quality by impacting the distribution of air masses and atmospheric chemistry. Temperature and pollutants jointly affect health. Meteorological conditions determine whether aerosols accumulate over time or if they are removed from the atmosphere by dry or wet deposition (Seinfeld and Pandis, 1998; van Zanten et al., 2017). The occurrence of inversion days in southern and central Austria, as well as inversion intensities and magnitudes, decreased from 1961 to 2017 due to climate change (Hiebl and Schöner, 2018). This should imply reduced particulate matter (PM) pollution and better air quality. On the other hand, an increasing amount of secondary aerosols can be expected because $NH_3$ is an important precursor of fine particulate formation in the atmosphere (Spangl et al., 2006; Xu and Penner, 2012; Anderl et al., 2016; Backes et al., 2016a, 2016b), and increasing $NH_3$ emissions were found in Austria from 1990 to 2017 (Anderl et al., 2019). Since the fraction of secondary aerosols in total aerosol concentration can be high (Spangl et al., 2006), a better understanding of PM pollution is required to reduce this major environmental health threat (Hendriks et al., 2013). Overall, the effects of climate warming on the change in PM pollution will vary by region and season and there is still a lot of uncertainty in model estimates. However, a recent global study (Gomez et al., 2023) estimates that annual PM2.5 levels will be about 10 µg/m³ higher in about 100 years due to GHG-induced warming for Europe and especially for the Alpine Region. While these increases are moderate compared to other parts of the world, notably Africa and South America, the agreement between the different models applied is comparatively good for the European region.

Due to hotter and drier weather events, forest fires are becoming more frequent, more intensive, and widespread. Wildfire smoke is characterized by high levels of PM with very small particle sizes and gases such as nitrogen oxides (Youssouf et al., 2014). Exposure to these pollutants in areas surrounding a wildfire can cause acute effects (e.g., irritation of the eyes, respiratory mucosa) or lead to the onset or exacerbation of acute and chronic respiratory diseases. Furthermore, exposure to forest-fire smoke is associated with cardiovascular diseases and mortality. Currently, wildfires are not yet perceived as a grave risk to health in Austria, but this could change in case of severe climate change (see Cross-Chapter Box 1 and Section 2.2.2).

Low air quality and climate change also increase allergies (Bergmann, 2016) and exposure to pollutants (ozone) can enhance allergic reactions to pollen (Berger et al., 2020), while pollen is predicted to increase in number, exposure duration, and allergenic potential (see Section 2.2.2). Climate change (mostly due to temperature and $CO_2$ increases) will have an effect on plant growth and pollination. Plants will react to heat stress and ozone, by producing more pollen or producing pollen more often, and the single pollen particles will often also present more allergenic proteins on their surface. Climate change will also affect the introduction and spread of new and potentially highly allergenic plants, like ambrosia (see Sections 1.6.4 and 2.2.2). So-called thunderstorm asthma is increasingly observed: Pollen break up and allergens are released (Thien et al., 2018; Fuchsig and Scholl-Bürgi, 2022; Huang et al., 2022).

Following the 'One Health' approach, the effects of climate change on the health of plants, animals and humans can be assessed together. In that regard, we refer to the detailed discussions in Section 2.2. Especially cultural ecosystem services have a direct bearing on human health and well-being.

In addition to immediate health risks from drowning, trauma, and infection, floods pose longer-term health risks from damaged homes, the need to relocate, or moldy homes. While data on immediate health effects are available in Austria, long-term effects including psychological and mental health impacts are still severely understudied. Therefore, only general conclusions can be drawn based on data from other countries, which indicate that severe effects might occur, especially on mental health (Fernandez et al., 2015; Matthews et al., 2019; Charlson et al., 2021; Schürr et al., 2023).

Hurricanes, tropical storms and tropical cyclones are not frequent in Europe. However, wind speeds of extra-tropical cyclones in Europe can reach 'hurricane force' according to the Beaufort wind scale (Goldman, 2014). Storms can affect human health either through direct effects, including injury or death during the storm from flying debris or falling trees, or indirect effects following the storm including reduced access to health care or medicines, exposure to carbon monoxide (from gasoline powered electrical generators), electrocution, and psychological impacts (Goldman, 2014).

Health related risks of droughts can be direct due to lack of (clean) water for drinking or hygiene measures. However, the danger of drinking water shortage due to droughts is currently not yet a major issue in Austria. Indirect effects are the adverse effects on agricultural outputs, which mainly lead to socio-economic consequences for producers.

While in Austria there is still room for adaptation to mitigate the above-mentioned consequences for health and livability, increasingly large parts of the world do not have this option. When an increasing number of people around the world face impoverishment, loss of resources for livelihood, and a mounting vulnerability to – among others – infectious diseases, this might ultimately also have consequences for public health in Austria (APCC, 2018) (*limited evidence, high agreement*).

### Health impacts of adaptation and mitigation measures

The number of climate change mitigation policies and adaptation measures increased in recent decades. Many adaptation measures will be effective immediately and contribute to reducing human vulnerability to climate variability. The benefits of other mitigations carried out today will not be evidenced until the coming decades because of the long residence time of GHG in the atmosphere.

**CCBox 2 Table 1** Estimated health gains from selected mitigation measures (APCC, 2018; Weisz et al., 2020).

| Measure | Description | Mitigation potential | Health benefits |
|---|---|---|---|
| Healthy diet | Reduced meat consumption in accordance with dietary recommendations | Up to 20 % reduction in individual footprint due to food intake (see also Table 2.3. and Section 2.3.2.) | 20 % reduction of deaths caused by dietary factors |
| Physically active mobility for Vienna, Graz and Linz | Green Mobility: Targets for the modal share of trips for the years 2020/2025 are almost achieved. E.g., Vienna: Share of car trips reduced from 40 to 28 % | 290,000 $tCO_2eq$ reduction | 27 deaths per year per 100,000 prevented |
| | Green Exercise: Targets exceeded; e.g., Vienna: Further reduction to 18 % | 530,000 $tCO_2eq$ reduction | 58 deaths per year per 100,000 prevented |
| Insulation of houses | Better insulation of houses will reduce heat loss in winter and, if well done, can mitigate heating up in summer | Reduced energy needed both for heating and for cooling | Increased comfort and well-being. Especially relevant for low-income households in poor housing conditions |
| Health care sector | More targeted use of antibiotics (antibiotic stewardship) | Antibiotics use for human health needs accounts for 1 $ktCO_2eq/yr$ | Indiscriminate use of antibiotics increases the risk of antibiotic resistance and has lots of adverse side effects |
| | Reduced use of metered dose inhalers (MDI) | Propellants from MDI account for 13 (2005) to 25.9 (2015) $ktCO_2eq/yr$ | Dry powder inhalers can be used without propellants and their use is often easier |

Mitigating climate change is often seen as an activity with local costs and global benefits. However, many mitigation measures also have a range of significant health benefits, both locally and in the near term, mainly because they also reduce other airborne emissions, for example, $NO_x$ and particulate matter (APCC, 2018; Wolkinger et al., 2018; Rieder et al., 2023). Examples of these win-win situations include a shift from motorized to physically active traveling (walking, cycling, and partial use of public transport), healthy (less meat) diets, or better insulation of houses (CCBox 2 Table 1).

However, when considering climate change mitigation and adaptation measures as a whole, unintended consequences might arise, resulting in an actual drawback for human health. Therefore, it might be difficult to create a coherent framework for planning interventions. For example, burning wood instead of gas or oil for heating might in certain cases reduce the carbon footprint (see Section 2.3.2), but will often increase particulate matter air pollution (Haluza et al., 2012). The technology for low emission furnaces is available, but current limit values still allow much higher emissions (Umweltbundesamt, 2023b). Replacing fossil fuels with biofuels is likely to reduce particulate matter pollution but increase emissions of nitrogen dioxide (Hutter et al., 2015). The balance of these effects remains controversial. For Austria, especially the AQUELLA project (Bauer et al., 2007, 2009; Jankowski et al., 2009) has demonstrated the important contribution of smoke from biomass burning to particulate air pollution confirming more global concerns (Sigsgaard et al., 2015).

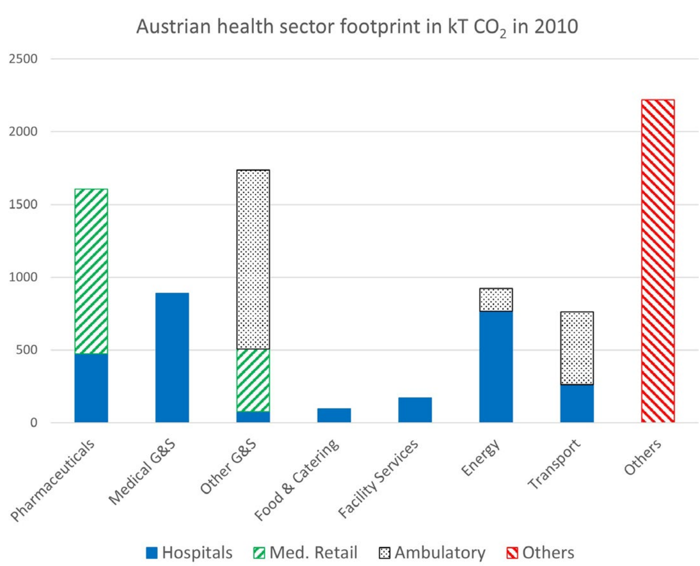
Air pollution contributes substantially to the burden of disease. Acute health effects of air pollution have also been demonstrated with Austrian data examining different endpoints and pollutants (Moshammer et al., 2013, 2019, 2020; Neuberger et al., 2013). Chronic effects have been demonstrated in Europe by the large ESCAPE project (Beelen et al., 2015), which also included a large cohort from Vorarlberg. The ESCAPE data have been recently merged with those from other studies in the ELAPSE study to demonstrate health effects even at low levels of pollution (Brunekreef et al., 2021). Two recent overviews (in German) of long-term and short-term health effects of air pollutants have been provided by Weinmayr (2023) and Moshammer (2023), respectively.

Another example is the impact of urban design strategies (see Section 3.2.3), while urban greening substantially influences the distribution of solar energy in urban areas, various health co-benefits are expected from these activities, such as reduced obesity and cardiovascular disease and improved mental health through increased physical activity, cooling spaces (e.g., shaded areas), and social connectivity (*limited evidence, high agreement*). On the other hand, other adverse health effects such as pollen allergies have to be taken into account, as allergies might increase with increased urban green space.

Adaptation strategies and measures can be planned directly to improve health. Climate change adaptation measures that are not primarily intended to improve health may have health-related side effects. Any adaptation measure (e.g., in forestry, agriculture, energy, industry, tourism) should therefore also be assessed regarding possible, unintended (negative) side effects on population health.

## The carbon footprint of the Austrian health care system and mitigation options

The Austrian health care industry as a whole is responsible for 7 % of the carbon footprint of Austria[1] (Weisz et al., 2020). Their estimates for 2010 are presented in CCBox 2 Figure 2. While medical goods and services account for about half of the total carbon footprint, direct energy use and transport account for roughly the other half, with direct energy use declining and transport emissions increasing. Reducing most of those emissions can be addressed with mitigation measures covered in Section 2.3 (food production), Chapter 3 (buildings, infrastructure, transport of goods and persons or information and communication technology) and Chapter 4 (industry, energy).




**CCBox 2 Figure 2** The carbon emissions of the Austrian health care system in 2010 according to Weisz et al. (2020): Pharmaceuticals, medical goods and services, other goods and services, food and catering, facility services, energy (for heating and cooling of buildings mostly), transport (of patients, staff and visitors), and others (including financing, administration, etc.) in hospitals, medical retail, ambulatory services and other parts of the health care system.

[1] This value encompasses the emissions of the goods and services consumed by the health system, and overlaps with various sectors.

However, there are at least some possible mitigation measures that are specific to the health care system. For example, some anesthetic gases (Koch and Pecher, 2020; Richter et al., 2020; Lehmann and Sander, 2021) and propellants of asthma inhalers (Rauchenwald et al., 2020; Wilkinson and Woodcock, 2022) have a large climate forcing potential. Weisz et al. (2020) estimate the greenhouse gas emissions of all anesthetic gases to be 21.4 kt$CO_2$eq in 2015. At the same time, metered dose inhalers account for 25.9 kt$CO_2$eq. While the former displayed a declining trend, emissions from inhalers increased (nearly doubled) since 2005. In addition to the emissions associated with the manufacturing of these medical devices (which are accounted for in the supply chain), the climate effects of the pharmaceuticals when released into the air must be considered.

Some health care providers are starting to implement reduction strategies. Some hospitals have declared a phase-out of the narcotic gases with the highest greenhouse potential, or are planning to install carbon filters to capture and reuse these gases. Dry-powder inhalers are often a viable alternative to the use of propellants in metered-dose inhalers. At present, it is difficult to establish industry-wide emission reduction targets, because data on current consumption and trends in Austria are not available.

A high-quality, sustainable health care system that focuses on prevention rather than disease would improve human health at scale, while further reducing the carbon footprint of health care. Sustainable health care would reduce unnecessary and emission-prone diagnostic and therapeutic interventions, with X-rays being a prime candidate for the former and antibiotics for the latter. Primary prevention and quality of life provisions are intrinsically more carbon neutral than the current emphasis on end-of-life, high-tech treatments and their associated supply chains.

Today, however, the evolution towards a sustainable health care system in Austria is in its infancy. Even with 'health check-ups' (now: preventive check-ups), the main aim is to discover illnesses in good time, not to maintain health. Our current health care system's orientation, facilities and financing are still primarily geared to the care of the sick and the treatment of illness (Green et al., 2002; Fiandaca, 2017). While treatment of illness is important, preventive care, avoidance of illness and maintenance of good health are not truly realized in the current system. While Austria proclaims goals such as 'Health in all Policies' as a strategy to introduce emphasis on prevention (Fonds Gesundes Österreich, 2015), the necessary budgetary commitments are still lacking (Rechnungshof Österreich, 2023).

## 2.2.3. Impacts of climate change on cultural ecosystem services and related benefits

Cultural ecosystem services are broadly defined as the non-material benefits that result from human interaction with the natural environment (Reid et al., 2005). Human well-being greatly depends on cultural ecosystem services, as they provide numerous non-material benefits that contribute to physical and mental health (Nowak-Olejnik et al., 2022; Schirpke et al., 2022). For example, landscapes, terrestrial and freshwater ecosystems, and natural features provide recreational activities, aesthetic experiences, inspiration and spiritual enrichment, and cultural identity (Table 2.A.1). While studies indicated the importance of maintaining cultural and (semi-)natural landscapes for the provision of cultural ecosystem services (Schirpke et al., 2018b; Lavorel et al., 2020; Schirpke et al., 2022), only few studies have explicitly addressed effects of climate change on cultural ecosystem services (Inglis and Vukomanovic, 2020; Mucioki et al., 2021; Schirpke and Ebner, 2022). Most studies focused on recreational activities, while aesthetic, symbolic and inspirational values, education and identity have been less examined (Schirpke et al., 2022, 2024). In the following, only those cultural ecosystem services are presented, for which climate change impacts were reported in the literature relevant to Austria, while there are research needs for educational, inspirational, spiritual, and existence values (Schirpke and Tasser, 2024; Schirpke et al., 2024).

### Impacts of climate change on recreational activities

Recreational activities comprise all kinds of outdoor activities practiced in natural and semi-natural ecosystems for recreational purposes. In Austria, particularly mountain areas and lakes offer manifold opportunities for outdoor recreational activities (Figure 2.6) (Schirpke et al., 2018a; Pröbstl-Haider et al., 2021), such as hiking, cycling, climbing, swimming, boating, skiing, and many others. Global warming has predominantly negative impacts on recreational activities (the economic relevance for the Austrian tourism industry is described in Sections 4.3.3 and 4.3.2). There is *high confidence* that warmer temperatures reduce opportunities for winter sport activities such as alpine skiing and cross-country skiing due to a shorter winter season and insufficient snow cover (see Sections 1.3, 4.3.3 and 7.4), particularly at lower elevated sites (Tervo-Kankare et al., 2013; Steiger et al., 2021). Due to a projected decrease of snow days to 50 % under a GWL 2.0°C scenario, it is expected that winter sport activities will shift upwards to higher elevations (Endler and Matzarakis, 2011). Moreover, people indicated lower intention to engage in recreational winter sport activities under a scenario with low natural snow (GWL not specified) (Frühauf et al., 2020). In summer, the increased potential for mountain hazards due to melting permafrost, such as rock falls and debris flows, may restrict the use of alpine trails and climbing routes, and hence, recreational activities such as hiking, mountaineering, climbing, and mountain biking (Pröbstl-Haider et al., 2016) (*medium confidence*). Moreover, the increased number of disturbances in mountain forests limits the access to forests due to increased salvage logging and increases the vulnerability of touristic infrastructure due to a reduced protective effect of forests (Lecina-Diaz et al., 2024; Müller, 2011). In contrast, warmer temperatures will extend the season for water-based activities (e.g., swimming, bathing, boating) at large lakes (see also Sections 1.4.2 and 4.3.3): Under GWL 2.0°C, a 40 % increase in warm days with temperatures above 25°C, and a doubling of hot days with temperatures above 30°C are expected by 2050 (Pröbstl-Haider et al., 2021). The increasing number of warm days will also increase recreational opportunities at mountain lakes (Schirpke and Ebner, 2022). However, climate change leads to more frequent low water levels (Soja et al., 2013), which reduces opportunities for water-based recreation (Wieland and Martinis, 2020). Warmer water temperatures also promote the occurrence of algae, cercariae, cyanobacteria (Gallina et al., 2011), which reduce the quality of water-based activities and increase health risks, especially in lowland lakes. Hot summers and increased evaporation will make lake water warmer and often more saline. This will increase the risk for swimmers to acquire wound infections from *Vibrio cholerae* (Le Roux et al., 2015; Hirk et al., 2016).

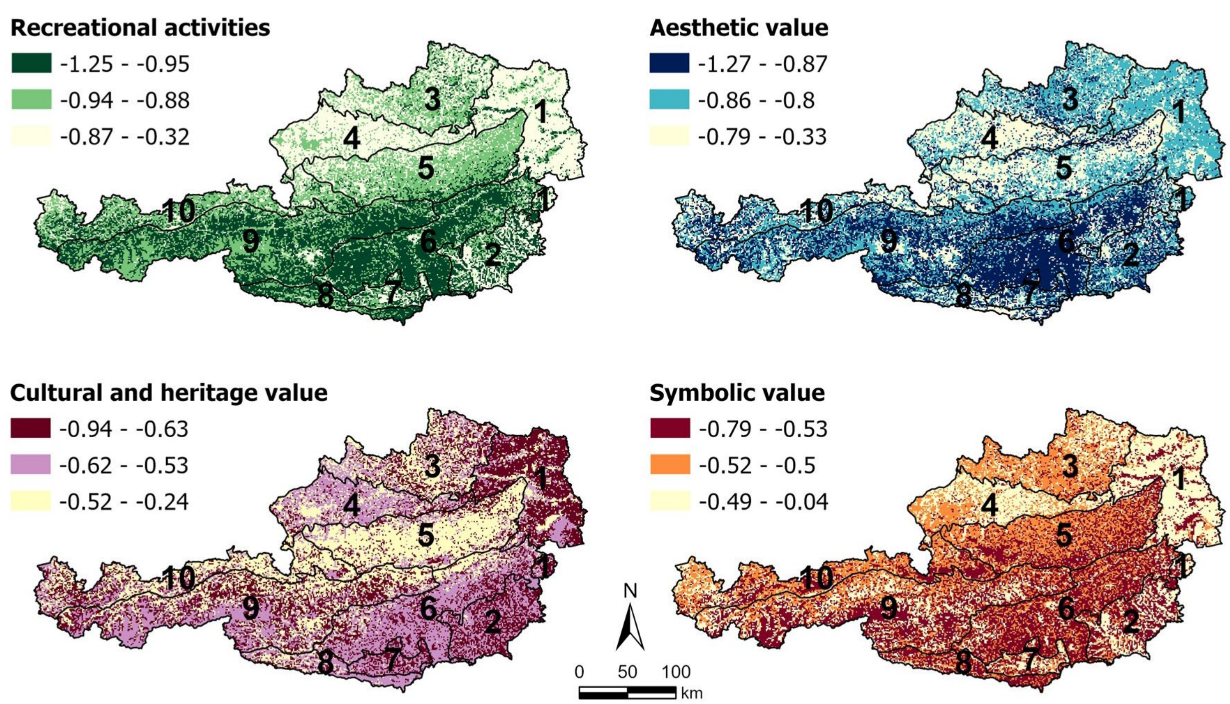



Figure 2.6 Potential climate change impacts on the provision of cultural ecosystem services (classification of impacts based on terciles). Impact values were derived by identifying potential impacts on multiple underlying indicators based on current literature, multiplied with ecosystem service supply and weighted with the spatial distribution of temperature and precipitation under GWL 5.0°C. Please note that the potential impacts on all cultural ecosystem services are negative. For methodology, see Schirpke and Tasser (2024). Numbers indicate major biogeographical regions (from data.gv.at/katalog/dataset/naturraumzonen): (1) Pannonian plains and hills, (2) Southern Alpine foothills, (3) Northern granite and gneiss highlands, (4) Northern Alpine foothills, (5) Northern Alps – east, (6) Central Alps – southeast, (7) Klagenfurt Basin, (8) Southern Alps, (9) Central Alps – central, (10) Northern Alps – west.

In general, there is *high confidence* that climate change induces a shift in the spatial and temporal demand for recreational ecosystem services (Vierikko and Yli-Pelkonen, 2019; Pröbstl-Haider et al., 2021; Wilkins et al., 2021). There will be an upshift in elevation where possible, i.e., high-mountain regions will become more attractive in summer due to cooler temperatures and in winter due to less uncertainty in snow cover compared to lower elevation mountain destinations (see Sections 1.3 and 4.3.4). Moreover, shoulder seasons, i.e., periods between peak and off-peak seasons, will become more attractive for recreational activities than hot summer periods.

### Impacts of climate change on cultural and heritage value

Quantitative assessments of climate change impacts on heritage, aesthetic, and symbolic values under global warming levels are not specified, as the literature mostly consists of qualitative studies or studies using worst-case scenarios.

Landscapes and natural features provide various cultural and heritage values, that are closely connected to the management of landscapes, especially cultural landscapes. As a result of climate change, it can be expected that agricultural use will be intensified at lower elevations where the climate is favorable or where irrigation is possible, while the spatial extent of forests will increase at higher elevations due to an upshift of the tree line and accelerated natural reforestation processes on abandoned grasslands. Both developments lead to a decline of cultural landscapes and thus reduce related spiritual and cultural values (Figure 2.6) (Pröbstl-Haider et al., 2015; von Heßberg et al., 2021) (*limited evidence, high agreement*). Furthermore, there is *high confidence* that, under increasing drought conditions, it may not be possible to maintain traditional agroforestry systems that are of high cultural value, such as larch meadows or orchard meadows (Zoderer et al., 2016; Flinzberger et al., 2020), because larch trees will lose their habitat at lower altitudes (Obojes et al., 2018), while the productivity of orchard trees will be reduced (Hammel and Arnold, 2012).

### Impacts of climate change on aesthetic value

The aesthetic value of a landscape depends on both biophysical characteristics of the environment and human perceptions (Daniel, 2001). Usually, this ecosystem service focuses on the visual characteristics of the landscape such as individual types of ecosystems, natural features, and spatial landscape patterns (Schirpke et al., 2016). While some studies worldwide explicitly address climate change impacts on aesthetic values, and report negative impacts, for example, induced by species shifts (Inglis and Vukomanovic, 2020), or invasive species and the disappearance of snow patches (Mameno et al., 2022), there are only few studies in the Austrian or Alpine-wide context. In general, there is *high confidence* that climate change impacts are strongly linked to changes in land-cover composition arising from global warming or changes in precipitation patterns (Figure 2.6). For example, the expansion of forests at higher elevations leads to a decline in aesthetic value due to a reduction of the viewing depth and lower preferences associated with forest ecosystems (Schirpke et al., 2016, 2017). Moreover, a higher number of forest disturbances (e.g., wind throw areas, burnt areas) might reduce the aesthetic value of forests (Fleischer et al., 2017). The retreat of glaciers and snowfields reduces the aesthetic value of landscapes due to the loss of highly appreciated landscape elements (Schirpke et al., 2021). It also leads to an increase in debris, dry and desolate environments, which is perceived negatively by most visitors (Salim et al., 2021). In lakes, direct and indirect effects of climate change are expected to have negative impacts on visual water quality (*high confidence*), mainly due to higher levels of eutrophication and declining ecosystem quality, depending on the level of human use and the specific social-ecological conditions of the lake (Schirpke and Ebner, 2022). While remote lakes and high elevation lakes are more exposed to changing climatic conditions, human use is more likely to impact cultural ecosystem services at easily accessible and lower-elevation lakes (Ebner et al., 2022).

### Impacts of climate change on symbolic value

Wild plant and animal species can provide a source of inspiration for people in different ways and may be used for symbolic representations (Schirpke et al., 2018b; Rüdisser et al., 2019). Climate change is expected to reduce suitable habitats for plants and animals that are symbolic for the European Alps, such as edelweiss, gentian, Alpine ibex, chamois, and marmot (Figure 2.6, see Section 1.6) (*medium evidence, high agreement*). For example, habitats of alpine plant species that occur in specific ecosystems and cold climates such as the edelweiss will be reduced or lost due to climate change (Grabherr, 2009; Maghiar et al., 2021). Symbolic animals such as chamois suffer from a decline in forage quality as a consequence of global warming (Reiner et al., 2022; Corlatti et al., 2023). In the case of marmots, the thinner snowpack, which reduces the insulation effect of snow during the snow season, as well as changes in social and demographic structures due to a longer summer season, both have negative effects on the juvenile survival (Rézouki et al., 2016; Glad and Mallard, 2022).

### Impacts of climate change on health related to cultural ecosystem services

Human well-being greatly depends on cultural ecosystem services, which provide important non-material benefits that contribute to mental and physical health (Nowak-Olejnik et al., 2022; Schirpke et al., 2022). A change of ecosystems also has a variety of effects on their health-supporting services. Most research on the recreational effects of ecosystems focuses on either greenery or biodiversity of natural surroundings, with some, but still insufficient supporting recreational influences of both. On the one hand, green landscapes have been shown to be associated with mental health and well-being, via various processes (Markevych et al., 2017): Greenery reduces harmful influences on (mental and physical) health, such as air pollution, noise, or heat, but it also provides a setting for building new capacities (via physical activity and social cohesion) and is also linked to the restoration of capacities. It has been shown that attention restoration (Kaplan, 1995) and a resulting slight enhancement of cognitive performance happens especially well in nature surroundings (Stevenson et al., 2018), although the results can sometimes be ambiguous (Ohly et al., 2016). Natural green surroundings also reduce stress (Ulrich et al., 1991) and even pain (Ulrich, 1984), thus contributing to well-being, mental health and recovery. Overall, and after controlling for socio-economic factors, living in green surroundings is associated with not only better physical health, but also better mental health (Maas et al., 2009; Triguero-Mas et al., 2015), although these studies are usually not able to identify causal mechanisms (Sandifer et al., 2015, for an overview). In addition, greenery leads to a cooler microclimate, which is important for reducing aggression and violence: Recent studies have shown increases in violent crime with rising temperatures (Hu et al., 2017; Miles-Novelo and Anderson, 2019). Whether nature and greenery indirectly promote social cohesion is a matter of discussion, but at least no direct connection between greenery and social cohesion could be found (Triguero-Mas et al., 2015). Similarly, no direct connection between greenery and physical activity could be confirmed (Triguero-Mas et al., 2015), but it has been shown that exercise, assessed by walking, is more restorative in a natural environment than in an urban one (Hartig et al., 2003).

Whether biodiversity has benefits for mental health beyond those of greenery or nature is rather denied, with overall ambiguous results (Marselle et al., 2021). Overall, the association of biodiversity with (mental) health and recovery can be seen as equivalent to that of greenery (via reducing harm, restoring capacities and building capacities), but it can also show some harmful effects on human health, e.g., via allergens (Marselle et al., 2021). Regarding specifics of biodiversity, single studies suggest that species diversity is positively related to well-being, especially bird diversity (Cameron et al., 2020; Methorst et al., 2021), but partly also plant richness (Fuller et al., 2007).

## 2.3. Transformations and measures in the land use system to mitigate and adapt to climate change

The land use system not only contributes to GHG emissions, but also provides carbon sinks when carbon stocks in biomass, soils, and harvested wood products increase. Human activities may strive to mitigate emissions, increase sinks, and/or maintain system functions by adaptation strategies.

The following subchapters assess activities aimed at realizing such mitigation potentials, as well as activities aimed at adapting to climate change. The subchapters build upon the Avoid-Shift-Improve approach (Cross-Chapter Box 4), which gained particular attention in the IPCC AR6 (Creutzig et al., 2022b). For reasons of simplicity, we merge 'shift' and 'avoid' activities, as it is not always straightforward to unambiguously separate these two with regard to the land system. Thus, we discern two sections on the effects of Avoid-Shift-Improve measures namely:

Section 2.3.1, detailing on 'improve' activities, which aim at an increased efficiency (of material or energy use) of providing goods or services. These activities aim to reduce emissions without focusing on changing the quantity produced and consumed of a certain good or service. They may also aim at optimizing outputs under conditions of climate change, by adapting to climate change.

Section 2.3.2 detailing on 'avoid and shift' activities that either reduce resource extraction and consumption, or provide services with different, less emission-intensive resources. An example for the first would be the reduction of food losses, for the second the shift from animal proteins to plant-based proteins.

In addition, Section 2.3.3 provides an assessment of nature-based climate solutions for adaptation and mitigation, including the technical mitigation potentials of existing land-system wide CDR approaches (Cross-Chapter Box 6).

Details on accompanying effects, such as the transformation from land to built-up area, are covered elsewhere in this report (e.g., Section 3.2.2).

Table 2.3 consolidates the knowledge on mitigation potentials of land-based avoid-shift-improve activities in Austria. Mitigation potentials have a large uncertainty range, e.g., due to limited knowledge on implied transformation processes or feasibility parameters. Caveats, limitations, and research gaps, which are specific to a measure are listed below the corresponding row in the table. General limitations which hold across all measures are discussed below the table.

Table 2.3 Overview of mitigation potentials of transformations in the Austrian land use systems. Detailed mitigation potentials of each considered study are listed in 2.A.16.

| Total potential* and sub-effects | Evidence on biogeophysical and technical feasibility and barriers | Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions | Mitigation potential compared to nowadays (ca. 2020) [$MtCO_2eq/yr$] | Mitigation potential compared to reference scenario** [$MtCO_2eq/yr$] | Confidence | Number of independent studies (independent models) for Austria |
|---|---|---|---|---|---|---|
| *The total potential is the sum of the sub-effects<br>** Referring to the reference scenario in each respective study – see limitations below and Appendix A2.16 for the list of studies.<br>Mitigation potentials represent estimated reductions in greenhouse gas emissions and increases in carbon sinks.<br>Positive values represent reduced emissions or increased sinks.<br>Negative values represent increased emissions or reduced sinks. | | | | | | |
| ***Improve measures:***<br>**Change in tree species composition: Switching to native non-coniferous species in forests – See Section 2.3.1** | | | | | | |
| *Long-term potential (Average ca. 2020–2150)* | | | | | | |
| Total potential | low | low | -9.5 to -10.6 | +1.1 to +1.9 | low | 2 (1) |
| Reduced processing emissions | n.a. | n.a. | n.a. | n.a. | n.a. | 0 |
| Effect on the sink in ecosystems (forest) | low | low | -0.1 to -1.2 | +4.1 to +4.9 | low | 2 (1) |
| Effect on the sink in harvested wood products (HWP) | low | low | -2.8 | -1.3 | low | 2 (1) |
| Effect on avoided emissions via substitution | low | low | -6.6 | -1.7 | low | 2 (1) |
| *Short-term potential (Average 2020–2060)* | | | | | | |
| Total potential | low | low | -3.7 to +0.3 | -0.3 to +1.1 | low | 2 (1) |
| Effect on the sink in ecosystems (forest) | low | low | +0.2 to +4.2 | -0.5 to +0.9 | low | 2 (1) |
| Effect on the sink in harvested wood products (HWP) | low | low | -0.7 | +0.1 | low | 2 (1) |
| Effect on avoided emissions via substitution | low | low | -3.2 | +0.1 | low | 2 (1) |
| Caveats: The effect on the forest sink materializes only under a high GWL (between GWL 4.0°C and GWL 5.0°C) and primarily beyond 2080. The interaction with increased disturbances from climate change is poorly known. Potentials of forestry measures are assessed as yearly averages over a long timeframe, up to 130 years, due to important non-linear dynamics (e.g., sink saturation and decarbonization of alternatives to wood). The comparison to 2020 (column 4) shows the difference in sinks/avoided emissions between the scenario with changed tree species composition, in a long-term average, and the value for 2020 in the reference scenario from the respective study. The increased emissions of the long-term average compared to 2020 are due to the decreasing trend in C sinks and avoided emissions, independently of the taken measures. The change in tree species composition moderately compensates for this overall trend (column 5). The potentials outlined here refer mostly to technical potentials from a current perspective. Time periods differ by studies. | | | | | | |

| Total potential* and sub-effects | Evidence on biogeophysical and technical feasibility and barriers | Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions | Mitigation potential compared to nowadays (ca. 2020) [$MtCO_2eq/yr$] | Mitigation potential compared to reference scenario** [$MtCO_2eq/yr$] | Confidence | Number of independent studies (independent models) for Austria |
|---|---|---|---|---|---|---|
| **Shorter rotation cycles: Immediate rapid rejuvenation of old stands by shortening the end-use age, to limit the risk of storm damage – See Section 2.3.1** | | | | | | |
| *Long-term potential (Average ca. 2020–2150)* | | | | | | |
| Total potential | low | low | -14.1 to -14.6 | -2.6 to -3.4 | low | 2 (1) |
| Effect on emissions | n.a. | low | n.a. | n.a. | n.a. | 0 |
| Effect on the sink in ecosystems (forest) | low | low | -7.6 to -8.1 | -2.4 to -3.2 | low | 2 (1) |
| Effect on the sink in harvested wood products (HWP) | low | low | -1.9 | -0.4 | low | 2 (1) |
| Effect on avoided emissions via substitution | low | low | -4.6 | +0.2 | low | 2 (1) |
| *Short-term potential (Average 2020–2060)* | | | | | | |
| Total potential | low | low | -1.5 to -10.1 | -0.7 to -6.8 | low | 2 (1) |
| Effect on the sink in ecosystems (forest) | low | low | -1.1 to -9.7 | -4.4 to -10.5 | low | 2 (1) |
| Effect on the sink in harvested wood products (HWP) | low | low | +0.9 | +1.7 | low | 2 (1) |
| Effect on avoided emissions via substitution | low | low | -1.3 | +2 | low | 2 (1) |
| Caveats: In total over all effects, this measure increases GHG emissions over the considered time period, mainly due to the reduced sink in forests. The interaction with increased disturbances from climate change is poorly known. Potentials of forestry measures are assessed as yearly averages over a long timeframe, up to 130 years, due to important non-linear dynamics (e.g., sink saturation and decarbonization of alternatives to wood). Time periods vary between studies. The potentials outlined here are mostly biogeophysical potentials, assessed from a current perspective. | | | | | | |
| **Other Adaptive Forest Management – See Section 2.3.1** | | | | | | |
| No data available, as no study exists for Austria. | | | | | | |
| Including: Fuel management strategies like selective thinning, prescribed burning, mechanical clearings, increasing structural diversity of stands, continuous forest cover, reduce game density, reduce stand density, etc. | | | | | | |
| **Total technical mitigation measures in agriculture – See Section 2.3.1** | | | | | | |
| Total potential | low | low | n.a. | +0.3 to +1.6 | medium | 2 |
| Effect on agricultural emissions | low | low | n.a. | +0.2 to +1.2 | low | 1 |
| Effect on agricultural soils and C sequestration | low | low | n.a. | +0.07 to +0.49 | medium | 1 |
| Caveats: Aggregate of the technical measures in agriculture, including those quantified in more detail below (agricultural inputs, livestock farming, rewetting peatlands under agricultural use). (i) Effect on agricultural emissions: Aggregate of technical mitigation measures targeting $CH_4$ and $N_2O$ emissions, including manure management, enteric fermentation, soil emissions, and fertilizer application, and assuming 80–100 % dissemination. (ii) Effect on agricultural soils and C sequestration: Including reduced tillage, non-inversion tillage on arable land (no data), broadening of crop rotations – increased soil biomass via field forage crops and legumes (no data), broadening of crop rotations – increased protein supply via forage legumes, implementation of catch/cover crops and greenings, use of manure instead of nitrogen fertilizer, amendment of organic substances such as biochar (no data), reducing soil compaction from wheel traffic, medium management intensity on permanent grassland, reducing conversion of permanent grassland, reducing cultivation on organic soils and reduced draining, organic farming with increased carbon sequestration measures, agroforestry (increasing tree cover in agricultural areas, silvopasture) (no data), and hedgerows. The effect on agricultural soils and C sequestration reflects mainly increased C sinks, but cannot be fully separated from decreased emissions and substitution effects of the above listed measures (about 0.1 to 0.2 $MtCO_2eq/yr$). Data comes from a meta-analysis, hence the *medium confidence*. | | | | | | |

| Total potential* and sub-effects | Evidence on biogeophysical and technical feasibility and barriers | Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions | Mitigation potential compared to nowadays (ca. 2020) [$MtCO_2eq/yr$] | Mitigation potential compared to reference scenario** [$MtCO_2eq/yr$] | Confidence | Number of independent studies (independent models) for Austria |
|---|---|---|---|---|---|---|
| **Reducing GHG emissions by the rewetting of peatlands under agricultural use – See Section 2.2.2** | | | | | | |
| Total effect on GHG emissions | low | low | +0.001 to +0.388* | | low | 2 |
| *Upper estimate for potential (expert judgement) assuming that rewetting of 50 % of 31,000 ha agriculturally used peatland area (Hogl et al., 2023) is possible, with a mean emission reduction of 25 $tCO_2eq/ha/yr$ (BMLRT, 2022).<br>Caveats: Estimates assume optimal restoration, with zero emissions after rewetting. Estimates don't include additional carbon sequestration due to regained carbon sink function after rewetting. Estimation of average emission reduction is based on German data; Austrian emission data are lacking. Knowledge on the amount of peatland area and future conditions for rewetting is low. | | | | | | |
| **Reducing GHG emissions from agricultural inputs (see sub-measures below the table) – See Section 2.3.1** | | | | | | |
| Total effect on emissions, sinks and substitution | medium | medium | n.a. | +0.05 to +0.330 | medium | 1 |
| Caveats: The study is a meta-analysis, hence the *medium confidence*.<br>Including: Reducing mineral fertilizers – increasing legume forage, reducing emissions from machinery upstream, improving fuel efficiency, reducing emissions from pesticides, systemically applied precision agriculture techniques, reducing N-fertilizer application in lanes, reduction of N-losses by close-to-ground application of slurry, reduction of energy demand in agricultural buildings | | | | | | |
| **Reducing GHG emissions from livestock farming; excluding the reduction of livestock (see sub-measures below the table) – See Section 2.3.1** | | | | | | |
| Total effect on emissions, sinks and substitution | medium | medium | n.a. | +0.015 to +0.8 | medium | 1 |
| Caveats: The study is a meta-analysis, hence the *medium confidence*.<br>Including: Optimization of housing, increase of pasture feed intake, reduction of the protein content in feed rations of pigs and poultry, reduction of the protein content in feed rations of bulls, reduction of the protein content in feed rations of cows, refining herd management and feeding protocols, solid manure instead of liquid manure systems (no data), utilization of excrements via biogas plants, feed additives (no data), increase livestock yield and efficiency, extend the productive life, improve animal health. | | | | | | |
| **Measures to reduce GHG emissions of processing, transport, and other processes in agricultural and wood supply-chains – See Section 2.3.2** | | | | | | |
| No data available, as no study exists for Austria. | | | | | | |
| **Increasing self-sufficiency for agriculture and forestry products and other trade related measures; effect on global GHG emissions embodied in consumption – See Section 2.3.2 and 2.A.12.** | | | | | | |
| No data available, as no study exists for Austria. | | | | | | |
| ***<u>Shift and avoid measures:</u>***<br>**Shift towards healthier and plant-based (EAT-Lancet) diets and according restructuring of agricultural production (incl. reduction of livestock products) – See Section 2.3.2 (protein transition, calories), and in Section 2.3.3 (*enabled afforestation/ renaturation*)** | | | | | | |
| Total potential | high | medium | +6.3 to +11.1 | +5.0 to +15.4 | high | 6 |
| Effect on agricultural emissions | high | low | +3.6 to + 3.7 | +2.5 to +5.6 | high | 6 |
| Effect on the sink in ecosystems (afforestation / renaturation on freed area | low | low | +2.7 to +7.4 | +2.5 to +9.8 | low | 3 |
| Effect on avoided emissions via substitution (additional production of bioenergy and bio-based materials on freed area | n.a | n.a | n.a | n.a | n.a | 0 |

| Total potential* and sub-effects | Evidence on biogeophysical and technical feasibility and barriers | Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions | Mitigation potential compared to nowadays (ca. 2020) [$MtCO_2eq/yr$] | Mitigation potential compared to reference scenario** [$MtCO_2eq/yr$] | Confidence | Number of independent studies (independent models) for Austria |
|---|---|---|---|---|---|---|
| Caveats: The sensitivity to the characterization metric needs to be evaluated. Socio-cultural transformation pathways are not described in the studies. Research gaps exist on transformation capacities, enabling conditions, and the contribution of institutions. Little is known about the regional-level and farm-level impacts and changes required for a shift from animal-based to plant-based food production. It is unclear to what degree this shift can be achieved through adjustments in farming practices and what fundamental changes to production systems would be needed in addition to that. Likewise, there is a clear research gap on the degree to which such a shift would induce farm closures and changes in rural structures. Impacts on ecosystem services, biodiversity, and landscapes are partly unclear. Available studies assume continuous population and emission growth. Hence, the mitigation potential comparing to the current situation (column 4) is smaller than when comparing to a reference scenario (column 5). | | | | | | |
| **Halving food losses – See Sections 2.3.2 and 2.3.3** | | | | | | |
| Total potential | medium | medium | +0.2 to +1.1 | +2.1 to +4.7 | medium | 2 |
| Effect on agricultural emissions | medium | medium | -0.4 to +0.5 | +1.6 | medium | 1 |
| Effect on the sink in ecosystems (afforestation / renaturation on freed area | low | medium | +0.6 | +0.5 to +3.1 | low | 2 |
| Effect on avoided emissions via substitution (additional production of bioenergy and bio-based materials on freed area | n.a | n.a. | n.a. | n.a. | n.a. | 0 |
| Caveats: Data on food waste and losses are poor (research gap). Estimating quantities and avoidability is a major challenge. Halving food losses appears as a plausible assumption. Research gaps on transformational pathways exist. Data on avoidability at various processing stages in the value chain are lacking. The increased agricultural emissions compared to present day are due to the assumed population growth (column 4). Halving food waste compensates for this overall trend (column 5). | | | | | | |
| **Reducing the overall use and harvest of wood to build up C stocks in forests – 'Vorratsaufbau' – See Sections 2.3.2 and 2.3.3** | | | | | | |
| *Long-term potential (Average ca. 2020–2150)* | | | | | | |
| Total potential | low | low | -2.6 to -4.2 | +7.0 to +8.4 | low | 2 (1) |
| Effect on the sink in ecosystems (forest) | low | low | +1.4 to +4.4 | +9.3 to +11.1 | low | 2 (1) |
| Effect on the sink in harvested wood products (HWP) | low | low | -2.2 to -3.4 | -0.7 | low | 2 (1) |
| Effect on avoided emissions via substitution | low | low | -6.4 to -0.6 | -1.6 to -2.0 | low | 2 (1) |
| *Short-term potential (Average 2020–2060)* | | | | | | |
| Total potential | low | low | +1.4 to +5.4 | +6.2 to +9.1 | low | 2 (1) |
| Effect on the sink in ecosystems (forest) | low | low | +4.7 to +12.0 | +8.7 to +12.3 | low | 2 (1) |
| Effect on the sink in harvested wood products (HWP) | low | low | -1.9 to -2.8 | -1.1 to -1.2 | low | 2 (1) |
| Effect on avoided emissions via substitution | low | low | -0.5 to -4.7 | -1.4 to -2.0 | low | 2 (1) |

| Total potential* and sub-effects | Evidence on biogeophysical and technical feasibility and barriers | Evidence on economic potential, socio-cultural and institutional barriers and enabling conditions | Mitigation potential compared to nowadays (ca. 2020) [$MtCO_2eq/yr$] | Mitigation potential compared to reference scenario** [$MtCO_2eq/yr$] | Confidence | Number of independent studies (independent models) for Austria |
|---|---|---|---|---|---|---|
| Caveats: The interaction with increased disturbances from climate change is poorly known. Scenarios have 2010 as base year and assume harvest of 20 million $m^3$/yr in the reference scenario and of 15 million $m^3$/yr on average between 2020 and 2150, excluding logging residues and natural losses ('Erntefestmeter'). Converted to 'Vorratsfestmeter' (i.e., including logging residues and natural losses), these volumes correspond to 30 million $m^3$/yr in the reference scenario and 25 million $m^3$ in the scenario with reduced harvest ('Vorratsaufbau'). Note that for 2020 the harvest volume assumed in the Care4Paris study (BFW, 2020) for the 'Vorratsaufbau' is close to the harvest level in 2016–2021 reported in the latest Austrian Forest Inventory (25 million $m^3$ 'Vorratsfestmeter'). The comparison to 2020 (column 4) shows the difference between the sinks/avoided emissions between the scenario with reduced harvest, in a long-term average, and the value for 2020 in the reference scenario from the respective study (Braun et al., 2016; BFW, 2020). The increased emissions of the long-term average compared to 2020 are due to the decreasing trend in C sinks and avoided emissions, independently of the taken measures. The reduction in harvest strongly compensates for this overall trend (column 5). The potentials outlined here refer mostly to technical potentials from a current perspective. Time periods differ by studies. | | | | | | |
| **Increase cascadic uses of wood: Prioritizing long-life harvested wood products over energy – See Section 2.3.2** | | | | | | |
| Total effect | Low | low | | +0.1 to +0.5 | low | 2 |
| Caveats: The comparability of the two studies is low. One study compares a scenario where policies either favor material uses or energy. The other study shows two case studies, in which chips are used for boards and lignocellulosic ethanol for ethylene instead of energy. | | | | | | |

Table 2.3 provides an overview of the mitigation potentials described in the scientific literature specifically applicable to Austria. The direct comparability of the studies is limited and any interpretation of the figures shown needs to consider the respective boundary conditions, baselines, methodological assumptions and resulting limitations, especially when attempting to provide information about combined potentials. It is strongly recommended to refer to the individual studies (listed in 2.A.16) and to examine their individual limitations, potential methodological differences, and research gaps more generally:

**Limitations of individual approaches** concern the quality including temporal, spatial, and categorial levels of aggregation and uncertainty ranges of the input data used. The boundary conditions and scope of the respective studies may differ from the purpose of describing mitigation potentials in this table, and therefore the adequacy may be limited. Potentials may differ whether measured against current conditions or future situations, in the latter case also strongly depending on projections and scenario assumptions. Some figures are based on rough, back-of-the-envelope calculations, which carry the risk of oversimplification. Moreover, much of the outlined potentials are theoretical, based on biogeophysical feasibility alone, without factoring in technical, socio-cultural, or political constraints that will affect real-world implementation, although some of the outlined strategies do take these aspects into account. In terms of economic feasibility, additional uncertainties arise from the use of price valuations in studies from different years. All studies assume the greenhouse gas characterization metric GWP100, which is also the metric adopted in the UNFCCC. Choosing a different metric such as GWP20 or GWP* would affect the results (see 2.A.10).

**Methodological differences** may also be the result of different original objectives of the studies used. This may lead to differences in the underlying assumptions (e.g., different market prices of end products, energy prices, political willingness for implementation) and to discrepancies between the baseline parameters against which mitigation potentials may be measured. Mitigation potentials derived from different studies may be mutually exclusive and thus not additive, adding complexity to the combination of individual mitigation potentials. Especially for measures requiring land area, careful consideration of land use priorities and constraints in terms of availability and additionality is needed. Sub-measures are often aggregated into larger measures, and sometimes grouped into bundles, but this is often done without a consistent or systematic approach. Furthermore, interaction effects between mitigation measures can result in unwanted impacts on other economic sectors. Some of the emissions reduction strategies might be effective immediately, while others have a delayed effect. The most prominent example is carbon sinks, which can play a crucial role in both short and long-term mitigation, but are effective over decades (e.g., 30–150 years) and have considerable uncertainties in their magnitude and stability. Such factors are treated inconsistently in different studies. Carbon stocks are reversible and depend on future activities. As carbon sinks can be affected not only by human intervention but also by natural biophysical processes, the impacts of climate change itself need to be considered, again leaving margins for different and contradicting approaches.

**Research gaps** exist in our understanding of the processes leading to the emission and sequestration of GHGs on land. Obviously, the table above only accounts for mitigation potentials that are known and have been addressed in research studies. Due to the complexity of biological processes and the small flux densities over large areas, many factors determining these fluxes remain poorly quantified and may not have been adequately studied. This is even more the case for factors that modify the fluxes (mitigation measures). Known examples are the emission behavior of organic soils or the feedback of climate change on many of the processes. Other research gaps relate to the synergies and trade-offs of mitigation measures with other sustainability objectives or their effectiveness under climate change.

## 2.3.1. 'Improve' measures

### Adaptive forest management – 'Improved' forest management to mitigate and adapt to climate change

Austrian forests, which had been carbon sinks varying around -15 Mt$CO_2$/yr for several decades, lately have been turning into a carbon source (+5.4 Mt$CO_2$/yr for 2023, which meant a source also on a five-year average: +0.2 Mt$CO_2$/yr, see Figure 2.2 and Table 2.A.2). This is the result of the net effects of removals of atmospheric $CO_2$ through biomass increment and carbon losses caused by natural disturbances, forest management (timber harvest, thinning) and changes in carbon stocks in soils, influenced by inflows and decomposition of organic matter. To maintain or enhance this sink, particularly in the light of expected future climate impacts, adaptive forest management (AFM) approaches to climate change propose three main principles (Bolte et al., 2009; Brang et al., 2014; Spathelf et al., 2018): (i) Increasing resistance to disturbances by improving the stability of forest stands, (ii) promoting resilience of forests for a rapid restoration of forest functions to desired conditions after disturbances, and (iii) promoting the adaptability of forest stands by selecting appropriate species during regeneration, changing species shares during mixture regulation, increasing the diversity and diversification of forests to facilitate the transition to new forest states (Spathelf et al., 2018). Optimizing the rotation length is also discussed for AFM, depending on site characteristics and market demands, to reduce the windthrow risk due to a limitation of the top height reached (Schelhaas et al., 2015) or reduce the risk of a higher mortality of not adapted tree species and to keep the increment rate on a high level (adaptation and focus on substitution). However, on average between 2020 and 2150, shortening rotation cycles would decrease the carbon sink in forests by 2.4 to 3.2 Mt$CO_2$eq/yr compared to a reference scenario. In addition the sink in harvested wood products will be decreased by 0.4 Mt$CO_2$eq/yr and the avoided emissions from substituting fossil fuels and abiotic materials will increase by 0.2 Mt$CO_2$eq/yr (see Table 2.3 and 2.A.16 for individual studies) (BFW, 2020; Ledermann et al., 2022). Changing tree species composition to species that are expected to perform better under a changed climate (Schelhaas et al., 2015) can avoid risks associated with specific pests, diseases or disturbances (Seidl et al., 2009) or drought-intolerant species at the stand or landscape level. According to the results of the Care4Paris project, changing the composition of species to native non-coniferous species would increase the carbon sink in forests by 4.1 to 4.9 Mt$CO_2$eq/yr on average between 2020 and 2150 compared to a reference scenario. On the other hand, the sink in harvested wood products would be reduced by 1.3 Mt$CO_2$eq/yr and the avoided emissions from the substitution of fossil fuels and abiotic materials by 1.7 Mt$CO_2$eq/yr (see Table 2.3 and 2.A.16 for individual studies) (BFW, 2020; Ledermann et al., 2022). Advanced planting with shade-tolerant tree species in mature stands can support tree species change, as harvesting mature stands and regeneration them with new species might result in lower forest carbon stocks in the short term (Kindermann, 2021). In this context, assisted migration strategies transfer more adapted or adaptive tree species (including non-natives) to regions outside their current natural range that are characterized by a suitable climate, thus artificially extending the range distribution of more resilient tree species (Gömöry et al., 2020; Mauri et al., 2023). Assisted migration of tree species has the potential to increase carbon sinks and might allow larger harvest volumes that remain below increment, but uncertainties are large and risks are manifold (Pötzelsberger et al., 2020; Chakraborty et al., 2024). Fuel management strategies like selective thinning, prescribed burning (along railroad embankments, on grasslands or meadows), mechanical clearing or grazing with goat, sheep, or donkey can reduce the fuel loads and thus the probability of large and stand-replacing forest fires (Ascoli et al., 2023; Müller et al., 2020).

There is strong evidence that tree species richness and high genetic diversity positively influence the adaptive capacity of forests to climate change (Brang et al., 2014;

Spathelf et al., 2018). Increasing the structural diversity of stands by retaining ecosystem legacies (e.g., seed trees, deadwood, stand remnants) after disturbances will enhance the restoration capacity (Spathelf et al., 2018). In addition, the heterogeneous ownership structure and different management strategies help to promote diversely structured forest ecosystems in Austria. There is *high confidence* that management for continuous forest cover can help maintain a favorable microclimate in forest stands and provide continuous natural regeneration (Spathelf et al., 2015; Vacek et al., 2019; Zellweger et al., 2020). However, the density and distribution of game populations is a key factor that in many cases jeopardizes a successful natural regeneration without protective measures (Schodterer, 2022). Moderate reductions in stand density have been shown to effectively mitigate drought stress (Elkin et al., 2015), but the effects vary across forest sites, species, and context (Castagneri et al., 2022). As forest management adjusts the tree species composition to increase the resistance and resilience of ecosystems while maintaining high levels of productivity, the supply to the timber, pulp and paper market will change in the long run (increasing the share of deciduous tree species). This development will entail transformation of the timber industry (Klein et al., 2016; Lantz et al., 2022). For more details about climate change adaptation, see Chapters 4 and 5 in the APCC Special Report on land use and climate change (Baumgarten et al., 2024; Kraxner et al., 2024).

Emissions linked to energy use along the supply chain of wood (see Section 2.1.1) are mostly influenced by road maintenance, biomass harvesting techniques, forwarding and biomass transport and depend on the considered tree species, age classes, rotation length, wood assortments, and site quality parameters (Klein et al., 2016). Mitigation measures that focus on these parameters are: Efficient transport, reduced fuel consumption or shifting to alternative energy sources, improved road and skidding line network.

### Agricultural management to mitigate and adapt to climate change

Emission reductions are linked to the activities responsible for the relevant emissions (see Section 2.1.1). In agriculture, an important mitigation option is to increase SOC (Table 2.1). The literature, as summarized by Kraxner et al. (2024), shows a wide range of measures, such as non-inversion tillage on arable land, changes in crop rotations including increased biomass supply from forage grasses and legumes, the integration of catch/cover crops and intercropping and greenings, the use of manure instead of mineral nitrogen fertilizers, or the addition of organic substances such as biochar. Systemic crop management approaches have been suggested to combine benefits of individual measures (Kraxner et al., 2024).

Adding N fertilizer to soils drives $N_2O$ emissions from soils, so reducing fertilizer application also reduces emissions. Minimizing N inputs may take advantage of more efficient fertilizers such as nitrification inhibitors or precision agriculture to reduce $N_2O$ emissions by up to 38 % (Winiwarter et al., 2018), possibly with minor yield losses (Foldal et al., 2024). The application of biochar has also been described to efficiently reduce $N_2O$ emissions (Liu et al., 2018; Borchard et al., 2019). The potential mitigation effects of systemically applied precision agriculture techniques (PAT) have a wide range (*limited evidence, medium agreement*). High investment costs, high demand for expertise, and a lack of training materials are barriers to the use of PAT (Kraxner et al., 2024).

The whole production chain is also relevant (Osterburg et al., 2013; Grassauer et al., 2021). For Germany, there are reports on the trickle-down effects of reducing N inputs from mineral fertilizer, e.g., through taxation (Isermeyer et al., 2021). Optimizing feed rations and livestock protein intake can reduce emissions associated with feed production and N fertilization (Pierer et al., 2016). A mitigation potential of >30,000 $tCO_2eq$/yr is estimated at costs below EUR 100/t for pig farming and between EUR 100–200/t for ruminant farming (Fritz et al., 2022; Sinabell et al., 2023) (*medium confidence*). Increasing legume forage reduces the need for protein feed imports and synthetic fertilizers (Stagnari et al., 2017), potentially abating emissions by >15,000 $tCO_2eq$/yr at costs between EUR 100–200/t (Fritz et al., 2022; Sinabell et al., 2023). Also, managing grasslands at medium intensity and increasing pasture feed intake can be cost-effective options, mitigating >45,000 $tCO_2eq$/yr at costs below EUR 100/t (Lorenz et al., 2019a; Fritz et al., 2022) (*medium confidence*). In addition, more efficient use of machinery offers an economically viable potential of mitigating >7,500 $tCO_2eq$/yr at costs below EUR 100/t (Fritz et al., 2022; Sinabell et al., 2023). For fossil fuel use, efficiency improvements and biofuels or electrified machinery can play a minor role, but no technique is available for substantial mitigation.

There are several mitigation options to tackle emissions from livestock farming (see also compilation by Kraxner et al., 2024). Feed additives can reduce enteric $CH_4$ formation in cattle by up to 30 % (no cost assessment available) (Lewis et al., 2013; Abecia et al., 2018; Van Wesemael et al., 2019). Indirect mitigation measures, such as refining herd management and feeding protocols, improving livestock management practices and animal health exhibit a mitigation potential of >20,000 $tCO_2eq$/yr and costs below EUR 100/t. Extending the productive life of cows may further mitigate >20,000 $tCO_2eq$/yr at costs below EUR 100/t (Dallago et al., 2021; Fritz et al., 2022; Sinabell et al., 2023). An option with high mitigation potential, but far-reaching socio-economic consequences for livestock producers and the entire value chain, is the (further) reduction of livestock numbers based on assumptions of reduced food losses, reduced protein intake or a shift towards plant-based diets and agriculture (see Section 2.3.2). Nevertheless, Austrian livestock production systems appear rather efficient in terms of GHG emissions in the international context due to higher N efficiency and lower $N_2O$ emissions, the dominance of dual-purpose breeds in cattle production and hence the allocation of GHGs to milk and beef, lower use of imported feedstuffs which are loaded with large amounts of GHGs from land use change. Weiss and Leip (2012) calculate average Austrian GHG emissions from meat and dairy production per unit of output to be among the lowest in the European Union. For example, average emissions are about 1 $kgCO_2eq$/kg for Austrian cows' milk compared to an EU average of about 1.3–1.7 $kgCO_2eq$/kg cows' milk and more than 2.5 $kgCO_2eq$/kg for cows' milk from Cyprus. Mitigation measures applicable to all livestock species are the optimization of housing and farm manure systems (e.g., Hörtenhuber et al., 2010; Sajeev et al., 2018).

Austria is still a long way from the number of animals per farm or per area found in other industrialized countries. However, even in Austria, there is a trend towards concentration and intensification with increasing problems of odor nuisance (Weitensfelder et al., 2019; Oettl et al., 2022) and bio-aerosols, while ammonia is also a precursor of fine particulate matter in the atmosphere (Liu et al., 2023).

The adaptation of agriculture to climate change requires first and foremost adapting current land use. For arable land, important adaptation measures are, similar to mitigation measures, the broadening of crop rotations, the diversification of crops and the integration of catch crops (protecting soils from drying out) and undersowings, which contribute to humus build-up (measures are described in Jandl et al., 2024c). Quddoos et al. (2023) show that adaptation options help to considerably reduce the adverse effects of climate change for Austrian farms. Similar to cropland, grassland productivity might also profit from moderately warmer temperatures as long as sufficient water is available (Haslmayr et al., 2018; Schaumberger et al., 2019; Volk et al., 2021). However, this requires the adaptation of cutting frequencies and fertilization to changing climatic conditions. Changing climatic conditions might allow an increased use of alpine pastures, but negative effects on biodiversity must be considered.

Climate change may affect the spread of harmful organisms. Universal predictions of pest and disease dynamics and universal control strategies are not possible, but have to be developed specifically. One basic option is to diversify crop rotations (which, e.g., can stop the spread of the maize rootworm: Feusthuber et al., 2017; Falkner et al., 2019). Adequate crop rotation with early, effective weed control and a monitoring system throughout the growing season can prevent the establishment and spread of invasive plants (AGES, 2023b, 2023a). New technologies, such as drone technology, are being used to control Datura spec. in crops (Riegler-Nurscher et al., 2023). Useful organisms such as pollinators may be lost, but improved agricultural management, such as near-natural elements or habitats with appropriate forage plants in agricultural landscapes, can counteract such losses (Roberts et al., 2011; Zulka and Götzl, 2015).

To adapt to climate change-induced water shortage, numerous adaptation measures are discussed (Jandl et al., 2024c): Active and efficient irrigation (where water sources are available), soil-related measures such as reduced tillage, permanent ground cover, and windbreaks are well-established means. Furthermore, fertilization should be adapted to changing nutrient dynamics, water balance and seasonal fertilization requirements. In practice, barriers to widespread implementation lie in farmers' risk attitudes and management practices, market mechanisms and institutional design (Mitter et al., 2019; Hanger-Kopp and Palka, 2022).

Climate change-induced summer heat waves and droughts affect growing conditions for crops. This requires the breeding and establishment of new crop species or varieties. In particular, plant breeding research particularly has to focus on heat and cold tolerance, efficient use of nutrients and water, and resistance to pests (VLK, 2019). In grasslands, the use of drought-resistant varieties is becoming increasingly important, which will also be reflected in breeding programs (Krautzer and Graiss, 2015). New crop species like chickpea (Neugschwandtner et al., 2013) or amaranth (Gimplinger et al., 2007) may become competitive. Rising temperatures, including milder winter conditions, allow the planting of winter forms of traditionally spring-sown crops like pea (Neugschwandtner et al., 2020), faba bean (Neugschwandtner et al., 2015, 2023a), and poppy (Neugschwandtner et al., 2023b). For winter wheat, facultative cultivars are a promising solution to avoid insufficient vernalization during very mild winter seasons (Koppensteiner et al., 2022).

Heat stress also poses a significant threat to livestock in terms of health, animal performance (e.g., feed conversion, daily weight gain, and milk production), well-being, and economic implications for farmers (Hörtenhuber et al., 2020; Herzog et al., 2021; Schauberger et al., 2021). The implementation of adaptation measures is crucial to reduce the adverse effects of heat stress in confined livestock facilities. Such techniques include cooling the inlet air, refining management protocols, and optimizing feeding strategies (Vitt et al., 2017; Mikovits et al., 2019; Schauberger et al., 2020; Herzog et al., 2021). For more details on climate change adaptation, see Chapter 4 of the APCC Special Report on land use and climate change (Baumgarten et al., 2024) and Smit and Wandel, 2006)..

The implementation of mitigation and adaptation measures at the local (farm) level requires adequate financial and technological resources, as well as the information and organization skills to manage these resources accordingly (Smit and Wandel, 2006); without these, adaptation success may be limited. Zeilinger et al. (2023) confirm such under-adaptation to climate change for Austrian farms in arable regions. Recent literature suggests that developing the adaptive capacity of farms is a promising policy tool to enhance adaptation (Vanschoenwinkel et al., 2020). Mitter et al. (2019) identify prerequisites for adaptation intentions of Austrian farmers, including awareness of effective adaptation measures, acceptance of personal responsibility for their farms, and positive adaptation costs.

### 2.3.2. 'Shift and avoid' measures

#### Protein transition – shift towards healthy, plant-based diets

There is *high confidence* that the composition of food produced and consumed has a highly significant impact on per capita carbon emissions, driven in particular by the number of farmed livestock and the amount of related products (Jandl et al., 2024c). Past and recent trends in diets in Austria are presented in 2.A.8. Dietary choices impact decisions on agricultural land use, livestock management, processing, transport, and ultimately disposal, and are therefore important for climate protection. Consequently, major potentials from a transformation of diets result from reducing the total amount of products produced and consumed (including total food intake and food waste), as well as shifting the type of products (degree of processing, transport requirements, seasonality) and the kind of products consumed (i.e., dietary choices such as vegan vs. livestock-based products).

This section tackles the role of choices in agricultural food products (protein transition, i.e., a shift to diets with decreased shares of animal products), with other options being discussed in Section 2.3.2. There is *high confidence* that dietary change cannot be understood as the sole responsibility of end consumers, and that achieving dietary change through a bundle of measures involving all actors across the food system could facilitate an effective and just protein transition (Harwatt, 2019; Willett et al., 2019; Vermeulen et al., 2020; Roux et al., 2022; Mempel et al., 2023; Penker et al., 2023; Voigt et al., 2024) (see 2.A.9 and Table 6.1 for policy instruments related to diets across the food system). Life cycle assessments typically show large differences in the GHG emissions of agricultural products, with livestock-based products having substantially higher emissions than plant-based products when related to the energy or protein content of the food as a functional unit (Table 2.4). This is true for both estimates per unit of kcal and per unit of protein (Tilman and Clark, 2014). The main reasons include the low feed-to-product conversion rates with correspondingly large land requirements and, especially in the case of ruminant livestock, $CH_4$ emissions from enteric fermentation. Consequently, ruminant products typically embed the most emissions among all animal products for typical GWP100 estimates. A discussion about GWP100 vs. GWP* can be found in 2.A.10.

Austria is among the world leaders in per capita meat consumption (including bones, tendons parts, and trim fat), with an annual per capita intake of 34.2 kg of pork, 12.8 kg of poultry, and 10.4 kg of beef in 2021 (Statistik Austria, 2022e). The study by Frey and Bruckner (2021) highlights that beef consumption accounts for 38 % of the greenhouse gas emissions from Austria's agricultural product consumption. These data, combined with the high emissions per unit of livestock products, indicate significant per-capita greenhouse gas emissions from the typical Austrian diet (*high confidence*).

Shifting towards the so-called Planetary Health Diet developed by the EAT-Lancet Commission (Willett et al., 2019), i.e., a dietary standard with high shares of vegetarian food that takes into account planetary boundaries and human health, would reduce the demand for animal products and correspondingly restructure agricultural production. It would yield a mitigation potential of 5.0 to

15.4 $MtCO_2eq$/yr (compared to individual reference scenarios), including reduced agricultural emissions and enabled afforestation (Schlatzer and Lindenthal, 2020; Lauk et al., 2022; Sun et al., 2022; Le Noë et al., 2023a; Preinfalk et al., 2024) (see Table 2.3 and 2.A.16 for the individual studies). From a consumption-based perspective, shifting to the Planetary Health Diet (EAT-Lancet) would reduce GHG emissions embodied in Austria's consumption of food by ca. 9.3 $MtCO_2eq$/yr, or 1.02 $tCO_2eq$/cap/yr (Semba et al., 2020). A shift to vegan diets increases the mitigation potential by ca. 2 $MtCO_2eq$/yr compared to a planetary health diet (Le Noë et al., 2023a). At the European level, Westhoek et al. (2014) estimate that a 50 % reduction in meat, dairy and eggs from a 2004 reference diet would reduce GHG emissions by 25–40 %.

Note that the diet proposed by the EAT-Lancet Commission (Willett et al., 2019) is beneficial in terms of a reduced carbon footprint and for the health of consumers (Ekmekcioglu et al., 2018). There is *high confidence* that shifting towards plant-based diets, especially reducing red and processed meat, reduces the risk of various diseases such as colorectal cancer and cardiovascular diseases (Chan et al., 2011; Yip et al., 2013; Bouvard et al., 2015; WHO, 2015; Farchi et al., 2017). The risk of colorectal cancer increases by 17 % for every 100 g of red meat consumed per day and by 18 % for every 50 g of processed meat consumed per day (Bouvard et al., 2015).

Furthermore, the production and consumption of agricultural commodities, such as livestock products, feed, or oil crops for food and bioenergy, is the world's leading driver of deforestation, prompting both climate change and the transmission of zoonotic diseases from wildlife to humans (Faust et al., 2018; Pendrill et al., 2022). Averting epidemics of wildlife-borne infectious diseases requires a socio-ecological transformation, a redesign of the global food system and a transition to diets that are plant-based or low in animal products (Wegner et al., 2022).

**Meat substitutes.** Livestock-based meat as protein source can be replaced by several substitutes, such as legumes and processed plant-based meat (PBM) (He et al., 2020), insect-based meat (IBM), and (in vitro) cultivated meat (CM) (Sinke et al., 2023). These innovations are poised to capture a significant share of the global meat market, estimated at 60 % by 2040 (Gerhard et al., 2019; He et al., 2020). Despite optimistic market and investment scenarios, regulatory, social, economic, ecological, and agronomic challenges (e.g., Codex Alimentarius Austriacus) have to be solved for these products (Eker et al., 2019; Kim et al., 2020; Moran and Blair, 2021; Noguerol et al., 2021; Siddiqui et al., 2022). Table 2.4 compares the environmental impacts of conventional meat (beef, pork, and chicken) and various meat substitutes, based on Life Cycle Assessments. Note that these assessments are based on current data and refer to relatively new processes, so there are large uncertainties and significant room for improvement. Meat substitutes exhibit notable ecological advantages, offering a viable strategy for transitioning away from high-impact beef production towards more environmentally sustainable meat options. Notably, the elevated energy requirements associated with CM and PBM production underscore the imperative for utilizing green energy sources to mitigate $CO_2$ emissions (Sinke et al., 2023).

Table 2.4 Comparison of the environmental impact of conventional meat (beef, pork, and chicken) (Nijdam et al., 2012; Willett et al., 2019; Sinke et al., 2023), cultured meat (Sinke et al., 2023) plant-based meat (Nijdam et al., 2012; Saget et al., 2021), and insect-based meat (Smetana et al., 2016), related to 1 kg meat. The protein content of meat was assumed at 22 %. Values for plant proteins are adapted from Poore and Nemecek (2018). Negative values show a carbon sink.

| Specific environmental impact related to meat production | Energy [MJ/kg] | GHG Emissions [$kgCO_2eq/kg$] | Land use [$m^2/kg$] |
|---|---|---|---|
| *Animal meat* | | | |
| Beef | 60–105 | 9.9–141 | 7–462 |
| Pork | 28–40 | 4.4–12.3 | 8.8–16.5 |
| Chicken | 24–26 | 2.2–9.9 | 5.1–8.8 |
| *Processed meat alternatives* | | | |
| Cultured Meat | 25–481 | 1.9–24.8 | 0.19–6.9 |
| Plant-based meat | 143 | 1.0–12.3 | 2–3 |
| Insect-based meat | 2–64 | 0.17–3.2 | 0.07–1.03 |
| *Plant proteins* | | | |
| Tofu | | 1.6–5.6 | 1.8–4.9 |
| Peas | | 0.6–1.7 | 2.8–14.2 |
| Other pulses | | 1.0–3.8 | 9.9–41.3 |
| Nuts | | -3.7–3.8 | 4.5–26.6 |

There are a number of trade-offs that need to be considered to enable a just transition to fewer livestock and animal products. While there are multiple alternative uses for arable land used for feed (e.g., food, fuel or fiber production), there are fewer alternative uses of permanent grasslands. Options include feedstock used in biogas plants or green biorefineries (Höltinger et al., 2014). A plausible option for marginal permanent grasslands is reforestation. Reforestation of grasslands is likely to increase total carbon sequestration in soils and biomass (Schirpke et al., 2017) but can create pressures on landscape quality or biodiversity, especially for extensively managed grasslands such as alpine meadows (Hussain et al., 2019). Dietary changes are also likely to have substantial impacts on farm incomes. Introducing the EAT-Lancet diet in the EU-27 has been estimated to increase agricultural income by 71 % in the long run (2050) due to shifts to high value-added crops such as fruits, vegetables and nuts (Rieger et al., 2023). In the short-run, however, there may be income losses (-12 % in Germany for partial EAT-Lancet implementations due to its specialization on livestock production) (Rieger et al., 2023). Similar impacts can be expected for Austria, although for permanent grassland regions, the shift to vegetables and fruits production is more costly and the income losses may be more pronounced. For further discussion on co-benefits and trade-offs related to dietary change and livestock reductions, see 2.A.10.

**Pets.** In Austria, there are approximately 2 million domestic cats and 766,000 dogs (FEDIAF EuropeanPetFood, 2023). These pets primarily subsist on meat-based diets (Swanson et al., 2013; Okin, 2017; Martens et al., 2019; Pedrinelli et al., 2022; Scherer et al., 2022). The IPCC report recognizes carnivorous pets as a significant factor in potential GHG mitigation, estimating their contribution at approximately 0.8 $MgCO_2eq/cap$ (Creutzig et al., 2022b). It is important to acknowledge that a substantial portion of pet food in the industrial sector is derived from animal by-products, which are inedible residuals obtained through animal rendering processes (Alexander et al., 2020; Acuff et al., 2021; Pedrinelli et al., 2022). Nevertheless, it should be noted that not all pet foods exclusively rely on by-products, and that some of them may contribute to GHG emissions (*robust evidence, low agreement*).

## Non-protein related food measures – 'avoid' measures

Non-protein-related food measures refer to all changes beyond changing protein sources in human diets (see above) and switching to products produced under climate-friendly management and technologies (see above). These measures include reducing the total amount of products consumed, i.e., avoiding excess calorie consumption, reducing food losses, and changing the origin and processing degrees of food products. Figure 2.7 shows the food system emissions from the two groups, pre- and post-agricultural production and agricultural sector emissions, according to the national GHG inventory for the years 1990 and 2020 (Umweltbundesamt, 2022). Both groups of emission sources are in the same order of magnitude with diverging development patterns.

In 2019, 34.5 % of adults in Austria were overweight and 16.5 % were obese. The number of obese people has increased since 2006 (Statistik Austria, 2022c). Reducing overall food intake, especially the production and consumption of high-calorie products, would hence not only spare agricultural land and GHG emissions, but also help to reduce obesity and its associated diseases, such as ischemic heart disease, stroke, hypertension, type 2 diabetes

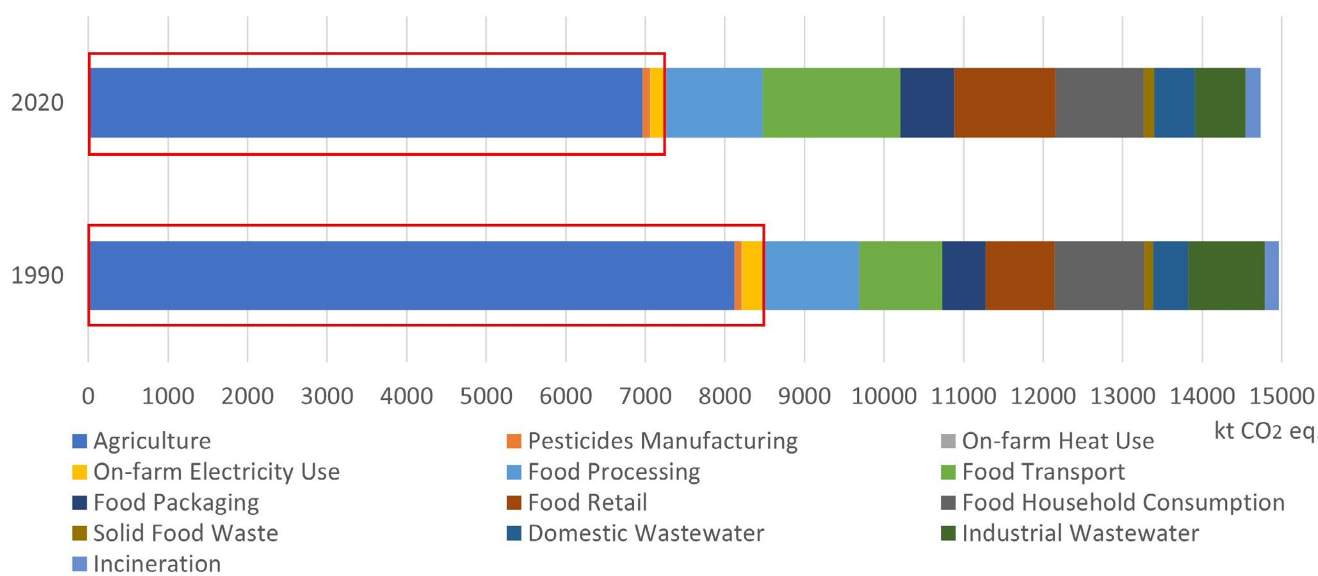



Figure 2.7 Agricultural, pre-production (red box) and post-production emissions ($ktCO_2eq$) of the Austrian food system by component in 1990 and 2020 (data: fao.org/faostat/en/#data/GPP; and Umweltbundesamt (2022)). A monochromatic version of the figure can be found in 2.A.11.

mellitus, colorectal cancer, postmenopausal breast cancer, endometrial cancer, kidney cancer and osteoarthritis (Lette et al., 2016). Estimates of the calorie intake in Austria range from 2,673 kcal/cap/day (3,100 kcal/cap/day including food waste) for the year 2022 (Pecher et al., 2024), to 3,117 kcal/cap/day (3,610 kcal/cap/day including food waste) for the year 2015 (Lauk et al., 2022), and 3,429 kcal/cap/day (excluding food losses) for the year 2010 (Sun et al., 2022). A large-scale survey of Austrians in the year 2014–2016 estimated the total calorie intake at 1,815 kcal/cap/day (women) and 2,453 kcal/cap/day (men; both excluding food waste), which is lower than other estimates but still above dietary recommendations for about 50 % of the Austrian population (Rust et al., 2017). Most estimates are substantially above FAO recommendations for a balanced average Austrian diet of 2,533 kcal for the year 2020 (FAOSTAT, 2023).

Thus, **adapting current diets** has a strong mitigation potential (*robust evidence, medium agreement*) and leads to synergies with human health. However, it is not straightforward to disentangle reductions in calorie uptake ('avoid') from changes in diet composition ('shift', see above), because even calorie reduction scenarios require assumptions on individual diet components, i.e., whether they reduce diet components proportionally or disproportionally (e.g., stronger reductions of products with large GHG emissions).

Linearly translating the current to the recommended levels (i.e., -25 % in calories uptake) according to FAO for Austria would reduce agricultural emissions by ca. 2 $MtCO_2eq$/yr, or ca 0.2 $tCO_2eq$/cap/yr. Hiç et al. (2016) estimate the average emissions related to food surplus are at 0.12 $tCO_2eq$/cap/yr. Kim et al. (2020) estimate country-level GHG emissions for different diets and show ranges for Germany from <0.5 to >1.5 $tCO_2eq$/cap/yr. These ranges are comparable to the mitigation potentials estimated for the Planetary Health Diet suggested by the EAT-Lancet commission (see above and Table 2.3), which also includes a calorie reduction, e.g., to a maximum of about 2,600 kcal/cap/day in Semba et al. (2020). Other authors concur with these estimates, reporting substantial sustainability impacts from over-consumption similar to consumers' food waste (Alexander et al., 2017). Creutzig et al. (2022a), however, assume small mitigation effects from calorie reductions due low GHG emissions from high-calorie products such as sugar.

The potential for carbon sequestration on land no longer needed for agricultural production – or needed for nourishment of a growing future world population to prevent forest loss and other land use changes – need to be added to these emission savings and are shown in Table 2.3.

**Food losses** occur throughout the value chain, while food waste refers to the consumption stage (Parfitt et al., 2010). Neither can be fully avoided, but substantially reduced. Estimates of mitigation potentials are smaller than for changes in overall diets (*robust evidence, medium agreement*), but reducing food losses and waste is considered an important and 'no-regret' climate mitigation measure (Springmann et al., 2018). Halving food losses in Austria would result in a mitigation potential of 2.1 to 4.7 $MtCO_2eq$/yr (compared to a reference scenario), including reduced agricultural emissions as well as a carbon sink due to enabled afforestation, assuming that these products would not have been produced (see Table 2.3 and 2.A.16 for the individual studies) (Le Noë et al., 2023a; Preinfalk et al., 2024). For comparison, Parfitt et al. (2010) estimate unavoidable household food waste in the UK to be around 20 %. Therefore, if similar reductions were to be applied to Austria, the mitigation potential would be 0.14 $tCO_2eq$/cap/yr. In Austria food waste amounts to 1.1 Mt/yr, of which 49 % comes from private households, 16 % from farms, 11 % from food production, 16 % from gastronomy and 8 % from trade (Luck and Obersteiner, 2021). Springmann et al. (2018) estimate the effect of waste and loss reduction on emissions to be about one-fifth that of dietary changes (the latter including a change in diet mix). Similar results are reported by global food system studies for Europe (Kalt, 2015; Mayer et al., 2022; Röös et al., 2022) However, specific data on food losses and food waste in Austria are scattered. Scherhaufer et al. (2016) summarize studies showing total losses of about 1.1 million tons of biomass per year, which would be about 0.12 t/cap/yr, with about half of the losses occurring in households, and the rest distributed among agricultural production, processing and retail, and outside-home catering. Crippa et al. (2021) estimate end-of-life emissions in the food system to be about 1.39 $MtCO_2eq$/yr, or about 6 % of Austrian food system emissions in 2015.

**Transport** between different locations of production, processing, consumption, and disposal along the food value chain offers further mitigation potentials. Crippa et al. (2021) estimate transport emissions in the Austrian food system at about 2.49 $MtCO_2eq$/yr, or 12 % of total food system emissions. Only part of these emissions are avoidable, with typical examples of high GHG emissions and thus mitigation potentials for air-transport of fresh products. Local food systems are defined by small geographical distances between the steps of the food value chain. Despite potential emission savings from transport, they can cause additional emissions at other stages along the value chain (Schönhart et al., 2009). Therefore, their overall potential must be regarded as being small (*high confidence*).

## A sufficiency-oriented bioeconomy – 'shift and avoid'

Like bioeconomy strategies in general, the Austrian Bioeconomy Strategy implemented in 2019 aims to reduce climate impacts by shifting resource use away from abiotic (especially fossil fuel-based) towards a higher share of biomass use. In Austria, biomass currently accounts for only 23 % of direct material consumption (38 Mt/yr), the rest being mineral, fossil and metallic resources (BMK, 2020). There is *high confidence* that a shift towards a bioeconomy needs to be complemented by additional measures to avoid the degradation of domestic and international resources and ecosystems. A key reason is that Austria, typical of European countries, already appropriates a high fraction (56 %) of its domestic potential net primary productivity through biomass use and land conversion (Gingrich et al., 2015), and net imports of agricultural products contribute to additional pressures on ecosystems abroad (Haberl et al., 2012). Such additional measures need to ensure (a) sustainable production processes, (b) efficiency improvements in the provision of energy and material services and well-being, and (c) reductions in production and consumption of material and energy sources, i.e., sufficiency (Rockström et al., 2021; Creutzig et al., 2022a). The prioritization of individual elements in bioeconomy strategies varies across stakeholders (Hausknost et al., 2017; Stern et al., 2018). Scientific debates have focused on substitution and efficiency gains, while sufficiency options in a bioeconomy have received much less attention, especially with regard to their social feasibility (Schipfer et al., 2024).

Many factors influence the climate impacts and sustainability of wood harvest and use, illustrated by red triangles in Figure 2.8. The mitigation effect of wood use ultimately results from the interplay of three major elements: (i) Changes in C-stocks in forests due to wood harvest, (ii) changes in socioeconomic wood pools (harvested wood products), and (iii) the substitution of emission-intensive products and services with wood products (see also 2.A.13). There is a large body of literature assessing the interplay of these elements (Bhan et al., 2021; Cowie et al., 2021), which in principle suggests two different approaches (see Box 1.1 in Formayer et al., 2024b, for a detailed comparison). One quantifies actual (observed) GHG emissions over time (e.g., the UNFCCC emissions account scheme; see 2.A.5) (Jandl et al., 2024c), while the other compares different counterfactual scenarios and calculates substitution effects as well as 'carbon opportunity costs' (Norton et al., 2019; Erb et al., 2022; Fehrenbach et al., 2022; Soimakallio et al., 2022; Peng et al., 2023).

The climate effect of substitution is particularly complex to assess (Formayer et al., 2024b, Box 1.1). In direct comparisons, the substitution of biomass for fossil fuels appears to be disadvantageous for biomass in terms of emission reduction, due to its high carbon emission factor. The combustion of solid biomass releases about 29.9 tC/TJ of carbon stored in the biomass, compared to 17.2 tC/TJ for natural gas liquids, 20.2 tC/TJ for diesel oil, and 27.6 tC/TJ for lignite. These 'smoke-stack' comparisons do not take into account the renewable nature of biomass and therefore provide only partial insights (Cowie et al., 2021). More comprehensive accounts therefore consider all greenhouse gas fluxes in ecosystems and society. The comparative climate impact of biomass use then depends on the actually achieved reduction of the product or process under consideration (substitution), which often is jeopardized by overcompensation and rebound effects (York, 2012; Harmon, 2019; Leturcq, 2020), as well as on the comparative emissions impact of the respective material or energy use. The latter is shaped by both the emissions intensity of the substituted product or process and the emissions impact of additionally harvested biomass, both of which are variable over time (Buschbeck and Pauliuk, 2022). Global results show that in many cases, natural succession of ecosystems has a more beneficial climate impact than growing crops for bioenergy – second-generation bioenergy production compete over natural succession only when the displacement factor is very high, i.e., when very emission-intensive processes are substituted (Kalt et al., 2019). Once wood is harvested, extending the lifetime of wood products (e.g., using wood in buildings rather than burning it as bioenergy) reduces their climate impact, because carbon is stored in socio-economic structures for some time before it is released to the atmosphere (Allianz Nachhaltige Universitäten in Österreich, 2021). However, comparing the relative climate impacts of using versus not using wood is particularly complex, because long-term stock-flow dynamics in both ecosystems and socio-economic structures affect the net emissions impact (Seppälä et al., 2019). Results for Germany point to the high temporal variability of displacement factors for wood use (Buschbeck and Pauliuk, 2022). Thus, the relative performance of different wood use strategies depends on the temporal scope of analysis and planning (*medium evidence, high agreement*).

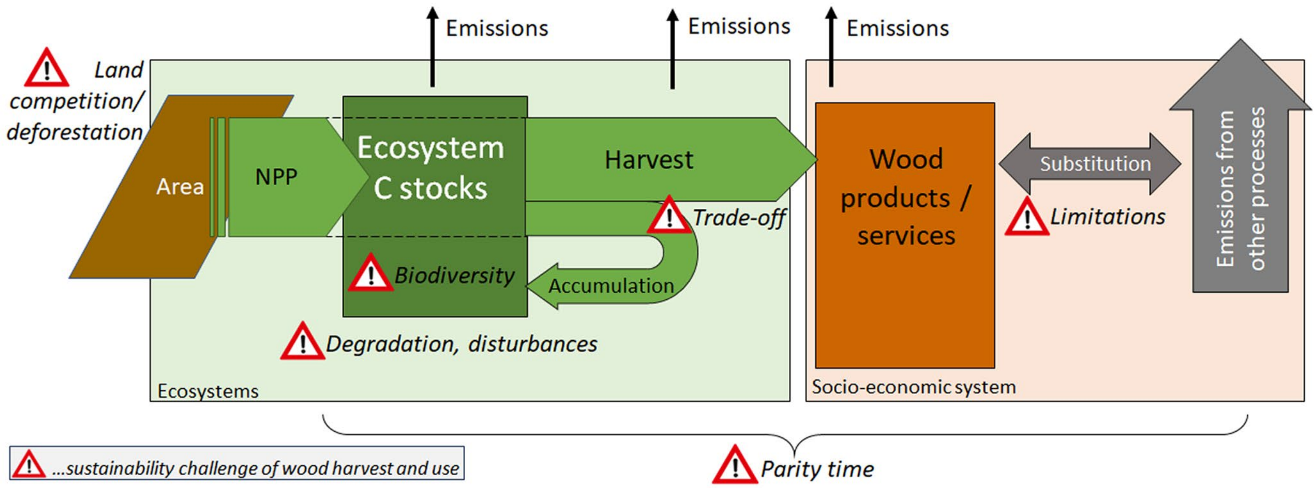



Figure 2.8 Carbon stocks and flows related to wood use and associated sustainability challenges. NPP refers to Net Primary Productivity.

There is no comprehensive assessment of displacement factors for Austria. Some researchers focus on the beneficial potential of providing biomass to substitute fossil fuels and abiotic materials and creating socio-economic carbon pools in harvested wood products (Braun et al., 2016; Jandl et al., 2018), while others argue that, particularly in the short term, wood harvest should be constrained to maintain net forest carbon sequestration due to the lack of readily available alternatives for carbon removal and to enhance biodiversity in forests (Bellassen and Luyssaert, 2014; Searchinger et al., 2018; Luick et al., 2021; Erb et al., 2022; Norton et al., 2022). For a description of contrasting positions and their main arguments, see Box on climate neutrality of wood use in Chapter 1 of the APCC Special Report on land use and climate change (Formayer et al., 2024b).

The overall global climate impact of wood use in construction and buildings is currently debated in the literature, with very optimistic (Mishra et al., 2022) and more cautious estimates coexisting (Johnston and Radeloff, 2019). However, there is consensus that from a climate change mitigation perspective, material uses of wood are favorable over energy uses (up to a factor 2 in a centennial perspective), as this result appears in practically all modeled conditions (Braun et al., 2016; Kalt et al., 2016; Fehrenbach et al., 2022). Furthermore, the 'cascading' use of wood is a powerful strategy, emphasizing that wood should first be used for material purposes – ideally over long periods – and only burned or pyrolyzed at the end of the product's lifecycle (*high confidence*) – although interpretations of what 'cascadic' means in practice vary across stakeholders (Ludvig et al., 2021). Estimates of the mitigation potential of using wood for materials rather than energy range from 0.1 to 0.5 $MtCO_2eq/yr$ (Braun et al., 2016; Kalt et al., 2016) (see Table 2.3 and 2.A.16 for individual studies). The lifetime of wood use varies across product categories (Braun et al., 2016), and increasing lifetimes can result in higher wood shares in a given product category, thus leading to C accumulation in socio-economic stocks. Longer lifetimes of wood products may also allow for lower annual wood demand and thus lower harvest volumes. Increased material wood use and increasing shares of long-lived products (as opposed to, e.g., wood bioenergy use) contributed to a long-term increase in the pool of harvested wood products of 115 MtC between 1830–2010 in Austria, while forest C pools increased by 240 MtC over the same period (Gingrich et al., 2016). For future trends, Braun et al. (2016) project a continuation of C accumulation in harvested wood product pools until 2100, corresponding to 180–350 $MtCO_2eq$ across scenarios. In their assessment, forest C stocks will increase in the scenario with less wood extraction, and decline in the scenario with higher wood extraction, while conversely, the effects of product substitution will be higher when more wood is used. Substitution effects are subject to time dynamics, and their mitigation effects decrease with the decarbonization of the economy (Buschbeck and Pauliuk, 2022; Jandl et al., 2024b).

In particular, the increased use of timber in construction, a sector which is currently responsible for 8 % and 14 % of Austria's $CO_2$ and material footprint, respectively (BMK, 2020), can both substitute highly emission-intensive products (e.g., steel) and remain in use for particularly long lifetimes, i.e., decades or more. However, if increased construction timber cannot be derived from current domestic wood processing chains, it would require more imports. In global assessments, there is *high confidence* that a shift towards more construction timber would require large-scale land use changes and intensive tree plantations (e.g., Hertwich et al., 2019; Mishra et al., 2022). For Austria, Kalt (2018) estimates that by ramping up the share of wood in residential building construction to 50 % (from currently 22 %), the C-stock expansion in timber buildings could amount to 9.2 MtC by 2050, and further savings of 2–4.2 MtC would be realized by substituting emissions for the provision of mineral construction materials. Kalt (2018) considers such a scenario theoretically feasible and without impact on international forest C pools (due to increased harvest volumes), as the additional wood demand would remain far below Austrian sawn wood and panelboard exports. However, the absolute emissions impact of using wood in construction depends on the carbon impact of wood harvesting on forests and the emissions intensity of the construction sector (Buschbeck and Pauliuk, 2022); a recent study for Austria finds that the climate change mitigation effect of increased wood use in buildings is in most cases overshadowed by the forgone carbon sink (carbon opportunity costs) in forests (Maierhofer et al., 2024) (see Section 3.2.2). Currently, stakeholders from the wood sector do not consider an increase in the share of timber in residential construction to be likely, because of institutional constraints (Vihemäki et al., 2019). In addition to wood, other bio-based materials have been proposed for sustainable construction, such as mycelium, hempcrete, flax boards, straw, and reed (Yadav and Agarwal, 2021), but no assessment is available for Austria.

In addition to increasing the share of wood in construction, further emissions could be avoided in the residential sector through demand-side (or sufficiency) strategies (see Sections 3.3.1 and 3.2.2): In a global meta-study, Creutzig et al. (2022a) quantify the potential reduction of emissions through building design, size and use at 25 % (10–40 %) of global residential emissions. Kalt (2018) includes a scenario of moderately declining per-capita floor space, but the additional emissions savings potentials that might be realized through demand-side strategies, such as ending the decline in household size (Ivanova and Büchs, 2022) or fostering co-housing (Ivanova et al., 2020), have not been systematically quantified for Austria.

After its lifetime, timber from demolished buildings can again serve as raw material for material or energy use. Kalcher et al. (2017) quantify scenarios for Austria and find that, in their ‘standard’ scenario, the amount of wood available annually from the demolition of residential buildings alone will double by 2100. However, they also stress the poor data availability on residential buildings in Austria.

Bioenergy use has increased in recent years and is currently the largest renewable energy use in Austria, accounting for 247 PJ, or 17.3 % of total primary energy supply, while the fraction in domestic primary energy production is 47.5 % (BMK, 2023). Increased use of bioenergy, as the last step in the wood use cascade, and derived from agricultural residues, can play a certain role in achieving renewable energy targets (*robust evidence, medium agreement*). The APCC Special Report on land use and climate change (Jandl et al., 2024c) concludes that no reliable estimate on sustainable bioenergy potentials can be made at present due to the many trade-offs that are difficult to account for. In the existing literature, bioenergy potentials for Austria are estimated to reach 310–420 PJ by 2030–2050 (Krutzler et al., 2016; Anca-Couce et al., 2021), but these estimates do not explicitly consider system-level interactions between wood harvest and forest biomass stocks (Erb et al., 2016; Olsson et al., 2019; Pingoud et al., 2018). For instance, Kalt et al. (2019) show that at the global level, in terms of climate change mitigation, bioenergy from short rotation coppice is only competitive with natural succession on abandoned agricultural land over longer time frames (>30 yr) and with high displacement factors.

Measures to save energy, such as insulation in residential buildings, have been described as being favorable over increased bioenergy use (Peng et al., 2023; Jandl et al., 2024c). Through efficiency gains and insulation, the demand for wood energy can be reduced in absolute terms: Kranzl et al. (2018) estimate that by 2050, wood in residential final energy use will decrease by 25 % compared to 2020, as building renovation reduces overall energy demand for residential heating. There are knowledge gaps regarding the future supply of timber in Austria, integrating the complex interplay between, on the one hand, climate change and forest management choices that impact the composition of tree species, and on the other hand, technological change or adaptation in the milling industry that might change the use or processing potentials of different wood qualities. Furthermore, inter- and transdisciplinary collaboration will be required to robustly assess the potentials and impacts of sufficiency measures in the context of bioeconomy strategies (Schipfer et al., 2024).

### 2.3.3. Nature-based (climate) solutions

#### Nature-based solutions to increase the carbon sink of managed ecosystems

Nature-based Solutions (NbS) are actions that protect, sustainably manage and restore natural and modified ecosystems to provide multiple benefits for human well-being and biodiversity (Cohen-Shacham et al., 2016; Keesstra et al., 2018; Oral et al., 2020). NbS have large potential benefits for the mitigation of and adaptation to climate change (*high confidence*).

Under certain conditions, land ecosystems can take up carbon and thus counterbalance the accumulation of $CO_2$ in the atmosphere. Besides soils, woody biomass is the largest carbon pool in terrestrial ecosystems both in Austria and on a global scale (Jandl et al., 2024c). Woody vegetation, particularly in forests, has acted as a net carbon sink in Austria since the 19th century (Gingrich et al., 2016, 2022), due to both the expansion of area under woody vegetation and the increase of timber stocks in existing forest areas. Timber stocks in existing forests increase due to an increase in average age. This occurs in protected forests, but also in managed forests if management intensity is low (e.g., as observed in small-scale forest ownerships). There is *high confidence* that both the expansion of woody area and the increase in timber stocks continue to have potentials for future carbon sequestration, but are constrained by ecological limitations and land-use competition (Jandl et al., 2024c). At the same time, they may have co-benefits with biodiversity (Oettel and Lapin, 2021).

Adapting forest management can contribute to reducing the gap between actual and potential biomass stocks (*high confidence*) (see Chapter Box 2.2). The effect has been quantified globally (Houghton and Nassikas, 2018; Cook-Patton et al., 2020; Walker et al., 2022; Mo et al., 2023; Roebroek et al., 2023), but not for Austria. For Austria, Braun et al. (2016) find that in a scenario of reduced timber extraction from all forests, the overall cumulative mitigation potential in the forest sector would range between 600 and 800 $MtCO_2$ until 2100, compared to any scenario of increased wood use. This difference comprises an increase in the forest sink of 1100 to 1300 $MtCO_2$, a decrease in the HWP sink of 100 to 200 $MtCO_2$, and a decrease in avoided emissions from fossil fuels of 300 to 400 $MtCO_2$. A similar finding is presented in Weiss et al. (2020) (see also Kirchmeir et al., 2022). In order to achieve a net mitigation effect, the reduction in wood harvest in Austria needs to coincide with strategies to reduce the overall material and energy use and to limit imports (at the EU level), to avoid leakage of wood harvest to other countries and an increased use of other materials and fuels (Meyfroidt and Lambin, 2009; Meyfroidt et al., 2022). According to the Weiss et al. (2020) study, between 2020 and 2150, the contribution of the forest-based sector to national GDP under a reduced harvest scenario would be about 80 % of the contribution under a reference scenario. This corresponds to ca. EUR 1.77 billion less per year, for an average mitigation effect of 7 $MtCO_2$/yr over the same period, i.e., ca. EUR 250/$tCO_2$ (Weiss et al., 2020).

Expanding the forest area in Austria is theoretically possible. Forests currently cover 48 % (2016/2021) of the domestic land, compared to 38 % in 1935 according to the Forest inventory (Waldinventur). Since 1981/1985, forest area has increased mainly due to the expansion of non-managed forests, by 0.135 Mha as opposed to 0.023 Mha for managed forests (Haszprunar et al., 1989). In addition, there are areas covered by trees that are not counted as forest. Due to competition with other land uses such as agriculture, the realistic potential of forest expansion appears to be limited, if demand for agricultural area is not reduced (Kraxner et al., 2024). See Table 2.3 for mitigation potentials of afforestation enabled by a protein transition and reduced food losses. The extent to which forest expansion is considered in climate-change mitigation scenarios is sometimes not explicitly quantified (e.g., Kirchner et al., 2016). But it can be assumed that the C sequestration effect of afforestation is small for time frames up to 2040. Increasing the area under trees in agricultural and urban settings, e.g., through agroforestry and urban trees, could contribute to sequestering additional C in managed ecosystems, with reported values for aboveground carbon storage ranging from 11–27.4 tC/ha in cities and up to 67.5 tC/ha in agroforestry systems (Nowak and Crane, 2002; Strohbach and Haase, 2012; Dorendorf et al., 2015; Bertsch-Hoermann et al., 2021; Golicz et al., 2021). If adequately implemented, such measures can achieve co-benefits for health, biodiversity and climate change adaptation (APCC, 2018; Jandl et al., 2024c) (*medium evidence, high agreement*). Biodiversity impacts can be positive when natural ecosystems such as mires and forests are restored, and negative when extensively-used agroecosystems are intensified or replaced by plantations (see Cross-Chapter Box 6). Expanding fast-growing tree plantations on previous cropland is one way to increase carbon pools, as they accumulate biomass very rapidly (Gonçalves et al., 2021) and increase the average carbon density per unit area compared to cropland. This can be done for example with energy plantations such as coppice forests of pure even-aged stands of fast-growing species, managed with a high density in very short rotations, sometimes fertilized and/or irrigated (Stojanović et al., 2017). Trade-offs with food production are possible. Highly pure or mixed even-aged forests managed only for carbon sequestration without considering the quality of timber and associated higher market prices (e.g., applying thinning from below, not removing forked or damaged trees of poor quality, maintaining wood of trees species with low market price) often do not meet the management objectives of forest owners. Compensation payments to forest owners have been shown to increase interest in biomass production for carbon sequestration (Ovando et al., 2019; Winkel et al., 2022).

Agroforestry has a medium potential to mitigate climate change (*medium evidence, high agreement*). Agroforestry systems currently cover 1.9 % of used agricultural land in Austria, dominated by sylvopastoral systems (Den Herder et al., 2017). Converting subalpine grasslands to sylvoarable systems can result in carbon sequestration, but reduces harvest due to reduced biomass growth under tree cover: In the Austrian Eisenwurzen, a scenario analysis found sequestration rates of 3.4 tC/ha/yr by 2050 while yields were more than halved (Bertsch-Hoermann et al., 2021). There is no assessment of biomass carbon pools in agricultural hedgerows for Austria, but a study for the Netherlands (Van Den Berge et al., 2021) concludes that trees in hedgerows show high and persistent increments of 0.7–4.3 tC/km/yr in stems alone, with basal areas of 22.1–44.9 $m^2$/km. Their exclusion hence represents a major gap in national greenhouse gas inventories. However, no time-frame is given for this estimate. Wenzel et al. (2023) quantify the effect of hedgerows on SOC in top soils in Upper Austria, and show that SOC increases under hedgerows for decades, albeit at declining rates, resulting in higher SOC of 16–106 MgC/ha and 35–119 MgC/ha under hedgerows aged 1–30 and 31–70 years, respectively.

There is an ongoing debate, *with medium evidence* and *low agreement*, whether it is more advantageous to combine forest production and pasture (by cattle) on the same area (forest pasture) or separate the two land uses by creating open pure pasture areas and allowing the surrounding forests to become increasingly dense and enhance the carbon sink (Stöckli, 2013). On the one hand, the heterogeneous forest structure typical of forest pastures has positive effects on species and landscape diversity, as well as on tourism (Schirpke et al., 2019; Anderle et al., 2022). On the other hand, the forest pasture reduces the growth and yield of the forests, hampers the successful natural regeneration of tree species, and can cause damage to the residual trees, making them vulnerable to pests and diseases (Noack et al., 2010) and reducing the potential carbon sink. Conflicts of interest emerge between agriculture, forestry and tourism when cooperation between actors and interest groups is limited (Johann, 2013).

The potential for carbon sequestration through rewetting of agricultural peat soils and uncertainties about the actual amount and use of agriculturally used peatland represent research gaps. The national greenhouse gas inventory reports 13,000 ha of organic soils in the category ‘grassland remaining grassland’ (Umweltbundesamt, 2024).

### Nature-based solutions to adapt to climate change and disaster risk reduction

Nature-based solutions are not only linked to climate change mitigation, but also entail multiple synergies and co-benefits for ecosystem services, contributing to multiple global agendas, including disaster risk reduction, climate change adaptation, and sustainable development (Martin et al., 2021). There is *high confidence* that taking advantage of nature-based solutions (NbS) helps to mitigate the negative impacts of climate change in urban settings and make cities more resilient to environmental changes (Faivre et al., 2017; Lafortezza and Sanesi, 2019). Urban forests, parks or simply tree-lined streets – urban greens in general – are known to facilitate adaptation to climate change in terms of temperature and water budget regulation (see urban heat islands in Section 3.2.3). Urban greening must consider climate-resilient tree species that can cope with future conditions to secure its benefits (Foldal et al., 2022). For example, non-native tree species already present in the urban Alpine area of Austria and neighboring countries were recorded and assessed for their drought tolerance (Herbsthofer et al., 2020). However, in terms of climate change mitigation, the contribution of urban green strategies remains small to moderate (Strohbach and Haase, 2012; Ariluoma et al., 2021) unless further indirect effects on avoided energy demand for cooling buildings are considered (Quaranta et al., 2021). See Section 3.2.2 for such indirect effects related to the built environment and urban planning.

Nature-based solutions entail strong health co-benefits (*high confidence*). In particular, increasing the number, distribution and density of green trees in urban areas improves urban public health and well-being of urban populations and contributes to sustainable living in terms of positive effects on humans, microclimate, soil and biodiversity (Haluza, 2024; Spörl et al., 2024). Nature-based solutions also support several ecosystem services and their health co-benefits described in Section 2.2 (food security, air pollution, psychological health, etc.).

Beyond urban areas, the development of near-natural areas increases the possibility of migration of plants and animals and thus also of pollinators, counteracting the negative impacts on pollination. There is *limited evidence*, but *high agreement* that nature-based adaptation measures such as the restoration of wetlands, revitalization of rivers, no-tillage and cover-cropping in agriculture, and urban green gardens may restore natural flood control capacity – by providing retention space and improving soil water holding capacity (Seddon, 2022). Despite several decades of experience with river restoration, evidence on its effectiveness is limited, as evaluation is difficult due to the context specificity of projects and realizations at diverse scales with differing objectives (e.g., Kurth and Schirmer, 2014 for Switzerland; Nilsson et al., 2016 for other European instances). Moreover, implementation is still often obstructed by the path dependencies of gray measures, such as straightened riverbeds, which have long lifetimes and are costly to reverse (Hanger-Kopp et al., 2022; Seebauer et al., 2023).

### Chapter Box 2.2. Carbon sequestration potentials of forests

Forests cover 48 % of the Austrian territory, of which 83.7 % are commercial forests. As forests are able to accumulate and store substantial amounts of carbon (Erb et al., 2018; Arneth et al., 2019), their potential to sequester atmospheric carbon dioxide and provide carbon sinks is relevant for the national GHG budget (Umweltbundesamt, 2023a; Jandl et al., 2024c). This box discusses the conditions for long-term carbon storage and the underlying assumptions needed for estimation. It (i) quantifies current stocks and their historical development, (ii) introduces management strategies to maintain and increase stocks, (iii) discusses theoretical and observed carbon densities, and (iv) examines the pathways to arrive at such quantities. For simplicity, land conversions (land use change to forests or from forests to other uses) are not considered here.

The C budget of forests is characterized by stocks and by stock changes. We only consider above- and below-ground woody biomass, including deadwood, since additional carbon pools such as soil organic carbon are still poorly understood (Le Noë et al., 2023b). Stock estimates (Table 2.1) are derived from the volumetric data of the Austrian Forest Inventory using an average conversion factor of 0.345 tC/m³ (2.9 m³=1 tC), a factor taken from 1990 forest inventory data as converted to total carbon (including branches, leaves, roots) by Umweltbundesamt (for 1990, 973 million m³ and 339 MtC) and which we maintain here for all comparisons. Stock changes reflect C uptake from the atmosphere (e.g., increment) and biomass C removal (harvest, decomposition and depletion). In Austrian commercial forests, the forest C stock increased from 80.7 tC/ha in the period 1961–70 to 121.0 tC/ha in 2016–18 (Gschwantner, 2019) (*high confidence*). This increase is the result of removals being lower than increment in most years (Figure 2.3).

Forest management options aimed at maintaining forest functions include selective cutting (both thinning and harvesting) as well as tree planting. Management may be directed to favor growth (to extract forest products, but also to remove atmospheric $CO_2$ efficiently), which requires relatively young forests (60–140 years) and management interventions such as 2–3 thinnings before the final harvest. By contrast, management can also aim to maximize carbon stocks in forests, by selecting tree species that can accumulate high stocks and have low damage risks, by making thinnings to allow long rotation times, making the final harvest before reaching the degradation phase and keeping regeneration times short.

In order to estimate C sequestration potentials, it is important to understand (although challenging to assess) what carbon densities can eventually be achieved in forests. Ecological considerations originate from biophysical principles using parameters such as the net primary production (Saugier et al., 2001) and applying the 'potential vegetation concept', i.e., the vegetation that can be expected under current or pre-industrial climatic and soil conditions, as a benchmark (Erb et al., 2018; Bastos et al., 2021). Actual biomass stocks are understood to be depleted due to the removal of organic material, such as wood or deadwood, and this depletion establishes a stock gap. Global studies of existing forest biomass stocks at the landscape level report that their carbon storage is 24–39 % below the natural potential in the temperate zone (Erb et al., 2018; Walker et al., 2022; Mo et al., 2023).

Data from existing primeval forests in Europe help to quantify this natural potential. Such forests are sparse and small, so results are uncertain and only partially representative. In a meta-study, Keith et al. (2024) present data from 18 sites in Central Europe characterized as primary forests (none in Austria). Several of these sites had carbon stocks exceeding 200 tC/ha, and only 3 sites had less than 150 tC/ha. For the Bialowieza forest in Poland, potential vegetation has been estimated at 189 tC/ha, while current C stocks are considered to be 123 tC/ha, even though the forest has been left unmanaged for centuries (Matuszkiewicz et al., 2021). In Austria, the small area of Rothwald showed an average stock of 175 tC/ha (timber stock decreases of more than 44 tC/ha were observed during a wind throw in 1966) while surrounding managed stands had 266 tC/ha (Schrempf, 1986). Similarly, the Bavarian Forest National Park (Nationalpark Bayerischer Wald) exhibits lower timber stocks (without deadwood) of 96 tC/ha in the unmanaged core zone, compared to 138 tC/ha in the managed zone next to the core zone (Heurich and Sinner, 2005).

Optimum management options from a forestry perspective have been outlined by Zeide (2004), differentiating between optimizing for harvest or for carbon stocks. A steady-state of forest development needs to cover the carbon pool in all stages of the forest cycle at the landscape scale, as well as site- and tree-specific growth and mortality rates caused by disturbances or due to physical age limits of trees (Wirth et al., 2009; Oettel et al., 2020; Ehbrecht et al., 2021; Kobler et al., 2024). Management decisions allow a managed forest to exceed the C storage of potential vegetation. Specifically, the planting of selective tree species (Douglas-fir, *Pseudotsuga menziesii*) (Spannlang, 2022) or the possibility to minimize calamities (Vanomsen, 2006; Kautz and Delb, 2023; Hurteau et al., 2024) are essential factors to increase carbon stocks beyond primeval forests.

C sequestration potentials have been quantified either as a carbon gap to an ecological potential or as an impact of forestry management. There is *robust evidence*, but *low agreement* on which approach is appropriate. When quantifying a C sink, it is not important whether that sink is man-made or natural. The difference becomes relevant for specific management decisions, and for the longer-term robustness of such a sink. The temporal aspect is also decisive for sink dynamics. Luyssaert et al. (2008) show that also old-growth forests further accumulate carbon over centennial time spans (which could explain differences to the potential C stocks observed by Matuszkiewicz et al. (2021)), despite disturbances and calamities (wind, insects, fire). Thus, C sequestration will also occur at the same time scale of centuries.

Specific modeling of such developments over time for Austria in the CareforParis study (BFW, 2020; Ledermann et al., 2022) estimated a peak stock of 193 tC/ha by 2130 for an RCP8.5 scenario (GWL 4.34°C for 2081–2100) assuming average extreme events combined with a management target to increase stocks. In contrast, in a scenario based on current management but with massive calamities, stocks were estimated at 55 tC/ha in 2150 (data presented includes standing deadwood). Here, calamities provide a decisive management risk, with potential impacts also for strategies aimed at maximizing C stocks. The lack of understanding of this risk is a research gap, which will remain challenging to close given the time scales of forest growth.

The above modeling approaches consider calamities as well as C-stocks in the form of standing deadwood. To put into perspective, in 2023, 1.03 MtC forest were destroyed by bark beetles and 0.74 MtC by windthrow (BFW, 2023), together about 0.4 tC/ha if evenly distributed over Austria's forested area. That is 2 ‰ of the biomass C stock, but around 20 % of the annual increment (see Figure 2.3b). The Austrian Forest Inventory measures 7.1 tC/ha deadwood for Austrian forests (Oettel et al., 2020), with values in the small areas of unmanaged natural forest reserves reaching 7.9–37.6 tC/ha, at half lives of several decades (Hararuk et al., 2020; Seibold et al., 2021), with large observed variation (Harmon et al., 2020).

Further challenges in estimating the future development of Austrian forests are related to the legacy of multiple uses in the past (Gingrich et al., 2007, 2021, 2022), which led to a dominance of spruce as a single tree species. Adapting forests to climate change requires, i.e., altering the tree composition (Wessely et al., 2024), which means replacing part of the existing forest stock. Using forests as carbon sinks adds to the complexity, especially if biodiversity is also taken into account (for diverging views on management impacts, see Luick et al., 2021; Jandl et al., 2024a). Assumptions about the use of harvested wood products to substitute more carbon-intensive materials or practices (Weiss et al., 2020) are excluded here and may conflict with the forests' C sequestration potential, see Table 2.3. For a systematic comparison of two differing perspectives on net C effects of forest management and wood use, see Box 1.1 in Jandl et al. (2024c).

## 2.4. Conflicts, lock-ins and enabling conditions – focusing on the example of agricultural land use

The land use system includes a network of actors, activities and institutions along the value chain, from production to food waste, embedded in ecological, social, political, cultural and economic contexts (Penker et al., 2023). Climate change and sustainable development are challenges to society that require action at local, national, transboundary and global scales. Forestry and agricultural legislation, urban and spatial planning, and nature conservation provide the (legal) framework for action and guidance. Climate change and environmental crises, partly driven by dynamics outside the land use sectors, can exacerbate existing conflicts or create new ones (Formayer et al., 2024b). Ongoing soil sealing and urban sprawl has been exacerbating the competition for and conflicts around biologically productive land (see Section 3.2.2).

Focusing mainly on the example of agricultural land use, this section looks into barriers, conflicts, and lock-ins as well as enabling conditions for a transformation. For illustrative purposes, forest-related literature is added in some parts.

### 2.4.1. Barriers, conflicts, and lock-ins

Land is a limited and scarce resource (Haberl and Erb, 2017). The land system, globally as well as in Austria (Formayer et al., 2024b), is coined by strong (intrinsic) trade-offs, target- and interest conflicts (*high confidence*). Land use, e.g., in forests and agroecosystems, has different societal functions, such as production, recreation, or nature conservation, entailing substantial goal conflicts (Bontempi et al., 2023). Moreover, people project different values onto land, from direct or instrumental use values to indirect or intrinsic values (Meyfroidt et al., 2022) and relational values (Leopold, 1949; Himes and Muraca, 2018).

The current specific allocation of the scarce resource land to different uses (Gerber et al., 2018) results from the interaction of a wide variety of stakeholders (land owners, land users, consumers, processors, retailers, public sector), natural site conditions, historical development, market conditions, and technological possibilities. Changes in the allocation of land use and the associated rights and duties to land have environmental, economic and societal effects bearing high conflict potentials. For example, maximizing the carbon sink through large scale reforestation might result in a fundamentally changed landscape and might negatively affect other ecosystem services such as food production or water provision (Jackson et al., 2005; Ferreira et al., 2018), and impact current land users such as farmers by decreasing or completely suppressing their current livelihoods. Such trade-offs are frequent in the land system (Meyfroidt et al., 2022). Negotiating the values and interests among stakeholders (Ellis et al., 2019), and measures to reduce the overall demand for certain ecosystem services (Haberl and Erb, 2017) can help to mitigate trade-offs. In contrast to the strong influence of sector-specific goals and interests, spatial planning struggles to fully assert its organizing and coordinating functions, significantly limiting its capacity to mitigate trade-offs across sectors and ensure climate-friendly decision-making (Svanda and Zech, 2023). There is *medium evidence* and *high agreement* that such trade-offs mostly affect less powerful, often also less wealthy, stakeholders (Howe et al., 2014; Pichler et al., 2022).

The outcomes of such land use conflicts are often reinforced by path dependencies and 'environmental amnesia' making them difficult to be reverted (Meyfroidt et al., 2022; Aigner et al., 2023). As noted in the APCC Special Report on land use and climate change (Jandl et al., 2024c), there is *high confidence* that a fundamental conflict unfolds between economic growth and environmental conservation. Under the current conditions of production and consumption, growing economic performance in Austria and worldwide is closely linked to increasing resource and energy consumption (BMK, 2020) and is associated with negative environmental impacts such as pressure on water resources, rising greenhouse gas emissions (at least in a multiannual average), biodiversity loss (Otero et al., 2020; Moranta et al., 2022; Santika et al., 2024) and soil sealing. This leads to an implicit preference for substitution-pathways and efficiency-pathways over conservation (restoration) or sufficiency pathways (Birch et al., 2010; Allain et al., 2022; Boyer et al., 2023; Eversberg et al., 2023; Fleischmann et al., 2024). However, there is *high confidence* that the effects of efficiency gains, including, e.g., yield increases, are often partly compensated or even overcompensated due to rebound effects, i.e., increases in consumption (Paul et al., 2019; García et al., 2020; Erb et al., 2023b; Haberl and Erb, 2023; Preinfalk et al., 2024).

In Austria, both, economic performance and resource and energy consumption are growing, albeit resource and energy consumption increase at a lower rate than GDP (relative decoupling) (BMK, 2020). There is *limited evidence,* but *high agreement*, that a climate-friendly land system cannot be achieved without fundamental, comprehensive structural changes, which involve industry and trade, technological innovations and individual approaches (IPCC, 2019a; Penker et al., 2023). The fundamental problem with regard to environmental problems is that landowners (e.g., farmers, forest owners) are not paid for delivering environmental services (as they are mostly public goods) and focus their production activities on private goods such as food, timber products, and recreation services (Cooper et al., 2009; Winkel et al., 2022). Long-term investment decisions by private actors (e.g., livestock housing) or cultural values and norms (e.g., on 'good farming' standards) can reduce the acceptance for alternative production systems. Consequently, the acceptance for environmentally oriented production is comparatively low, if not made mandatory or subsidized by the government. Fostering payments for ecosystem services, better monitoring of ecosystem supply and demand, enhanced policy integration, and improved bottom-up participation and learning among ecosystem service innovators are therefore important strategies (Winkel et al., 2022). Non-acceptance is often reinforced through lobbying by interest groups or even protests (Nature Food, 2024) of the respective sectors, which render it difficult to integrate climate and environmental policies with sectoral policies (Plank et al., 2021).

Difficulties might also arise to change the diverse drivers of current land use. One example is the apparent difficulty in reducing the share of animal products in diets, in Austria and in the EU as a whole, despite the apparent benefits and synergies between climate and biodiversity protection and human health (see Section 2.3.2). To avoid facing the conflicts related to a transformation towards less animal protein production and consumption, dietary change is often hidden behind consumer-narratives (Vermeulen et al., 2020; Duluins and Baret, 2024), preventing structural discussions on solutions to incentivize and support producers in the protein transition. A media analysis of three Austrian newspapers published between 2000 and 2019 shows evolving informal institutions, such as behavioral norms embracing meat-free or reduced-meat diets and no debates about changes in formal institutions, such as regulations and other policy interventions (Hundscheid et al., 2022). Hundscheid et al. (2022) attribute this lack of debates about changes in formal institutions to the deeply entrenched cultural significance of meat, which is actively defended by actors safeguarding the status quo. Kortleve et al. (2024) conclude that in the EU agricultural subsidy system, animal husbandry receives far more support (>80 % of all subsidies) than plant production. On the other hand, animal production, which is to a large degree export oriented, is of key economic importance and a significant reduction in animal husbandry would impact companies as well as numerous family farms. Farms are mostly faced with a small number of comparatively large retail chains and processors and consequently have little bargaining power in the value chain (Jäger et al., 2024), and consumers are mostly not prepared to pay the corresponding higher prices. Thus, while farmers often have to implement environmental and climate mitigation measures, they cannot simply pass on the resulting costs to retail chains or consumers.

The mechanisms of international markets are also relevant in this context. National regulations need to respect the European frame and international trade agreements (e.g., WTO), and the development of international competitiveness of the strongly export-oriented Austrian agricultural, forestry and timber sectors (see Section 2.1.1) is a key factor for the development of (environmental) regulations. A sole focus on consumer responsibility and market-based mechanisms would affect the social justice dimensions, i.e., the distribution of costs and benefits of the transformation towards climate-friendly structures. From a consumer perspective, there is *high confidence* that unhealthy foods or 'empty calories' (Tilman and Clark, 2014) are cheaper, more readily available, and also constantly featured in advertising compared to healthier alternatives, which contradicts a socially just transformation towards climate-friendly living and is associated with higher C-emissions on-average (Rao et al., 2013; Ravensbergen et al., 2015; Penne and Goedemé, 2021). A 'climate-social policy' aimed at exploiting synergies between reduction of social inequalities and climate change mitigation has not yet been formulated for Austria (Armutskonferenz et al., 2021). Structures of social inequality are key, for example for dietary practices (Penker et al., 2023), and can result in food poverty or obesity due to the unaffordability of healthy food in terms of quantity and quality (Bonaccio et al., 2012).

A further key sustainability conflict in the current land production system relates to working conditions (*medium evidence, high agreement*). Many economic activities related to the land system (production, processing, retail) rely on low or comparatively low wages and/or profits, and precarious working conditions are widespread (Penker et al., 2023). Additionally, the number of serious accidents at work is still very high in the Austrian agriculture and forestry, despite improved technology and prevention measures (Kogler et al., 2015). Barriers to the implementation of resource-conserving or emission-reducing measures often lie in higher labor or capital inputs, which increase production costs, and in reduced land productivity (Jäger et al., 2024), although this is not always the case (Fontana et al., 2013). In this context, it should be noted that farms in Austria are comparatively small and mostly run as family farms, where labor is usually a scarce resource.

Further barriers and lock-ins can be found in existing and contradictory policy frameworks and funding systems, within the CAP direct payments and even within agri-environmental-climate schemes (Kletzan-Slamanig et al., 2022; Jäger et al., 2024).

### 2.4.2. Enabling the transformation

A successful transformation strategy must consider all these barriers, conflicts and lock-ins, including the international nature of markets and policies. 'Climate-friendly' land use changes, e.g., in agriculture or forestry, affect not only land use and the land users themselves, but also society via several socially relevant public goods and bads (Sauvage, 2014). Many of these goods (e.g., agrobiodiversity, cultivated landscapes, recreation and experience in nature) and bads (e.g., nitrogen and phosphorus inputs resulting in greenhouse gas emissions or water pollution) have no market (as opposed to food, animal feed, timber, etc.) and are therefore not coordinated through market mechanisms (Cooper et al., 2009). (Agri-environment-climate) policy interventions represent a means to compensate for management and opportunity costs, as is already implemented in Austria, e.g., under the agri-environmental program ÖPUL. This program offers a broad range of measures aimed at mitigating greenhouse gas emissions and supporting agriculture in adapting to new conditions, such as greening, manure storage, or manure spreading. In the forestry sector, several CDR measures are also proposed to improve the overall mitigation, but there are no policy instruments in place to compensate forest landowners for potential financial losses and foster strategies to increase sufficiency, recycling and product-lifetime of timber products (Jandl et al., 2024b). Financial compensation for the provision of public goods or the avoidance of public bads provides income opportunities for land users, resulting in negative net taxes on farm production in Austria and other OECD countries – in contrast to positive net taxes in most countries of the Global South (Eastwood et al., 2010). For a successful transformation, social questions of poverty and inequality have to be effectively addressed at the national and international levels (Club of Rome, 2022; Hoffmann et al., 2024).

The Austrian Court of Auditors recommended the definition of quantifiable objectives, assessment indicators and the collection and use of data on the state and change of the environment for effective agri-environmental schemes – ÖPUL (Österreichischer Rechnungshof, 2013). According to the follow-up report, these recommendations were not or only partially implemented (Österreichischer Rechnungshof, 2016). In 2024, at the European level, the European Court of Auditors (ECA) identified a gap between farming incentives and the EU's green targets (European Court of Auditors, 2024). A key finding of the ECA is that, with the exception of organic farming, the European Commission will not be able to measure the contribution of the Common Agricultural Policy, which accounts for just under a third of the EU's total budget for 2021–2027, to its climate goals (European Court of Auditors, 2024). Therefore, a comprehensive provision of knowledge and information is a prerequisite for a successful transformation. Nevertheless, research efforts and innovations (such as agrivoltaics) are currently not well transferred to land use stakeholders. Education systems play a key role in ensuring that knowledge is passed on effectively, e.g., to farmers but also to consumers (Jäger et al., 2024). The development of suitable information and indicator systems is a key aspect and can be enhanced (Wolfslehner and Vacik, 2011; Grima et al., 2023). Austria-supported developments such as the further elaboration of the Agricultural Knowledge and Innovation Systems (AKIS) or the transformation of the European Farm Accountancy Data Network (FADN) into a Farm Sustainability Data Network (FSDN) are positive examples. However, providing information is hardly sufficient to steer transformations such as reducing the consumption and production of meat and avoiding food waste (Jäger et al., 2024). Further progress needs to identify and develop synergies between technological innovations (digitalization, precision farming or robotics), regional development and the mitigation of greenhouse gas emissions (Kraxner et al., 2024; Schipfer et al., 2024).

Austria lacks a systemic approach to sufficiency strategies, reducing consumption and production levels through avoid-shift-improve approaches (Plank et al., 2021)(see Sections 6.5.1, 6.5.4 and Table 6.2). Such an approach would take as its starting point the highly integrated, complex-dynamic nature of socio-ecological dynamics, acknowledging that land systems are cross-cutting and involve various policy areas (including environment and climate, health, agriculture, consumer protection). There is a need for a climate protection law that contains strategic targets in line with the Paris climate goals as well as effective sanction mechanisms and requirements for improvement in order to protect Austria's climate goals against regression (Hollaus et al., 2023) (*medium evidence, high agreement*) (see Section 6.2.3).

It becomes clear that only an integrative policy development allows for an orchestrated embedment of climate protection into various policy areas. International assessment reports conclude that food, energy and water security as well as biodiversity conservation rank high on the Agenda 2030 for Sustainable Development, rendering the promotion of synergies between and across sectoral policies a key strategy (IPBES, 2018). However, the current policy design and formulation in Austria is often sectoral. Moreover, the long-standing concentration of environmental and agricultural agendas in one ministry (2000–2020) has contributed to the concealment of potential conflicts of interest (Penker et al., 2023). Promising developments include a new organization on sustainable food (AGES, 2024) that bridges the three Ministries of Health, Agriculture and Climate, as well as the Sustainable Food Initiative by the Austrian Promotional Bank (AWS, 2024).

Abandoning the current attribution of responsibility for climate protection, which is largely placed on consumers by policymakers and businesses, has the potential to create enabling conditions for a sustainability transformation (Penker et al., 2023). Public food procurement (meals in schools, hospitals, canteens) or reducing taxes on plant-based foods are examples of transformative policies that can support the co-benefits for climate friendly and healthy food supply (see Table 2.A.4 for further measures along the entire food system). Ensuring the resilience and resistance of forests through diverse forest management practices, implementing integrative measures to maintain biodiversity and promoting payments for non-marketable goods and services are key elements for a sustainable transformation. The measures described in the report of the UniNetz initiative provide a wide array of measures in this direction (Vacik et al., 2022). Identifying and engaging with potential repercussions of climate policies on land users can enhance the legitimacy of such effective regime destabilizing measures and can thus contribute to resolving lock-ins (Hundscheid et al., 2024). An integrative food policy relies on combining different policy areas and has been shown to foster decentralized self-organization, entrepreneurship and social learning (Penker et al., 2023), which could open windows for transformative innovations.

Polycentric governance is proposed as an appropriate way to deal with resource management problems, in which decision-making centers take each other into account in competitive and cooperative relationships and have recourse to conflict resolution mechanisms (Arneth et al., 2019). Polycentric governance aims to open the scope of action for context-specific solutions and coordinated interaction between actors at different levels (local, regional, national, and global) and to foster decentralized self-organization, entrepreneurship and social learning. Such approaches have been shown to allow for flexibility and context-specificity in the light of the uncertainties inherent in, for example, the food system and for successful adaptation (*medium evidence, high agreement*) and require horizontal as well as vertical integration of policy areas or levels (Plank et al., 2021). The need for a common nutrition policy is discussed at both European and national level (IPBES, 2019; SAPEA, 2020; Penker et al., 2023), as is the need to use all governance instruments in the field of nutrition (SAPEA, 2020; WBAE, 2020). See Section 6.4 for more details on governance mechanisms.

A climate-friendly coordination between the production of food, feed, fiber and fuel, and between production, conservation and restoration can be supported by scaling up local land use planning to the regional or even to the national level (Svanda and Zech, 2023). Further suggestions from the spatial planning literature for achieving climate goals involve legal requirements for sectoral plans to contribute to climate-friendly structures, avoiding financial incentives for climate-harmful land use structures (e.g., commuter bonus 'Pendlerpauschale'), or new incentives for unsealing former industrial areas or parking lots (Svanda and Zech, 2023) (*medium evidence, high agreement*) (see Sections 3.2, 3.4, 6.5.1 and Table 6.2).

Environmental programs can reduce conflicts by financially supporting the provision of public goods such as climate-resilient soils, mitigation, biodiversity, and other land-based ecosystem services. However, utilitarian and transactional approaches to trade-offs are likely to depreciate the conservation of biodiversity and ecosystems, for example when forests are mostly used for timber production or carbon sequestration, neglecting a wide array of human–nature relations and associated values. New approaches are emerging to address trade-offs considering both social and ecological aspects and the values of different people, while counteracting uneven power relations among actors (Ellis et al., 2019). Other recent examples involve nature-positive scenarios based on the Future Nature Framework (Pereira et al., 2020).

Here, a research gap emerges as well: Chapter 6 of the APCC Special Report on land use and climate change (Jäger et al., 2024) concludes that in the field of emission developments of the LULUCF sector, there are hardly any cross-sectoral scenario analyses that quantify and map the different land use types and their feedbacks on other sectors for Austria (Jäger et al., 2024). This gap has not yet been filled, but such scenario analyses would be of great importance for the development of a climate protection strategy in the area of land use in Austria and for the analysis of possible land use conflicts between sectors.

Transforming or building new structures is seen as essential to achieving climate goals (Aigner et al., 2023). A holistic view of the agri-food sector, for example one that looks at farmers' land use decisions, the structure of the food industry, the retail sector and consumer demand in an integrated way (Meynard et al., 2017), proves to be beneficial (*high confidence*), as noticed in Chapter 6 of the APCC Special Report on land use and climate change (Jäger et al., 2024) and the APCC Special Report on climate-friendly living (Penker et al., 2023). Adoption also depends on whether the envisaged measures are in line with the values and goals of the farmers, foresters and other entrepreneurs (de Sainte Marie, 2014; Schermer et al., 2018; Walder and Kantelhardt, 2018) and if schemes exist to compensate land users for their additional expenses, since market compensation is often not given due to the public-good-character of ecosystem services.

Literature shows that substantial progress can be made when transformation pathways are developed together with the land users (Kraxner et al., 2017; Berthet et al., 2019; Meyfroidt et al., 2022). There is *high confidence* that stakeholder involvement in policy development is a prerequisite for effective implementation of climate policies (e.g., Renn, 2006; Newig et al., 2008; O'Faircheallaigh, 2010; Prutsch et al., 2018). For government policies to be effective in practice, their implementation by firms is a key precondition and thus needs a systemic design of government measures (requirements, processing, information, advice, documentation effort, conditions attached to subsidies) (Van Herzele et al., 2013; Darnhofer et al., 2017). Furthermore, it is important to note that many regulations that farmers or forest owners must adhere to are formulated not only by the government but also by private companies. Therefore, the establishment of a governance system that includes all participants in the value chain is essential, warranting a fair exchange of information and a balanced distribution of power within the chain.

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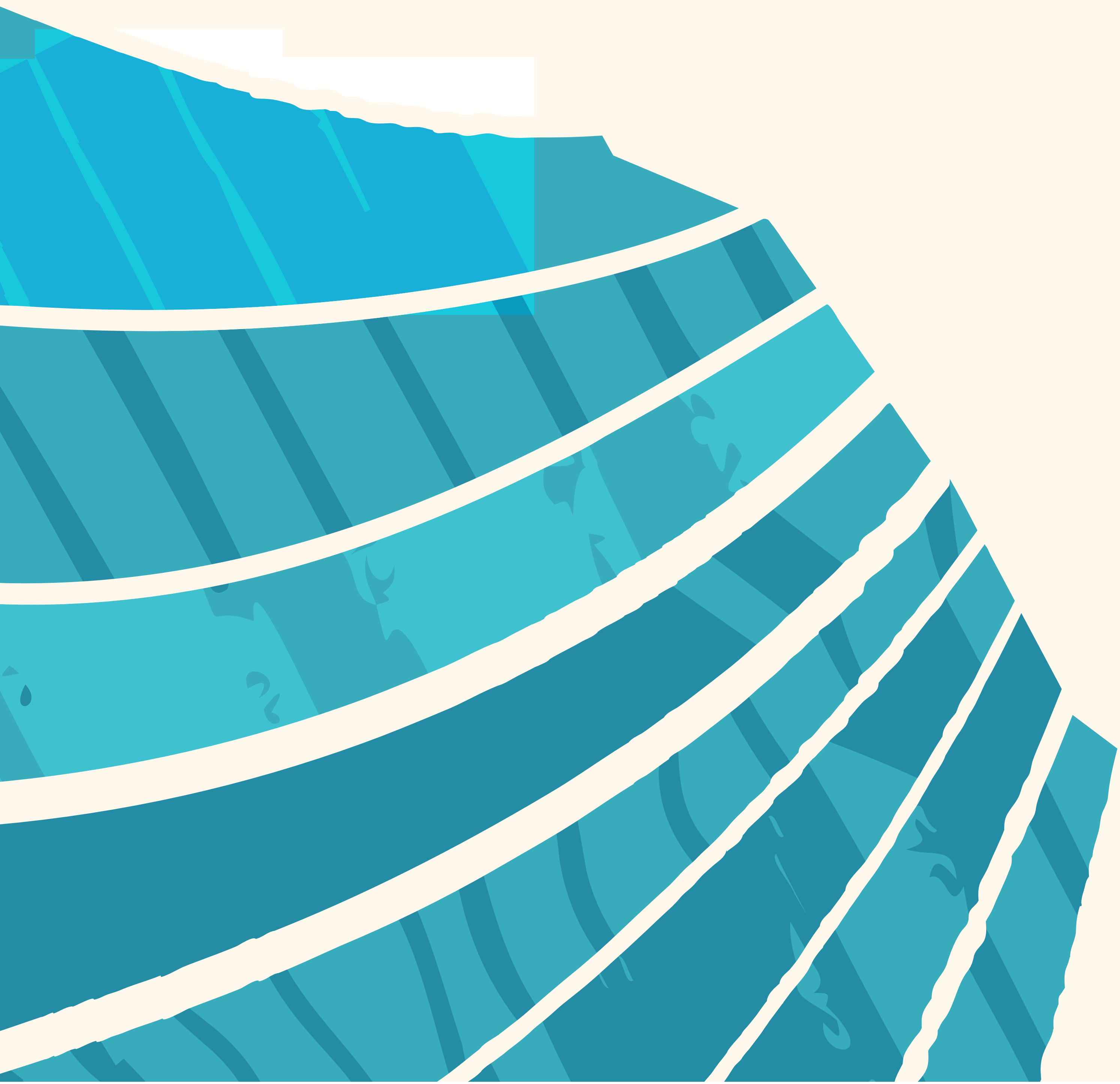
## Chapter 3

# Built environments and mobility



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## EXECUTIVE SUMMARY

**Buildings and transportation provide essential services, while direct energy use accounts for 36 % and 34 % of Austria's total end-use energy consumption in 2023, contributing 9 % and 29 % of total national greenhouse gas (GHG) emissions, respectively (*high confidence*).** Including indirect GHG emissions from district heating and electricity used in buildings and mobility (e.g., heat pumps, electric vehicles) in their respective sectors would increase these shares, accounting for 3.4 % (buildings) and 0.3 % (transport) of the total national emissions in 2022 (*high confidence*). {3.3.1, 3.4.1}

**Sustainable cities, villages, and settlements feature short distances for work, leisure, schools, and daily necessities as well as appropriate infrastructure for diverse modes of active mobility. Settlement areas have significant potential for GHG emissions savings, with urban households emitting about one-half to one-third of suburban ones due to smaller physical footprints, shorter distances traveled, and lower car dependency (*high confidence*).** 'Urban' and 'rural' here align along a continuum, with continued **suburbanization representing the most direct climate policy challenge.** This points to the need to avoid green-field development in favor of maintaining and fostering compact settlements (*high confidence*). {3.2, 3.4.2}

**Compact urban development and densification can be achieved by improved utilization of existing planning instruments and the development of strong multi-level governance and coordination (*high confidence*). Challenges include urban heat island (UHI) effects and preferences for single-family homes and car ownership (*high confidence*).** Addressing these deeply ingrained lifestyles – rooted in prevailing social norms and perceived convenience – is a crucial challenge for advancing decarbonization in the housing and transport sector (*high confidence*). {3.2, 3.4.2}

**Adapting Austria's built environment to climate change entails prioritizing resilient water management, greening initiatives for local ambient air cooling and water retention, protection of infrastructure from landslides and flooding as well as robust information, communication and early warning systems (*high confidence*).** This necessitates integrating climate considerations into spatial planning as well as building design guidelines and standards, including adaptable building codes and infrastructure regulations (*high confidence*). Localized limits to adaptation may arise under extreme warming scenarios (*low confidence*). {3.2.3, 3.3.3, 3.4.4}

**Absolute building GHG emissions decreased by about 43 % between 1990 and 2022, despite increases in the number and size of housing units (*high confidence*).** This decoupling was due to rapid deployment of renewable energy sources and district heating, better insulated buildings and less need for heating due to higher ambient temperatures (*high confidence*). {3.3.1}

**Main pathways for further reduction of building-sector GHG emissions include replacement of oil and gas burners by renewable energy driven systems, implementing air-heat recovery in mechanical ventilation systems, building retrofitting by further improving insulation levels, adopting circular design principles and the use of low-emission construction materials – while considering embedded environmental impacts across their entire lifecycle (*high confidence*).** Main uncertain countervailing factors stem from potential population growth – according to official Austrian projections – and a potential shortage of installers qualified to deploy transition technologies based on renewables. Climate change is projected to decrease heating and moderately increase cooling demand in buildings – reducing net energy consumption and increasing the need for combined heating and cooling systems (adaptation) (*high confidence*). {3.3.1, 3.3.2}

**Electrification of buildings and road transport – with heat pumps and electric vehicles pivotal – will lead to a dominant role for electricity as the main source of energy in both sectors (*high confidence*).** Supporting policies, regulations, and infrastructure investments are expected to accelerate this transition (*high confidence*). {3.3.1, 3.4.2, 3.4.3}

**Road transport accounts for 99 % of GHG emissions in the Austrian transport sector (excluding international flights), with freight transport contributing 35 % in 2023 (*high confidence*).** After peaking in 2005, GHG emissions in transport saw a steady rise from 2012 onward. Substantial reductions occurred only in recent years, beginning in 2020, largely driven by external factors such as the COVID-19 pandemic and Russia's invasion of Ukraine. Nevertheless, in 2023, transport-related emissions remained 42 % above the 1990 level (*high confidence*). {3.4.1, 3.4.3}

**An expected increasing demand for freight transport, combined with limited potential for rail modal shifts, and a still limited availability of competitive low-carbon trucking alternatives render it difficult to achieve full transport sector decarbonization by 2040 (*medium evidence, high agreement*).** {3.4.1, 3.4.3}

**A combination of 'pull' and 'push' measures provides the most effective strategy for decarbonizing transport and housing. Push measures, including higher fuel taxes or bans on fossil-fuel-based heating systems, are essential for creating disincentives for carbon-intensive choices. Pull measures – such as affordable public transport, improved cycling infrastructure, and incentives for building renovations or switching from fossil-fuel heating to renewable alternatives – further encourage behavioral change by improving the attractiveness of low-carbon choices. Pull measures can also help in improving the public acceptability of push measures, in particular by mitigating potential negative distributional impacts of push measures (*medium confidence*).** Aligned with the ASI (Avoid/Shift/Improve) framework, these measures can reduce demand for emission-intensive activities and construction (avoid), promote sustainable alternatives like public transport and heat pumps (shift), and improve efficiency through technological advances, such as electric vehicles, deep building retrofits, circular design and the utilization of low-emission materials – while considering embedded lifecycle impacts (improve) (*medium confidence*). {3.3.1, 3.3.2, 3.3.3, 3.4.2, 3.4.3, Cross-Chapter Box 4}

**Reduced dependence on motorized transport has multiple co-benefits and positive spillover effects: Lower energy and resource requirements for vehicle production and recycling, improved traffic safety, less noise and local pollution, improved public space quality due to parking and road space freed up for alternative uses (e.g., green space), and improved health through the use of active mobility (*high confidence*).** {3.4.1, 3.4.2, 3.4.3}

**GHG emissions from constructing, maintaining and renovating buildings and infrastructure present a major challenge (*high confidence*). Key levers to drive reductions are revised building codes, infrastructure regulations (e.g., minimum parking requirements) as well as tendering and procurement policies that take embedded emissions and circular design approaches into account (*medium confidence*).** {3.3.1, 3.3.2, 3.3.3, 3.4.4}

## 3.1. Chapter introduction

Climate change affects the built environment and transport, both via long-term trends (e.g., rising temperatures) and via extreme weather events like floods, droughts, and storms. Spatial planning, transport and building infrastructure are thus relevant for adapting to climate change and also play a crucial role in cutting greenhouse gas (GHG) emissions (Creutzig et al., 2015; Haberl et al., 2023). This requires a reconsideration of traditional village and urban configurations on the one hand, and building codes and mobility cultures on the other hand.

While assessing the sectors fundamental to the built environment and mobility in the context of climate change and sustainability, Figure 3.1 outlines the various, often interconnected disciplines considered. Hence, this chapter starts with a macro view of the impact of cities and settlements on the climate, and vice versa, as well as the potential to use spatial planning to reduce GHG emissions (Section 3.2). After detailing key developments and projections (Section 3.2.1), the chapter focuses on reducing land consumption in times of population and economic growth (Section 3.2.2), an important lever to lessen overall climate impacts and exposures, and impacts and risks of climate change within urban environments (Section 3.2.3). Section 3.3 focuses on buildings and their past, present, and future climate impacts and exposures from the perspectives of building technology and renewables (3.3.1), construction material (3.3.2) and legislation (3.3.3). Section 3.4 does the same for the passenger (3.4.2) and freight transport sector (3.4.3), as well as the related road and rail infrastructure (3.4.4). Notably for infrastructure, adaptation to climate change plays a crucial role. The spatial structure shapes behavioral choices, in particular with respect to buildings and mobility. Accordingly, urban and regional spatial planning, buildings and transport systems are closely related to demand-side climate change mitigation. Therefore, it is critical to understand household-level GHG emissions-footprints as linked to broader land-use, building, and mobility choices.

Chapter 3 is closely linked to the other chapters of the report. It builds on the estimates of Chapter 1 regarding changes in the frequency of extreme weather events in order to assess potential adaptations to climate change in spatial planning, buildings, and transport (infrastructure). The emphasis on spatial planning in Chapter 3 has implications for land available for other uses (agriculture, forests, etc.), which are the focus of Chapter 2. Chapter 3 and Chapter 4 are particularly related via the energy sector, as electrification is a

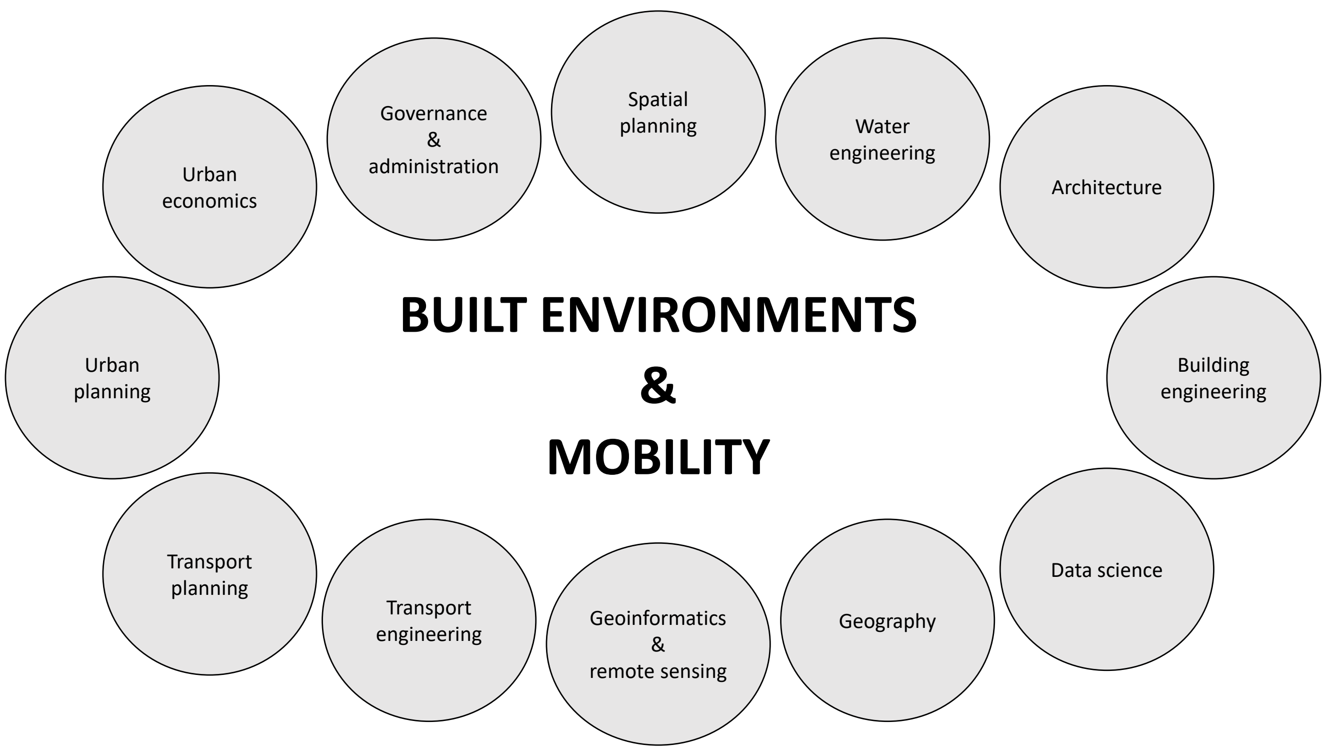



Figure 3.1 Disciplines involved in the study of climate change and solutions, specifically for climate change mitigation and adaptation, as considered in this chapter. Each discipline adds its own perspective and limits to the analysis. Given the complexity and open system nature of urban issues, it is necessary to consider and move between different perspectives.

main strategy for the decarbonization of the building and transport sectors. Further links exist to other topics of Chapter 4, including the volume of freight transport correlating closely with economic activities, tourism and work being a main source of travel demand, or teleworking as a form of work that does not require daily commuting. Links to Chapter 5 arise from demand patterns and lifestyle choices that impact the desirability and acceptance of different forms of housing and mobility behavior, and of different types of spatial surroundings; the distributional impacts of buildings, mobility, and spatial planning policies link these two chapters. Following the understanding of the recent IPCC report (Creutzig et al., 2022; IPCC, 2022b), demand-side mitigation includes both socio-behavioral shifts (the lifestyle domain of Chapter 5 of this report) and physical infrastructures as major modifiers enabling or prohibiting certain lifestyles (the domain of this chapter). Due to the involvement of different governmental levels (EU, national, provincial, municipal, local) in spatial planning, buildings, and transport, Chapter 6 provides an important governance/political context to Chapter 3. Chapter 7, meanwhile, intersects with Chapter 3 along multiple dimensions, including spatial and infrastructure planning, mobility, and buildings, as they are related to mountain regions. With its overarching focus on transformation pathways, Chapter 8 encompasses sectoral scenarios in particular for buildings and transportation.

## 3.2. Cities, settlements, and spatial planning

This section evaluates how urban areas and spatial planning influence climate change mitigation and adaptation. Section 3.2.1 discusses trends and projections in urban development, while Section 3.2.2 explores land-use strategies for reducing greenhouse gas (GHG) emissions. Section 3.2.3 focuses on climate risks to cities and settlements, addressing the resilience of infrastructure and adaptive capacity. Additionally, Chapter Box 3.1 highlights the 'Zukunft Linz' climate adaptation plan as a case study in urban resilience.

### 3.2.1. Cities and settlements

Cities and urban settlements are both impacted by and likewise directly contribute to climate change, via a host of interwoven demographic, economic, land use and infrastructural changes (Rosenzweig et al., 2010; Weichselbaumer et al., 2022). Worldwide, roughly 75 % of global GHG emissions come from urban and suburban settlements, attributable primarily to residential buildings, followed by commercial/industrial buildings, transport, and waste/sewage (e.g., Satterthwaite, 2008; Hickman and Banister, 2015).

Meanwhile, both Europe and Austria are experiencing continued urbanization: In Europe approximately 75 % live in urban settlements with more than 10,000 inhabitants today (UN DESA, 2019), a figure that is expected to rise to 83.7 % by 2050. Austria represents a lower rate of urbanization, at 59.2 % of its 8.7 million inhabitants (in 2019), expected to rise to 71 % in 2050, according to UN DESA (2019). Recent statistics show that the total population of Austria has increased to 9.2 million in 2024 (Statistik Austria, 2024b).

Further analysis points to the importance of a nuanced view of urbanization, e.g., drawing clear distinctions between the dense urban core with multi-family housing and efficient, multimodal transport infrastructure, and the continuing suburbanization at the urban periphery of larger cities and between cities and small(er) settlements, often with single-family housing and limited mobility choices (Steinegger, 2023). This increasingly pressures local administrations to ensure adequate, affordable, and climate-resilient housing while simultaneously expanding infrastructure to support more climate-friendly mobility (see Section 3.2.3). Divergent regional population growth rates call for detailed plans and planning instruments for both mitigation and adaptation, while also necessitating cross-regional coordination and management. The long-term nature of spatial planning creates particular urgency, given Austria's climate neutrality goal for 2040.

Climate change affects cities and urban settlements most directly via intensity and frequency of extreme weather events, including heavy rain fall, droughts, and heat (see also Section 1.2). Heat events are becoming more frequent in Austria (see Figure 3.2 for increase in hot days, i.e., with a daily maximum temperature over 30°C). This is of particular significance for the built environment, exacerbated by urban heat island (UHI) effects (Oke and Fuggle, 1972). Meanwhile, cold stress in winter is reduced by increasing temperature, as, e.g., illustrated in Figure 3.3, showing historic trends in hot and ice days in Vienna (see Section 3.3.1 and Section 4.5.2 for the impacts on space heating and cooling). These phenomena are exacerbated by continued surface sealing and loss of open and green space, which impairs natural cooling and water retention functions. There is wide regional variation in exposure, susceptibility, and coping capacities both across and within cities, especially those with

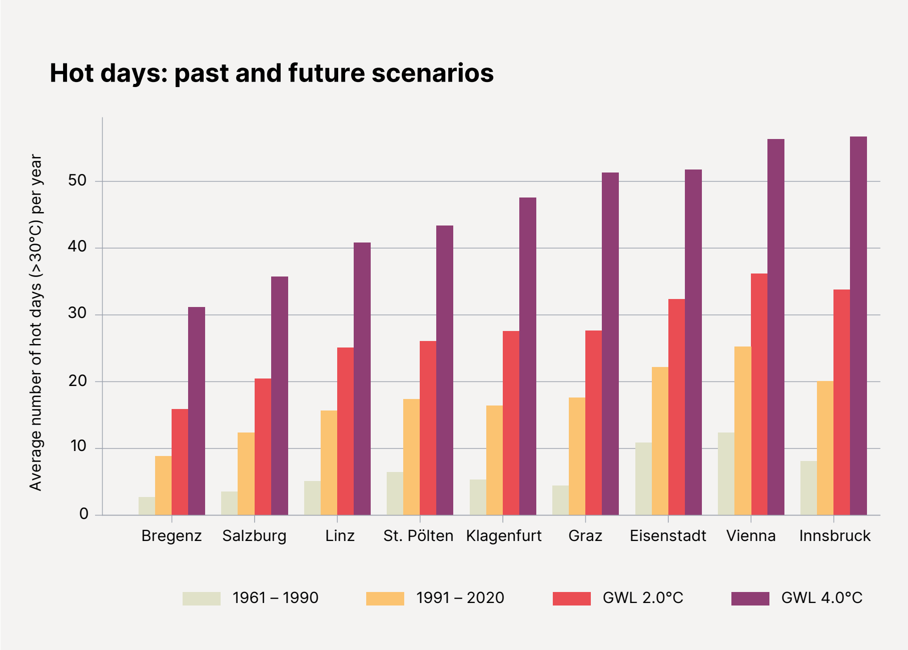



**Figure 3.2** Hot days yearly average in the nine provincial capitals measured in the past decades and forecasted for two different climate scenarios (with and without global climate protection measures, i.e., GWL 2.0°C and GWL 4.0°C, resp.) (GeoSphere Austria, 2022).

high socio-spatial differentiation, e.g., access to public transport and green spaces (Krellenberg et al., 2017). In Vienna, for example, socio-spatial inequalities have increased in the context of rising labor inequality and an uneven restructuring of the urban housing market (Kadi et al., 2022). There is some evidence of 'green gentrification', referring to the fact that the renaturation of urban spaces can lead to rising housing prices and socio-demographic upgrading, and thereby to the (in)direct displacement of underprivileged groups, who already suffer most from environmental injustices, in the private rental segment (Friesenecker et al., 2023).

Overall, detailed geospatial information on urban vulnerability in Austria is limited, with some exceptions, e.g., Linz (see Chapter Box 3.1) and Vienna (e.g., Weatherpark GmbH, 2021, with a grid resolution of 10 m). The 'Urban Heat Island Strategy City of Vienna' (Magistrat der Stadt Wien, 2015) demonstrates various actions and their implementation that reduce heat in the summer months, including strategic and technical measures, to improve micro- and neighborhood climates. The 'Heat Action Plan' (Stadt Wien, 2022) identifies 'vulnerable' people and groups, such as elderly and socially isolated people, people in need of care, people with chronic care-dependency, and people with chronic or mental illnesses, pregnant women, young children, or people living and working in particularly difficult conditions. The change adaptation in 'Graz Action Plan' (Stadt Graz, 2018) defines action fields but does not address vulnerable areas or place-based adaptation measures.

Making Austrian cities and the broader built environment 'climate-fit' involves both climate adaptation and mitigation efforts which are highly interwoven and need both be considered in integrated urban planning and development processes. Strong linkages exist to both, the transport sector (Section 3.4) and the building sector (Section 3.3), in terms of retrofitting existing structures and buildings but also to make efficient use of public space in terms of de-sealing, multifunctional uses and greening, which likewise enhance the quality of life in a broader sense. In addition, new development projects should be planned and designed from the ground up to be climate-fit by implementing integrated sustainable development approaches, thus contributing to the necessary sustainable urban transformations. Overall, compact cities with reduced mobility needs through short-

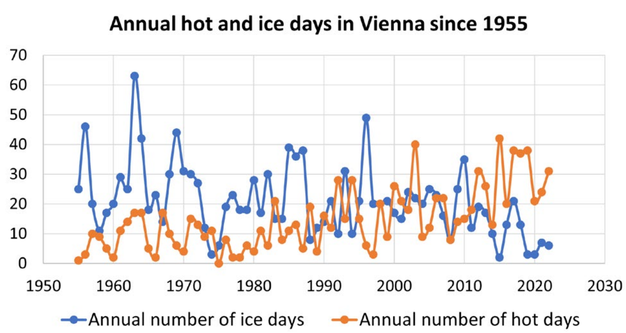
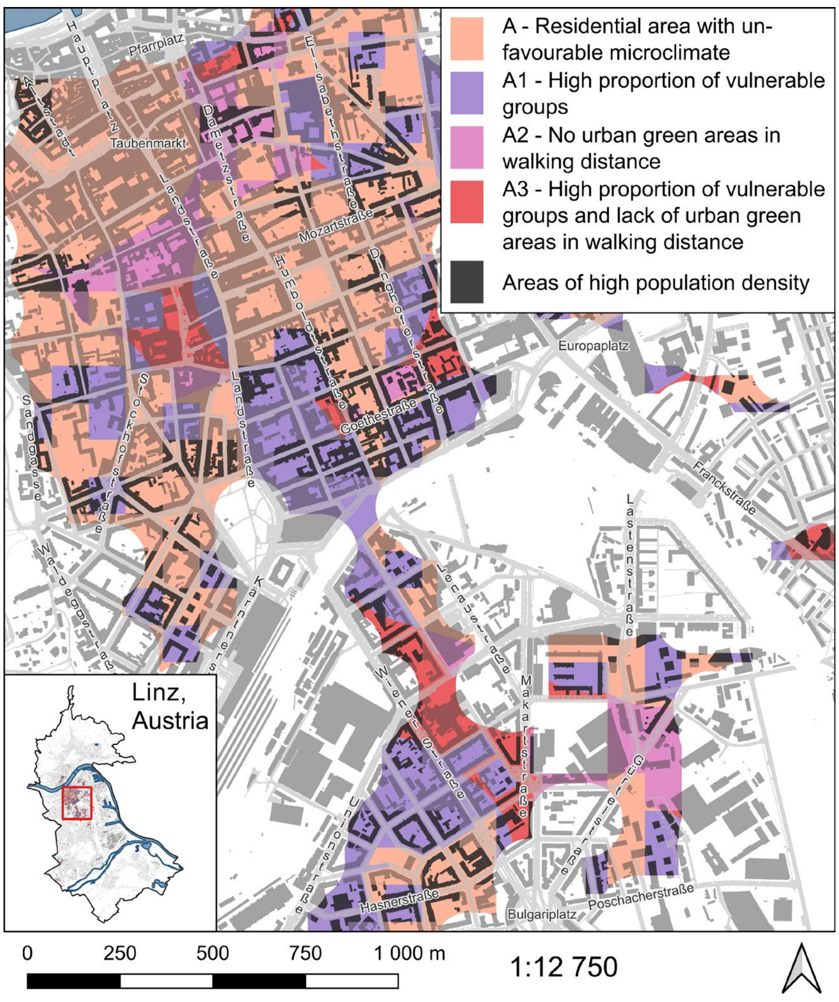



**Figure 3.3** Frequency of hot days (maximum daily temperature exceeding 30°C) and ice days (maximum daily temperature below 0°C) recorded in Vienna (Stadt Wien, 2024).

er distances (e.g., the '15-minute city' concept) and more inclusive planning and design of public space (e.g., the 'superblock' approach) to support multiple uses of open space, will allow mitigation and adaptation measures to be considered together, supporting the fundamental transformations needed in urban development and spatial planning (WBGU – Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen, 2011, 2016).

## Chapter Box 3.1. Climate change adaptation plan 'Zukunft Linz' ('Future Linz')

'Zukunft Linz' ('Future Linz') forms the basis for climate change adaptation in Linz (Magistrat Linz, 2023), based on detailed, spatially disaggregated risk assessments linked to exposure and vulnerability, taking into account adaptive capacity (Box 3.1 Figure 1). The map shows regions of high priority for heat-related adaptation measures. Additionally, exposure maps exist for hail, fluvial floods, and storms, allowing for the prioritization of adaptation efforts and risk monitoring (BML, 2023). The expertise is housed within Linz's urban climatology and environmental management (UCEM) division, with an urban climatologist and two additional climate change adaptation staff members who help prioritize and coordinate city-wide adaptation efforts across city departments. This includes, e.g., planning for heat events negatively affecting public health and thermal comfort. For example, Linz's medium- to long-term projects include a greening initiative focused on tree planting to address UHI effects, a stream renaturation program to restore natural habitats and prevent flooding, and a heat emergency plan based on spatially disaggregated risk events (Box 3.1 Figure 1).




**Box 3.1 Figure 1** Excerpt of the heat risk map of Linz focused on the districts 'Innere Stadt' and 'Bulgariplatzviertel', showing spatially resolved vulnerabilities and adaptive capacities (Horak and Peßenteiner, 2023). Vulnerability considers residents' age, pre-existing medical conditions, and socio-economic status. Adaptive capacity is based on publicly accessible urban green areas >7,500 m² and tree cover within walking distance of at most 250 m.

### 3.2.2. Land-use and spatial planning

#### Strategic context in Austria

Land-use planning takes account of and aims to influence spatial development trends. In 2021, the office of the Austrian Conference on Spatial Planning (ÖROK) published the 'ÖREK 2030', the Austrian Spatial Development Concept for Austria (ÖROK, 2021), elaborated with input by stakeholders from all governmental levels including the state, the federal provinces, districts and municipalities. The strategy is the most important federal document providing a joint vision for future development foci. The ÖREK 2030 outlines the key themes of need for urban and regional transformation for the next 10 years in four pillars (ÖROK, 2021):

- A parsimonious and sparing use of spatial resources;
- The strengthening of the social and spatial cohesion;
- The sustainable and climate sensitive development of economic spaces and systems;
- The development of vertical and horizontal governance.

Land-use planning remains a key tool for enhancing Austria's resilience and adaptive capacity while guiding contemporary development trends, such as multilocality, connectivity, mobility, land use, economic activities, digitalization, and housing. It plays a crucial role in both preventing additional emissions and enabling effective adaptation and mitigation measures (ÖROK, 2021).

The governance of and legal systems in Austria imply that these overall goals can only be achieved through efficient vertical and horizontal governmental coordination (see Section 6.4). There are three main levels: The federal government is only legally responsible for the development of sectoral plans and, through the ÖROK, for the development of the spatial development strategy. Due to the Austrian Constitution, which grants the right to develop their own laws in any policy area that is not regulated at the federal level, the nine federal provinces have the right to develop spatial development laws ('Raumordnungsgesetze') in the absence of a federal spatial planning regulation (BGBl. Nr. 1/1930, 2024, art. 15). As a result, each of the nine federal provinces has its own legal framework. In general, the federal level remains with competences to outline strategy documents as well as sectoral plans. Further, the federal provinces have the obligation to provide the frameworks and legal specifications for local land-use regulation (Gruber et al., 2018). In line with the subsidiarity principle, the right for legal instruments linked to land-use regulation lies with the municipal level. The municipalities in Austria have the responsibility to develop strategic development concepts, zoning plans, and/or building regulation plans (BGBl. Nr. 1/1930, 2024, art. 118). In some federal provinces, development plans and strategies may also be developed at the regional level.

This multi-level governance framework implies that the federal government only can act through strategic guidelines to address many of Austria's developmental changes. To address certain developmental challenges, such as land take, the ÖROK can devise implementation plans – for instance the Land Protection Strategy for Austria ('Bodenstrategie für Österreich') (ÖROK, 2023b). Recently, the limitations of the multi-level governance system have become evident: Although the federal provinces – who hold the legal authority – have adopted the Land Protection Strategy, the final version omits the commitment to limit land take to a maximum of 2.5 hectares per day, as originally outlined in the 2020–2024 government program. This case illustrates the complexity of tackling critical challenges in spatial planning within a multi-level governance context. Effective land use monitoring and planning are essential for identifying areas that are exposed and vulnerable to, or likely to be impacted by, climate change-related extreme events, such as severe droughts or intense rainfalls causing floods (see also Cross-Chapter Box 1). Land use planning plays an important role in managing spatial development in a sustainable way.

#### Key development trends and risk factors

Overall, climate change is associated with more extreme weather events (IPCC, 2021a), an increase in the number of hot days, and a shift in seasonal extremes (Fuchs et al., 2015, 2022) (see Section 3.2.1). Impacts differ between urban and rural areas, and between lowland and mountainous areas, which is particularly relevant for Austria (see Section 1.2.2). For example, an increase in extreme rainfall events after long periods of drought can have potentially devastating impacts on agricultural practices in mountainous areas (see Sections 2.2.1, 7.4.2 and Table 2.2) and an increased occurrence of avalanches puts more settlements at risk (Permanent Secretariat of the Alpine Convention, 2017).

The projected increase of annual mean temperatures also suggests that several European regions, especially Austria, will be particularly affected (IPCC, 2022a). The increased amplitude of phenomena associated with extreme hydro-meteorological or compound events, as well as their increased number, can have devastating impacts on existing economic systems, social justice, human health, existing infrastructure, and the built environment in general (see also Cross-Chapter Box 1 and the Cross-Chapter Box 2). In addition to these meteorological developments, soil sealing exacerbates the negative impacts of heat waves, particularly in urban areas, by increasing the UHI effect (see Section 3.2.3).

Demographic development trends, such as ageing regions, do not necessarily coincide with land consumption patterns. The ÖROK estimates a population growth of 3.2 % to 9.22 million inhabitants in 2030 compared to 2021 (ÖROK, 2021). This growth is not equally distributed. On the contrary, some Austrian regions, especially urban areas, continue to grow while others continue to shrink: The ÖREK 2030 estimates that the population of the Vienna Region will grow by more than 15 % by 2040, while some regions, such as the Lavanttal, will shrink by around 10 % (ÖROK, 2021).

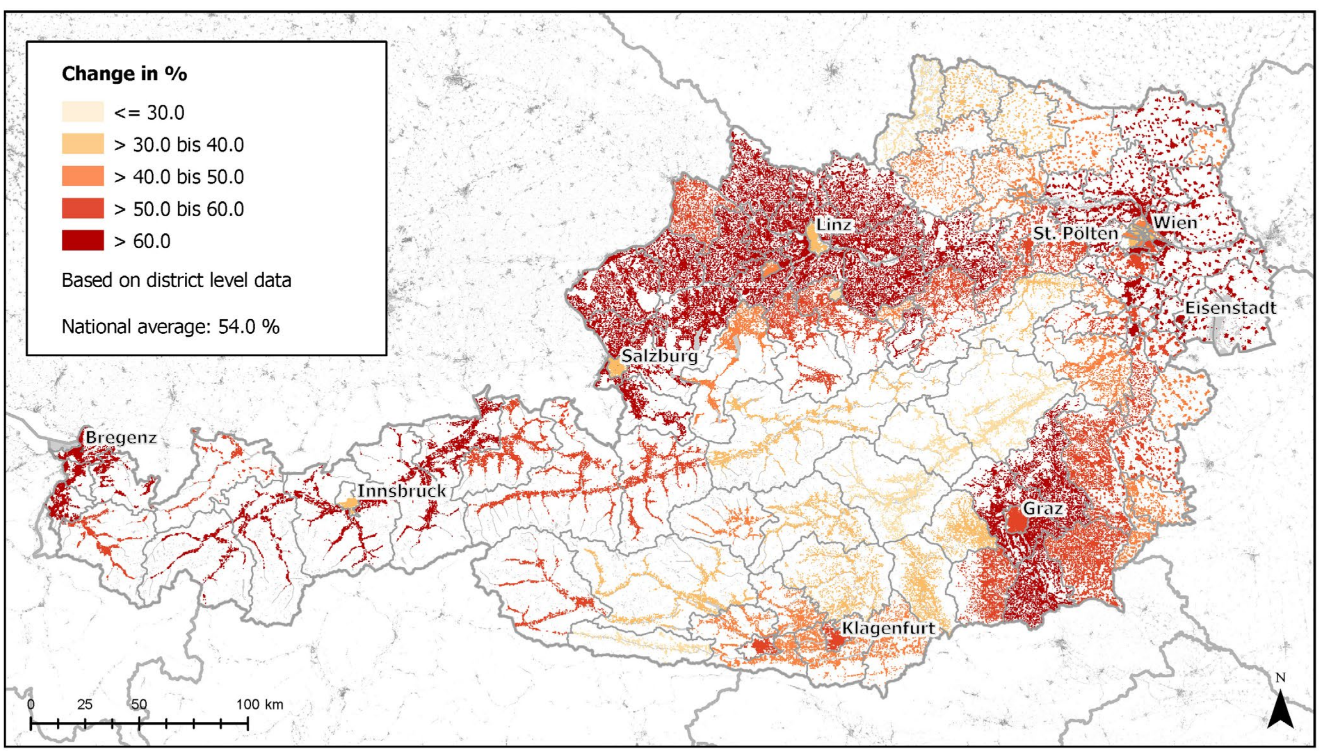
It is striking that land consumption continues even in areas with declining population (Dallhammer et al., 2022). While some regions are experiencing shrinkage, Austria's overall population continues to grow, creating demand for additional housing units in urban areas. In rural areas, this new demand is being met primarily with single-family and two-family homes, mostly detached or semi-detached. In urbanized areas, apartment buildings are the norm. These housing demands, as well as industrial developments, result in new soil sealing.

At the same time, demographic development trends will lead to a higher percentage of older people in many regions of Austria. The ÖROK regional forecast up to January 2050 suggests a continuous trend towards an ageing population, especially in rural areas (ÖROK, 2023c). Figure 3.4 illustrates these ageing trends occurring in mountainous areas and rural Austria.

## Reducing land consumption in times of population and economic growth

The European Commission called for target of No-Net-Land-Take by 2050, which was concretized in 2021 with the Soil Protection Strategy for 2030 (European Commission,

**Population change 2021-2050: Age 65+**




Origin of data: ÖROK Regionalprognosen 2021 - Bevölkerung, Statistik Austria - data.statistik.gv.at 2024, European Union's Copernicus Land Monitoring Service 2020
Administrative boundaries: ÖROK Regionalprognosen 2021 - Bevölkerung, Eurostat 2020 und 2021, BEV 2023 (CC BY 4.0); Digitales Landschaftsmodell: BEV 2023
Cartographic implementation: Franziska Sielker and Alexandra Pintilie, TU Wien 2024

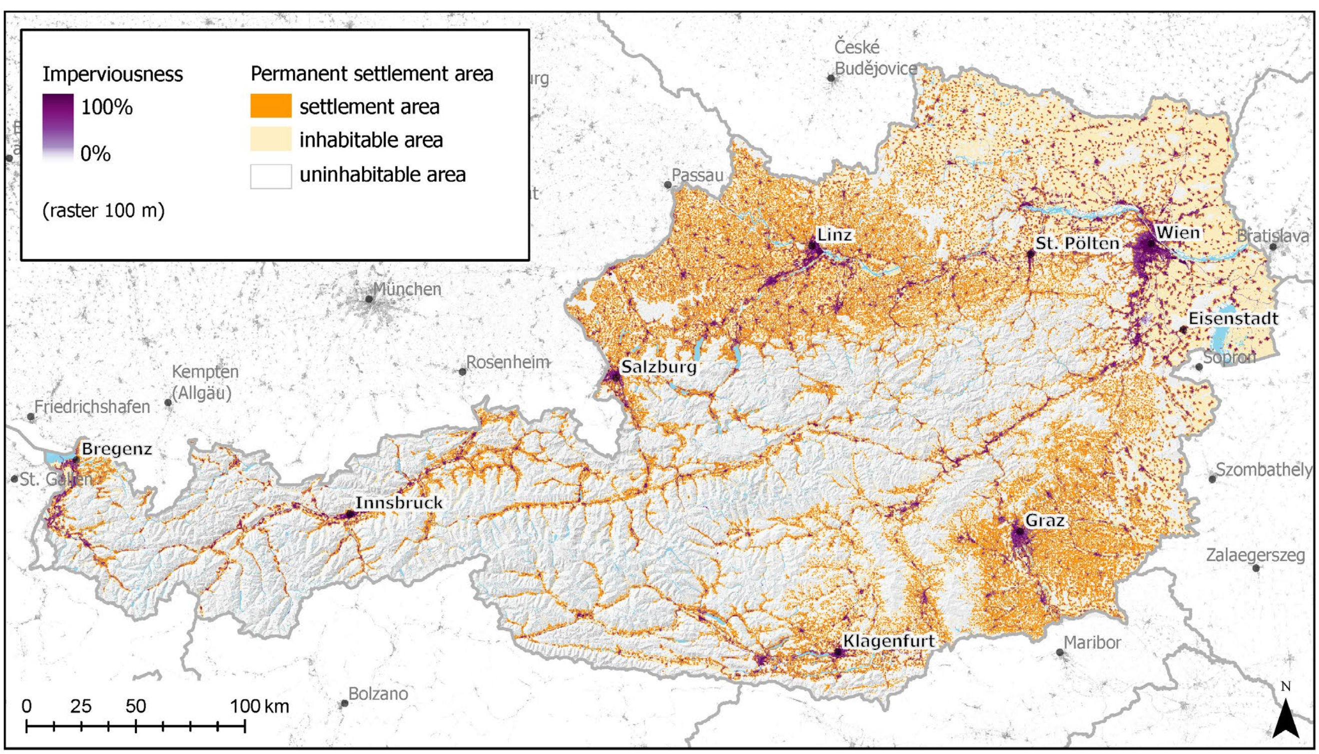
**Figure 3.4** Projected regional population changes in Austria from 2021 to 2050, focusing on individuals aged 65 and older, based on the regional forecast from ÖROK (Sielker and Pintilie, 2024, based on ÖROK, 2021).

2022c). By 2023, Member States were required to set their objectives for reducing land take. In 2022, the ÖROK introduced a new methodology to measure land take and soil sealing in Austria (ÖROK, 2023d).

In parallel, both on the EU level and in Austria, a process is underway to provide conceptual clarity on the difference between land take and soil sealing. The term 'land take' in the sense of 'land consumption' includes built-up areas as well as urban green areas and land used for agricultural, forestry, or other economic activities. The term 'soil sealing' or 'imperviousness' refers to the situation in which the nature of the soil changes in a way that it becomes an impermeable medium (Marquard et al., 2020; Decoville and Feltgen, 2023). Land take, including buildings for housing, infrastructure, recreational activities as well as cultivation areas, involves the long-term loss of biologically productive soil.

Figure 3.5 visualizes the degree of soil sealing and potential permanent settlement areas. Especially in Austria, which has a high proportion of alpine areas, the concept of permanent settlement area is of great importance. It refers to the inhabited and (economically) usable area available for settlement development, agricultural production, and infrastructure. It consists of a settlement area and a potentially inhabitable area, the latter including agricultural and green areas. The uninhabitable area (non-settlement area) is made up of forest areas, alpine grassland, wasteland, and water bodies. The CORINE Land Cover data as well as population and employment data (see ÖROK, 2015; Statistik Austria, 2023a) form the basis for the delineation of permanent settlement areas. This data was overlayed with information regarding the imperviousness degree. Soil sealing, as mentioned above, refers to areas that are continuously covered with a layer that is completely impermeable to water and air. The data from the Copernicus Land Monitoring Service represent the degree of sealing, in percent and aggregated to a 100 x 100 m grid (European Environment Agency, 2020). This method was chosen to add to the existing ÖROK Atlas (ÖROK, 2023d), which maps the proportion of soil sealing in administrative units. By making use of the granularity of the most recent Copernicus data, Figure 3.5 overlaps soil

**Soil Sealing in Austria (2018)**




Origin of data: European Environment Agency, European Union's Copernicus Land Monitoring Service 2020, Statistik Austria - data.statistik.gv.at 2023
Administrative boundaries: Eurostat 2020 and 2021, BEV 2023 (CC BY 4.0); Digitales Gelände- und Landschaftsmodell: BEV 2023, Geoland.at 2015
Cartographic implementation: Franziska Sielker and Alexandra Pintilie, TU Wien 2024

**Figure 3.5** Soil sealing in Austria, as observed in the year 2018, showing the extent of land covered by impervious surfaces (Sielker and Pintilie, 2024, based on European Environment Agency, 2020).

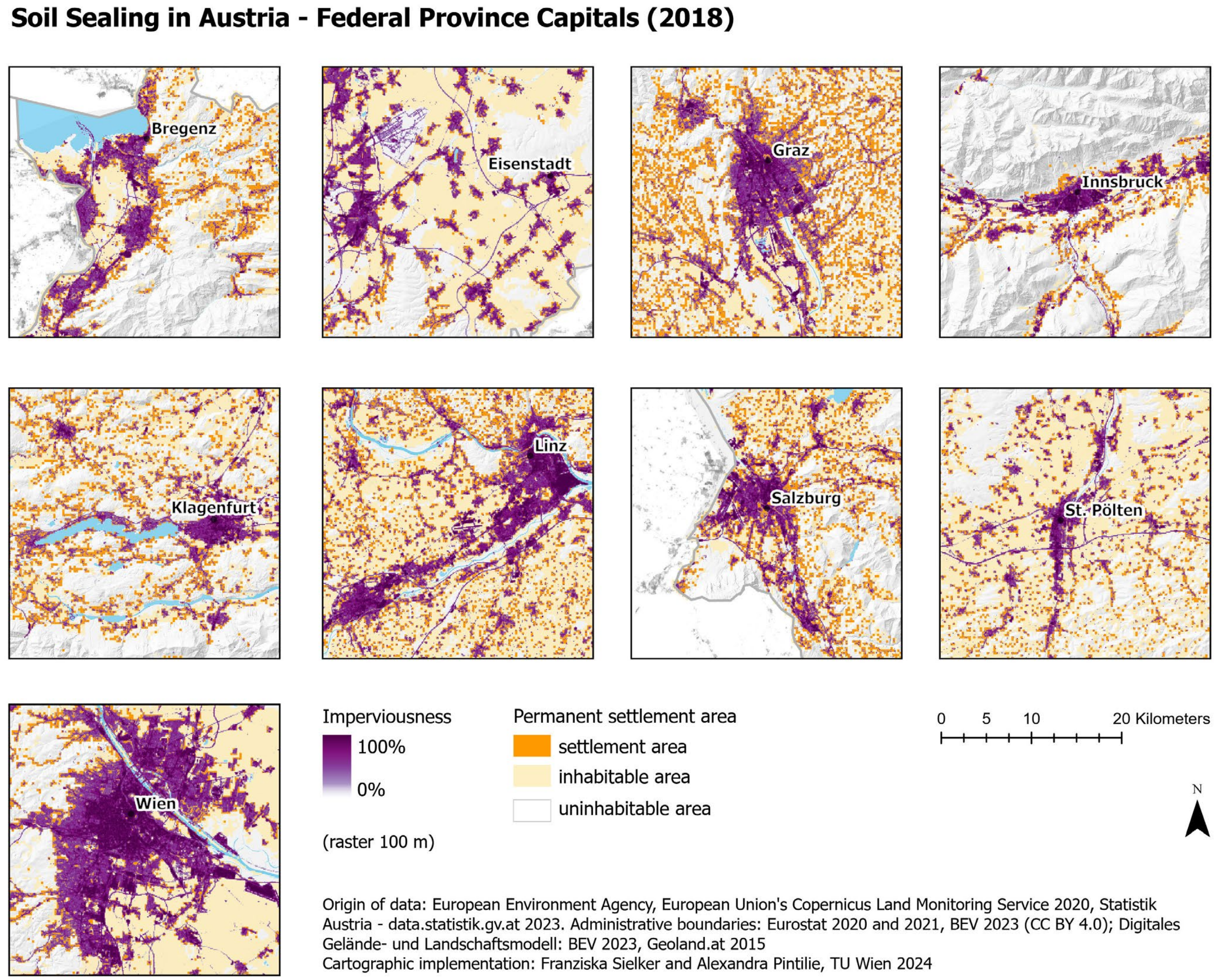



**Figure 3.6** Soil sealing in the capitals of Austria's federal provinces in the year 2018 (Sielker and Pintilie, 2024, based on European Environment Agency, 2020).

imperviousness with the potentially inhabitable land, allowing for a spatially detailed visualization. To get a sense of this granularity, Figure 3.6 provides zoom views for the capitals of the federal provinces.

Austria's continued excessive land consumption is in stark contrast to the objective of climate resilience, as open spaces continue to be sealed. Using its own methodology, which is also based on data on building land zoning, the ÖROK presented relevant figures in its report on land take and soil sealing in Austria. Accordingly, in 2022, an area of approximately 5,648 km² has been changed in a way that the land is no longer available for agricultural and/or forestry production or as natural habitat. This is described as land take in contrast to soil sealing. Land take marks roughly 17.3 % of the permanent settlement areas in Austria. More than half of this area (52 % or 2,964 km²) was already sealed in 2022 (ÖROK, 2022). If the land consumption within Austria continues at this pace, conflicts around land use will increase in the inhabitable settlement areas, as is shown in Figure 3.5 and Figure 3.6.

A key takeaway from Figure 3.5 is that in the potentially inhabitable areas of Austria, a diversity of uses has to be realized. In many cases, these are mutually exclusive land use demands, as for example agriculture and housing. Considering the diversity of land use demands in the context of population development, the pressure on urbanized areas in particular will continue to increase. Decisions on new land take, and in particular soil sealing, need to take into account the potential negative impacts in other areas. In the long-term, land take in general and sealed soil in particular has serious implications for natural ecosystems. Biodiversity loss and habitat fragmentation are some of the consequences.

Similarly, as mentioned above, the systems of governance and planning in Austria tend towards a strong executive power with substantial planning-relevant competences at the district level, followed by the provincial level and a relatively weak state level with its main competences in sectoral plans. With regard to soil sealing, local development strategies and zoning are key to prevention. However, there is no overall Austrian strategy that sets targets for local authorities. In addition to land use plans, there are a number of instruments that can support the goal of no-net-land-take. These include, for example, climate checks for potential building land, environmental impact assessments for new construction projects, funding schemes for area recycling and unsealing, and using the opportunity to define settlement boundaries for local development (see also ÖROK, 2023a).

A key challenge for the future is therefore to make better use of existing instruments and to develop incentives to reduce new designations of building land. In order for local authorities to achieve overarching goals such as improving resilience and adaptive capacity, greater multi-level governance coordination may be useful. Multi-level governance discourses, including additional training and education, as well as raising awareness of the role of each local authority in contributing to these overarching goals, will be key.

### Spatial energy and infrastructure planning

Achieving climate neutrality in the built environment is closely linked to the transformation of energy infrastructure (Camarasa et al., 2022; European Commission: Directorate-General for Energy et al., 2022; Billerbeck et al., 2024; Fallahnejad et al., 2024). This applies to the grids used to transport energy (electricity, district heating and eventually gases) and distribute it to end-users. It also applies to renewable energy generation, some of which is on-site, directly connected to buildings, such as building mounted photovoltaics (PV), or in the form of renewable energy generation sites, such as wind farms or ground-mounted PV. Both components have a strong spatial component and are linked to the planning of settlements in urban and rural contexts. While the second component is more closely related to renewable energy generation (Sections 4.5.2, 4.5.3) and biomass (Sections 2.1.1, 2.2.1, 2.3.2), this section will focus on the first component, i.e., the spatial component of energy grid infrastructure in relation to settlement structure, energy densities and related planning activities.

A key question in the decarbonization of the built environment is which part of the building stock should be connected to which energy infrastructure in order to provide a full supply of renewable energy (also taking into account the potential of measures to reduce energy demand). While more or less all buildings in Austria with a relevant energy demand are connected to the electricity grid, this is not the case for district heating and gas grids. High infrastructure costs for supplying only a low number of connected end-users should be avoided. In this context, spatial planning is important to ensure high connection rates and thus a high economic utilization of infrastructure investments. For district heating grids, the challenge is to identify and implement district heating areas in line with decarbonization plans, connecting climate neutral, renewable heat supply resources with heat demand (Billerbeck et al., 2024; Fallahnejad et al., 2024). For the gas grid infrastructure, spatial energy planning will become even more important, considering that the simple substitution of fossil gas by renewable gases may not be fully possible or very expensive, thus requiring a gradual decommissioning of the gas grid (see, e.g., Zwickl-Bernhard and Auer, 2022).

Recognizing these needs, the revised energy efficiency directive (Directive (EU) 2023/1791) of the European Union foresees the enforcement of local heating and cooling plans at least in municipalities with a population greater than 45,000. These plans should include a strategy for enforcing renewable heating and cooling, waste heat, and district heating and cooling. This should be based on a thorough analysis of heating and cooling systems in the local building stock as well as an analysis of energy efficiency measures. Clearly, these provisions will also need to be implemented in Austria with the corresponding effects.

In some European countries, municipal and spatial energy planning have a long tradition, particularly in Denmark (see, e.g., Chittum and Østergaard, 2014; Büchele, 2019). In addition, there is a considerable tradition of developing tools for spatial energy planning and municipal strategic energy planning, as described, for example, in Mirakyan and De Guio (2013), Stöglehner et al. (2016), Büchele et al. (2019), and Mandel et al. (2023). In addition, several tools have been developed in recent years to support municipalities in particular in the task of municipal heat planning, such as the 'Hotmaps' tool (Hotmaps Project, 2023) or 'Thermos' (Thermos, 2021). However, one of the main bottlenecks for effective spatial energy planning is a solid database, first of all on the buildings, their energy performance and related energy consumption, the resulting energy density and their existing technologies, in particular heating systems. Activities to improve data availability in this respect in Austria in recent years can be summarized along two lines. The first is mainly based on open access data and applies different algorithms to merge these datasets in order to derive the required data on a high spatial resolution, e.g., at the hectare level. Examples include the 'Energiemosaik', the project 'Enerspired cities' (Schardinger et al., 2021) and the 'Austrian Heatmap'[1]. The second line of activities aims to provide a higher resolution, i.e., at the building level, and also builds on non-open data sources, such as the building registry 'AGWR' (Statistik Austria, 2024a), including information from building energy performance certificates or datasets from chimney sweeps and plumbers. Here, mainly the project 'Spatial Energy Planning'[2], within the framework of the 'green energy lab' program, developed new methods and approaches for the three regions of Salzburg, Styria and Vienna.

Several municipalities, local and regional authorities have implemented approaches and partly regulatory policy instruments of spatial energy planning. For example, the city of Vienna established the concept of 'climate protection areas' in 2018, and since then, the energy planning department 'MA 20' has been gradually implementing this concept by defining different areas where the use of fossil fuels is restricted by law (see also Erker et al., 2021).

In part, the concept of spatial energy planning also needs to be redefined and placed in the context of full climate neutrality targets, i.e., restricting the use of fossil fuels in some areas makes sense in a policy regime where fossil fuels in general are not restricted. However, since an overall policy regime is needed in which fossil fuels are completely phased out, spatial energy planning needs to support this goal by defining the areas where this phase-out must take place first. Moreover, in such a policy regime, spatial energy planning is also needed to define areas where shared energy infrastructure facilitating the phase-out of fossil fuels should be preferred to individual (even renewable) solutions. This applies, e.g., to renewable district heating and cooling or public transportation infrastructure. Overall, there is a consensus in the scientific community that gases (be it fossil or renewable) should be used for high-temperature, high-exergy applications and not for low-temperature applications such as space and water heating (see, e.g., European Commission: Directorate-General for Energy et al., 2022; Rosenow, 2022).

For spatial energy planning, this implies that gas grids in residential areas should be decommissioned (see also Rodgarkia-Dara et al., 2023). The supply of gases to industrial processes is closely linked to other dimensions of spatial energy planning.

While spatial energy planning has historically relied heavily on one-time data collection efforts, there is now a strong trend toward more innovative data approaches that rely on cross-regional, dynamic, automated, digitalized, continuously updated, and flexible data collection approaches to support planning and policy processes at different spatial scales. There is a strong consensus in the literature on the relevance of spatial energy planning and related energy infrastructure planning in achieving climate neutrality (see, e.g., Büchele, 2019; Büchele et al., 2019; Horak et al., 2022; Dumke et al., 2024; Fallahnejad et al., 2024).

### 3.2.3. Climate impacts and risks

#### Urban heat islands

Urban settlements are particularly vulnerable to heat island effects, which affect human health (Tong et al., 2021) (see also Cross-Chapter Box 2). The spatial variation of urban temperature is highly specific to urban form (Zekar et al., 2023), with a direct link between surface sealing and surface temperatures, especially at night, as the built environment (asphalt, buildings) stores heat during the day and releases it at night, resulting in tropical nights (not below 20°C) (Rippstein et al., 2023, fig. 3.7). This poses particular health risks, despite behavioral and physiological adaptations over time (Hagen and Weihs, 2023).

Ameliorating extreme heat in urban environments is critical to reducing heat-related mortality (Martilli et al., 2020). Similar to studies on land surface temperature, studies on air temperature stress the impact of vegetation cover and tree canopy presence, which results in a cooling effect and reduces the ambient temperature (Zumwald et al., 2021). Integrated mitigation and adaptation strategies, such as improved building insulation, are key to ameliorating urban heat island effects (see Section 3.2.3 Integrated mitigation and adaptation strategies).

Older and higher-income neighborhoods are typically associated with more vegetation cover and thus less pronounced urban heat island effects. Heat mitigation may need to focus particularly on lower-income communities, where historical underinvestment has resulted in less green space and more surface sealing (Section 3.2.1).

1 austrian-heatmap.gv.at (BMK, 2022a), building also on the methods developed by Müller et al. (2019)

2 waermeplanung.at (SEP, 2021)

## Urban water impacts

Austria's urban water infrastructure is highly developed, with 95 % of the Austrian population connected to central drainage systems and 93 % to central water supplies. Both combined sewer systems – where wastewater and stormwater flow through a single pipe – and separate sewer systems – where wastewater and stormwater are carried in distinct pipes – are used. While combined sewer systems are efficient during normal conditions, they can cause overflows during heavy rainfall, leading to untreated or partially treated stormwater and wastewater discharges into nearby waterbodies, called combined sewer overflow (CSO) emissions. Using separate sewer systems reduces the risk of CSO but requires additional infrastructure. Over the last 20 years, decentralized stormwater treatment has been increasingly adopted to mitigate the challenges of urban runoff. As Austria's urban water management sector has a net estimated annual energy consumption of 282 GWh and GHG emissions of 278,000 $tCO_2eq$ (Zach, 2022) (*limited evidence, medium agreement*), energy recovery from wastewater is considered a critical strategy to make the sector carbon neutral or even a carbon dioxide ($CO_2$) sink.

Relevant climate change impacts on urban water infrastructure are changing precipitation and temperature patterns, including increased occurrences of dry periods, excessive heat, extreme precipitation events, and tropical nights (Arnbjerg-Nielsen et al., 2013; Kourtis and Tsihrintzis, 2021). Detailed information on climate projections for Austrian settlements is provided in Chapter 1 (Section 1.2.2; Figures 1.4, 1.5, 1.7 and 1.8) and Section 2.2.2. While there are seasonal and regional variations, there is *medium to high confidence* that rainfall intensities for typical design events (return period 5-10 years) and extreme events (return >100 years) will grow (see Cross-Chapter Box 1). Rainfall intensities for short-duration events are expected to increase by 10 % per degree of temperature rise. Additionally, as mentioned in Section 3.2.2, soil sealing in urban areas is on the rise, resulting in more paved spaces.

Intensified precipitation and soil sealing together boost surface runoff and hence challenge urban drainage systems. For combined sewer systems, this results in increased runoff to wastewater treatment plants and increased CSO emissions, clearly increasing impacts for already slightly shorter event return periods (*medium evidence, high agreement*). As of 2024, the EU proposal for a revised 'Urban Wastewater Treatment Directive' (European Commission, 2022a) limits combined sewer overflow emissions to be below 2 % of annual wastewater runoff. Currently, several Austrian cities are expected to exceed this limit (Muschalla, 2023), and as climate change impacts are expected to worsen, this will lead to adaptation and investment requirements (*limited evidence, high agreement*).

For both combined and separate systems, an increase in rainfall intensities of extreme events also elevates the risk of pluvial floods. To enhance resilience to these climate impacts, necessary adaptation measures include either (1) expanding existing drainage infrastructure or (2) implementing strategies such as de-sealing surfaces, decentralized stormwater management to reduce runoff into drainage systems, and integrating blue-green infrastructure (e.g., vegetation and stormwater ponds) (Kleidorfer et al., 2018). The second approach seems economically and ecologically superior, however, detailed investment demand is unclear and needs to be assessed. De-coupling and de-sealing of surfaces would improve the water and energy balance by increasing infiltration, evapotranspiration and storage of water (Oral et al., 2020; Probst et al., 2022; Ferreira et al., 2024) (*high confidence*). Moreover, such adaptation strategies offer the opportunity to transform existing systems by integrating sustainable, ecological solutions and providing aesthetic, social, and economic benefits. However, compared to existing central systems, this can complexify planning and maintenance procedures (Fletcher et al., 2015).

A transition pathway towards sustainable drainage concepts requires mandatory decentralized stormwater management for new and reconstructed buildings and the implementation of adaptation measures into spatial planning, prohibiting sealing of surfaces and providing the necessary data sources for decision making (e.g., risk maps for pluvial flooding) (Mikovits et al., 2017). Decentralized stormwater management systems often require construction on private property, making it crucial to develop strategies and incentives to facilitate the disconnection of existing stormwater inflows from the drainage system. While many cities and settlements already require that new buildings refrain from connecting stormwater to existing drainage systems, there are generally no incentives to encourage retrofitting in older developments. Introducing split fees – where stormwater and wastewater discharges to the drainage system are billed separately – could serve as a potential financial motivator. Alternatively, providing financial support or subsidies to encourage disconnection of currently connected areas from the drainage system is another viable approach.

In addition to runoff reduction, stormwater harvesting and reuse are becoming increasingly important as precipitation patterns change and water resources are reduced due to longer dry periods between rainfall events and increased water demand for irrigation of nature-based-solutions (vegetation) for urban cooling (Funke and Kleidorfer, 2024) (see Section 3.2.3 Urban heat islands). Therefore, investments in long-term storage systems can not only reduce the demand for drinking water, but also reduce peak flows and provide water to urban vegetation to increase cooling during heat waves.

Overall, urban areas need to prepare for extreme events by establishing risk maps, early warning systems and emergency plans, and by collecting and providing the necessary data to develop such plans. Consequently, water management is part of integrated climate change mitigation and adaptation planning (Ürge-Vorsatz et al., 2018) (see below).

### Integrated mitigation and adaptation strategies

Urban development and spatial planning can support both mitigation and adaptation. While sometimes in conflict, some strategies, such as better insulated buildings, can address both simultaneously (see, e.g., Section 3.2.3 Urban heat islands).

Compact cities are widely understood as a main strategy for designing low-carbon cities (see also Cross-Chapter Box 4 and Cross-Chapter Box 5) (Stöglehner et al., 2016; Stöglehner and Abart-Heriszt, 2022; Statistik Austria, 2024d). Short distances translate to less distance driven by car and/or higher modal shares of active modes of transportation. High density also means that public transit fulfills the economics of density preconditions to become more financially viable (Creutzig, 2014).

Urban infrastructures can reduce energy use and resulting GHG emissions, for example by reducing thermal loss in denser buildings (Borck and Brueckner, 2018). Avoiding urban sprawl, associated with several externalities (Dieleman and Wegener, 2004), can, in turn, be guided macro-economically by increasing fuel prices and marginal costs of motorized transport to obtain a spatially optimal equilibrium (Creutzig, 2014). Compact cities can lead to urban heat islands and sealed surfaces can prevent water storage and effective water management strategies (see Section 3.2.3 Urban heat islands, Urban water impacts).

Two key strategies can help moderate this trade-off. First, at the macro-scale, new urban developments could follow a star-shaped design, with public transit lines radiating out from the city center while preserving green space in between transit axes (Pierer and Creutzig, 2019). Second, particularly in already built environments, a key strategy is to focus on urban space readaptation. This includes changing inefficient use of street space, such as by unsealing and repurposing parking spaces, or thinking in terms of multi-purpose uses. This would discourage private automobility (the main driver of urban transport GHG emissions; see Section 3.4.2) and support the management of both water extremes and heat waves. Other options include vertical greening of buildings, green roofs, increasing tree cover along city streets, and improved long-term water storage.

Public health is another motivation for compact '15-minute cities' (Caprotti et al., 2024). Highly accessible walkable and cyclable urban design is not only a major mitigation option, it also provides more inclusive city services related to well-being (Lwasa et al., 2023). Solutions include planning cities around walkable sub-centers where multiple destinations such as shopping, work, leisure activities, and others, can be reached without driving (Newman and Kenworthy, 2006; Oswald et al., 2020).

## 3.3. Buildings

This section assesses the building sector's contribution to climate change mitigation and adaptation, emphasizing technology, materials, policy, and legislation. Section 3.3.1 examines energy demand, renewable technologies, and emission reduction pathways in buildings. Section 3.3.2 addresses the decarbonization of construction materials, while Section 3.3.3 reviews legal frameworks, barriers, and opportunities for reducing emissions in the building sector. Chapter Box 3.2 further explores energy storage in buildings, highlighting key technological needs and solutions.

### 3.3.1. Statistics and scenarios of technologies and renewables in buildings

#### Current status

This section outlines the current baseline for the Austrian building sector, based on recent statistics, including data on building numbers and types, energy demand, energy carriers, and greenhouse gas (GHG) emissions. The sector is dominated by single- and two-apartment residential buildings, while nonresidential structures make up 11.6 % of the total building stock (Table 3.1). This section provides an overview of the key assumptions and outcomes of scenarios and measures aimed at reducing energy demand and GHG

Table 3.1 Number of buildings in Austria in 2021 (Statistik Austria, 2024d).

| Building type →<br>↓ Ownership | Residential building with 1 apartment | Residential building with 2 apartments | Residential building with 3 or more apartments | Other buildings |
|---|---|---|---|---|
| Private persons | 1,477,870 | 287,101 | 160,002 | 175,819 |
| Corporations under public law | 11,006 | 1,868 | 28,086 | 42,541 |
| Non-profit building associations | 27,785 | 1,575 | 60,242 | 2,268 |
| Other legal persons | 14,853 | 2,208 | 25,400 | 56,153 |
| Total by type | 1,531,514 | 292,752 | 273,730 | 276,781 |
| Total overall | 2,374,777 | | | |

emissions (refer to Section 3.3.3 for a legislative perspective on the topic).

Austria's housing stock totals 4.91 million apartments (Statistik Austria, 2021). Of these, 4.02 million are classified as primary residences, while the remaining 0.89 million consist of second homes, holiday properties, or vacant units for various reasons. This distribution is key to understanding residential trends and housing market dynamics in Austria.

Almost all subsidies for housing decarbonization in Austria are contingent upon the registration of a primary residence. In the multi-apartment sector, the legal framework plays a crucial role in shaping the conditions for decarbonization efforts. Housing law regulations vary significantly across different types of properties, including owner-occupied apartments, privately rented apartments, housing association rentals, and municipal rentals.

Of the 1.78 million main-residence apartments in detached houses with one or two units, 1.45 million are owner-occupied. In multi-apartment buildings, about a third of the 2.23 million apartments are privately rented, a quarter are housing association rentals, and a fifth are owner-occupied. The remaining apartments are municipal or have another legal status (Statistik Austria, 2023c).

The end-use energy demand presented in Table 3.2 indicates that, according to the statistics of 2022, fossil fuels account for 29 % of the total demand, primarily from gas and oil. Biomass accounts for about 19 %, while district heating has grown significantly to 15.5 %, with a relative increase of 175 % from 1990 to 2022. Electricity demand, which comprises 29.5 % of the total, includes space heating, domestic hot water (such as direct electric heating, heat pump compressors, hot water preparation, and heating system controls, including ventilation and heat recovery), as well as air conditioning, household electricity, and other uses. The 12 % reduction in end-use energy demand from 2021 to 2022 is largely attributed to the milder weather conditions in 2022 compared to 2021. From 2022 to 2023, this demand decreased by a further 6 %, resulting in a 36 % share of total end-use energy consumption, partly due to the increasing replacement of fossil fuel boilers with heat pumps (BMK, 2024a).

Table 3.2 End-use energy demand in the Austrian building sector, expressed in terajoules [TJ] (Umweltbundesamt, 2024b).

| Type →<br>↓ Year | Oil | Coal | Gas | Biomass | Electricity* | District heating* | Ambient heat, etc.** | Total*** |
|---|---|---|---|---|---|---|---|---|
| 1990 | 93,451 | 27,578 | 46,093 | 60,457 | 73,412 | 21,798 | 2,239 | 326,143 |
| 2005 | 92,796 | 4,682 | 88,876 | 61,791 | 103,487 | 43,050 | 7,042 | 402,803 |
| 2021 | 51,143 | 478 | 83,024 | 90,944 | 118,456 | 68,098 | 24,914 | 437,062 |
| 2022 | 44,025 | 358 | 67,438 | 72,722 | 113,321 | 59,730 | 27,074 | 384,673 |
| 2021–2022 | -14 % | -25 % | -19 % | -20 % | -4,3 % | -12 % | +8.7 % | -12 % |
| 1990–2022 | -53 % | -99 % | +46 % | +20 % | +54 % | +174 % | +1,109 % | +18 % |
| Share 2022 | 11.4 % | 0.1 % | 17.5 % | 18.9 % | 29.5 % | 15.5 % | 7.0 % | 100 % |

* *GHG emissions from electricity generation and district heating are attributed to the energy and industry sector.*
** *Geothermal, ambient heat (for heat pumps) and solar thermal.*
*** *Including other fuels (combustible waste, peat).*

**Table 3.3** The GHG emissions from the operation of the Austrian building sector, broken down into private households and commercial buildings, measured in million tons $CO_2$eq [Mt$CO_2$eq] (Umweltbundesamt, 2024b).

| Year →<br>↓ Main contributor | 1990 | 2021 | 2022 | Rel. change 2021–2022 | Rel. change 1990–2022 | Share of national GHG emissions 2022 |
|---|---|---|---|---|---|---|
| Private households | 10.605 | 7.326 | 6.154 | -16 % | -42 % | 8.4 % |
| *thereof stationary* | *10.414* | *7.219* | *6.047* | *-16 %* | *-42 %* | *8.3 %* |
| *thereof mobile* | *0.191* | *0.108* | *0.107* | *-0.9 %* | *-44 %* | *0.1 %* |
| Public and private services | 2.313 | 1.537 | 1.224 | -20 % | -47 % | 1.7 % |
| Building sector | 12.918 | 8.863 | 7.378 | -17 % | -43 % | 10 % |

Table 3.3 shows GHG emissions and their relative reductions in Austria's building sector between 1990 and 2022. GHG emissions from district heating and electricity generation are allocated to the energy and industry sector. However, when accounting for the GHG emissions linked to the electricity demand of buildings – 26.6 % of total electricity demand for private households, 16.3 % for public and private services as well as 82.5 % for district heating (Umweltbundesamt, 2024b) – the building sector's share of total emissions in 2022 increases from 10 to 13.5 % (*high confidence*). The share of direct emissions decreased by 20 % to 5.886 Mt$CO_2$eq from 2022 to 2023, driven by the increased adoption of heat pumps, which shifts fossil fuel demand to electricity need, accounted for in the energy sector. As heat pumps are far more efficient than fossil fuel boilers, this transition reduces the overall emissions. However, the figures for 2023 cannot be determined as the corresponding data is not available yet.

## Greenhouse gas reduction and climate change mitigation scenarios

Relevant climate change impacts for buildings are changes in maximum, minimum and monthly ambient temperature, which reduces space heating demand in winter but increases space cooling demand in summer. All available mitigation scenarios take into account: The projected number of buildings (considering increases due to population growth), the projected thermal state of buildings (new, renovated, divided by building type and age), the thermal renovation rate and thermal quality (the space heating demand after renovation), the proposed share of renewable energy carriers for new and exchanged old heating, ventilation and air-conditioning (HVAC) systems, and the HVAC exchange rate. Using these values, the scenarios calculate a combination of enhanced energy efficiency and a transition to renewable energy sources. Regarding future population development, quantitative international migration scenarios that take into account different climate change scenarios (RCPs) are not available at the moment. Therefore, the predictions of Statistik Austria (2024c), which are based on the current situation, are used for Austria. A more detailed discussion can be found in Section 6.8.2.

While the scenarios outlined in the literature vary in scope, they share a high degree of similarity in their assumptions and outcomes. Some studies focus exclusively on technical aspects and address annual energy balances for buildings without considering seasonal storage or broader geographic areas (Pfeifer et al., 2016; Dobler et al., 2018). Others adopt a more comprehensive approach, encompassing all sectors (Ebenbichler et al., 2018; Umweltbundesamt, 2019; Kranzl et al., 2020; Steininger et al., 2021). Additionally, some studies incorporate pricing mechanisms and macroeconomic factors, extending their analyses to cover Austria in its entirety as well as the dynamics of European energy markets. Brandes et al. (2021) and Luderer et al. (2021) perform scenario calculations for Germany with hourly resolution, incorporating energy storage solutions into their analyses. Ebenbichler et al. (2024) developed a Tyrol-focused scenario on an hourly basis, incorporating short- and long-term storage solutions while considering 2050 projections for Austria, Germany, Italy, France, and the broader European context (see also Chapter Box 3.2 for more information on energy storage in buildings). The official Austrian scenarios WEM (With Existing Measures), WAM (With Advanced Measures) and Transition (reaching nearly fossil free energy system by 2040), are presented in a report by the Environment Agency Austria (Umweltbundesamt, 2023a). In the WAM scenario, fossil fuels are not used directly for space heating or cooling; however, fossil fuels are still included in electricity production. At the time of writing, the input data for the NetZero2040 scenarios (such as renovation rate, thermal quality, exchange rate to renewables) have not yet been published (NetZero2040, 2024).

Projections for Austrian settlements in the scenarios show population growth and a similar renovation rate as today, but with deeper renovations resulting in lower energy demand per square meter of renovated space. Overall, the final energy demand for heating is expected to decrease by 10 to 50 % by 2040/2050, despite population growth and increasing heated area, due to an assumed constant capita per floor area. This reduction is largely driven by thermal renovation and partly driven by climate change. The demand for cooling energy is anticipated to rise significantly, depending on the climate scenario, but remains low in absolute terms (see Figure 3.7 and Figure 4.12). Building design must account for rising temperatures to minimize cooling demand (Frischknecht et al., 2020). HVAC systems will shift from fossil fuels to renewable sources, primarily heat pumps, but also district heating (fossil-free), biomass and, to a lesser extent, direct electric heating. In all back-casting scenarios, building operations can be achieved without fossil fuels. However, achieving this sooner requires a higher renovation rate and faster replacement of HVAC systems. Yet, all forecasting scenarios still include some fossil fuel use by 2050, while all of the backcasting scenarios, by definition, phase out fossil fuels.

Biomass use for heating is constrained by its sustainable potential, primarily sourced from residues in the saw, paper, and pulp industries, with some contributions from wood. The biomass must be allocated across different applications, including combined heat and power (CHP) plants, direct heat use in district heating systems, and decentralized biomass stoves. Additionally, wood is used as a building material, acting as a temporary $CO_2$ sink. However, the growing demand for biomass in the industry, particularly as a raw material for chemical products, limits its availability for energy use. As a result, the share of biomass in the overall energy system will remain small compared to electricity generated from renewable sources. Some biomass may also come from sawmill waste or imported biomass (see Sections 2.1.1, 2.3.2).

Required adaptation measures for buildings will be the renovation to much lower space heating energy demand values than current building codes require. Additionally, the adaptation to higher ambient temperatures decreases the winter space heating demand (at times when energy costs are high due to reduced renewable energy production) and increases the need for space cooling energy (at times when sufficient renewable energy from PV and hydropower is available) (see Sections 4.5.2, 4.5.3). As a result, further tightening building code requirements remains a topic of debate.

Figure 3.7 shows that across all climate scenarios analyzed (from +1.3°C for RCP 2.6 in 2050 to +4.3°C for RCP 8.5 in 2080 – i.e., the projected future local mean temperature increases, in this case in Innsbruck, compared to today's mean), the reduction in heating demand exceeds the increase in cooling demand for single-family houses (OIB, 2019, 2023; Streicher et al., 2024b). Cooling demand only becomes evident when temperatures rise more than 2°C. Similar findings are, e.g., reported by Schöniger et al. (2023), Suna et al. (2024), and Sonnleithner et al. (2023). Ziemele et

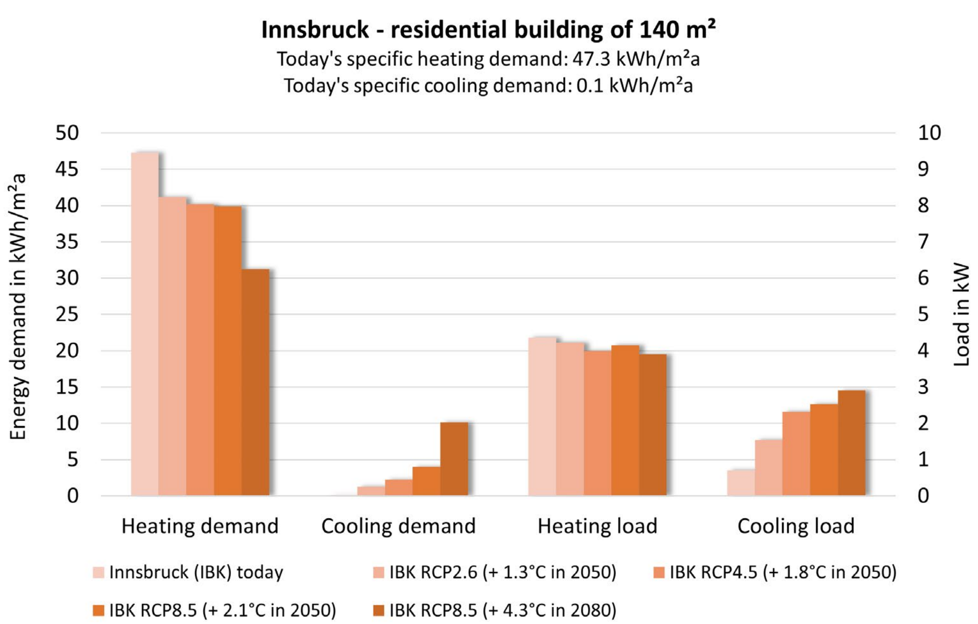



**Figure 3.7** Space heating and cooling energy demand (left y-axis) and corresponding heating and cooling loads (right y-axis) for a single-family house in Innsbruck, comparing current conditions (based on 2000–2019 weather data, with radiation data from 1996–2015) with future projections for 2050 (under three distinct climate scenarios) and 2080 (under one scenario) in Innsbruck (Streicher et al., 2024b).

al. (2023) found comparable results for Riga, while Wilbanks et al. (2008) reviewed studies in the U.S., and Elnagar et al. (2023) performed an analysis for cases in Belgium, factoring in renovation rates.

In summary, the literature consistently shows a decrease in winter heating demand during periods of limited renewable energy production, coupled with an increase in summer cooling demand during periods of high renewable energy availability. Therefore, climate change does not pose an increased risk to the energy system in terms of heating and cooling demand. However, the design of flexible HVAC systems that can provide both heating and cooling – such as heat pumps integrated into ceiling- or air-based systems – is a cost-effective adaptation strategy to address climate variability (*high confidence*).

### Improve, Shift and Avoid measures in the building sector

The thermal renovation rates and renovation depth, i.e., space heating demand after renovation (improve) and replacement of heating system rates (shift), are estimated to be between 1.3 and 3 % per year for renovation and 3 and 5 % per year for replacement of HVAC equipment in all scenarios mentioned in the previous section. The lower end of this range reflects historical trends, where most renovations or replacements occur only when components fail, reach the end of their lifecycle, or change ownership. The classification of improve and avoid is done according to the Cross-Chapter Box 4.

Based on these assumptions, the costs for high level renovation or replacement are calculated as the difference between the standard renovation/replacement costs and those for achieving high energy efficiency and renewable energy standards (i.e., additional costs). Using the historic renovation/replacement rate, a reduction of the final energy demand of buildings (including household electricity, domestic hot water, space heating and cooling) is calculated to be approximately 14 % (WEM/WAM) to 30 % (Ebenbichler et al., 2018) by 2050, for different renovation depth assumptions, i.e., the space heating energy consumption assumed in the renovation scenarios after the thermal renovation of a building is varied between current maximum allowable space heating demand values of OIB 6 (thematic guideline number 6 by the 'Österreichisches Institut für Bautechnik') (OIB, 2019) down to half of these values.

In all backcasting scenarios (Tyrol 2050, Transition Scenario, Ebenbichler et al., 2018) 100 % renewable energy supply is achieved. However, in some forward scenarios (WEM/WAM), the electricity demand for buildings is not fully decarbonized (see the previous Section). In some scenarios, the renovation/replacement rate is increased to achieve reduced energy consumption sooner, e.g., by 2040. In such cases, still functioning building components with residual value must be replaced, which increases the costs. With a thermal renovation rate of 3 % and a high renovation depth, the total final energy demand of buildings could be reduced by about 26 % by 2050 (Steininger et al., 2024) (*high confidence*).

Additionally, the production of essential renovation materials (insulation, windows, shading) and renewable-based HVAC systems (in all cited scenarios primarily heat pumps, but also district heating and biomass) will need to slightly increase. This has to be accompanied by the training and education of a larger workforce, including planners, plumbers, and craftsmen. Streicher et al. (2024a) estimate that the Tyrol 2050 scenario (Ebenbichler et al., 2018) would require an additional 580 and 660 installers and 44 and 36 planners for heat pumps and photovoltaic systems, respectively. These numbers can be multiplied by a factor of 12 to approximate the total Austrian demand (in relation to the population of Tyrol). Furthermore, legislation banning new oil and gas boilers has already been enacted (BGBl. I Nr. 6/2020; BGBl. I Nr. 8/2024). At present, a substantial subsidy for phasing out oil and gas is stimulating market growth (KPC, 2022; BMK, 2024c), and as economies of scale take effect and more products become available, both investment and installation costs are expected to decrease.

Steininger et al. (2024) recommend a combination of push and pull measures to drive policy action (for legislation, see Section 3.3.3). These include stricter building codes, prohibitions on new fossil-based HVAC systems, and incentives to accelerate the transition to fossil-free HVAC solutions. Subsidies should target technologies that are not yet widely available or lack sufficient expertise in production, planning, and installation. Current building codes (OIB, 2019) optimize investment and operating costs, resulting in designs close to passive house standards. However, buildings with higher energy demand (and cost) are allowed if the efficiency of the HVAC system is 30 % higher than a reference system or a rooftop PV is integrated (dual way), even if the efficiency of the building itself is not directly linked to the HVAC system or the renewable energy produced by the building. The WEM and WAM scenarios, as well as the Tyrol 2050 scenario (Ebenbichler et al., 2018), slightly reduce the allowable OIB 6 useful energy demand for space heating; Ebenbichler et al. (2018) even halve the current OIB 6 values. Listed buildings are not included in OIB 6 as they represent a small proportion of the total building stock. Subsidies for these measures should be phased out once market demand is met or prices fall to sustainable levels. Public acceptance can be improved ensuring sufficient skilled labor and affordable costs to normalize these technologies (similar to the adoption of triple-pane windows in Austria, Germany and Switzerland) (*robust evidence, medium agreement*).

The current standards for snow loads (Austrian Standards, 2022; last adaptation in 2022, ÖNORM B1991-1-3:2022-05) or the publicly available data on flood zones, landslides, etc. in a report from the Austrian Government (BML, 2023) show that the requirements are continuously adapted and used to improve related building standards. Existing buildings may need to be adapted to the changing requirements (*medium evidence, high agreement*).

Avoid (sufficiency) measures in the building sector include, e.g., reducing the square meters of living space per person, reducing heating/increasing cooling set-temperatures, and reducing the number of technical appliances (Zimmermann, 2018). The current average net-living-area in Austria is about 47 $m^2$/person. This has increased from about 32 $m^2$/person in the year 1990 (Statistik Austria, 2004, 2022c). The room temperature for the calculation of energy certificates has even been increased from 20 to 22°C in recent years to better reflect reality (e.g., Austrian Standards, 2019). One avoiding strategy is the taxation of long-term vacant apartments, a measure currently implemented in the federal provinces of Tyrol, Styria, and Salzburg, and planned for adoption throughout Austria (Koller et al., 2023; Parlamentsdirektion, 2024b) (*robust evidence, medium agreement*).

### Chapter Box 3.2. Energy storage in buildings – technologies and needs

**Introduction:** The growing reliance on variable renewable energy sources has heightened the need for energy storage and demand adjustments. Buildings, due to their size and thermal inertia, represent significant opportunities for flexibility. This chapter box explores (1) current energy storage technologies and demand response in buildings, (2) load-shifting and storage potential in Austria's building stock, and (3) barriers, drivers, and policy requirements. Related e-mobility considerations are addressed in Chapter Box 3.3.

**State-of-the-art energy storage and demand response in buildings:** Thermal energy storage, the most common method in buildings, is used for domestic hot water and space heating. Storage types include (Borri et al., 2021):

- Sensible heat storage: Uses water tanks or the thermal mass of buildings (e.g., concrete floors). Effective for day-to-night storage up to a maximum of 2-3 days, it is widely used for its simplicity and cost-effectiveness, allowing for short term demand shifting in systems with heat pumps or electric boilers (Miara et al., 2014; Bechtel et al., 2020; Fitzpatrick et al., 2020). However, it involves increased heating demands due to thermal losses in water storage systems or slight overheating in winter (and undercooling in summer) within buildings (Pasqui et al., 2023). Despite this, local renewables and off-peak electricity can offset costs and GHG emissions (Mascherbauer et al., 2022b; Schöniger et al., 2024).
- Latent heat storage: Relies on phase-change materials (PCMs) to maintain specific temperatures but faces challenges in efficiency and implementation. Streicher et al. (2008) could find no advantages of phase change materials as energy storage in buildings compared to water or thermal masses.
- Chemical and sorption-based storage: Offers high-capacity, long-term storage with minimal losses, but remains costly and complex (Ding and Riffat, 2013; Bao and Ma, 2022). As a result, this type is virtually absent from the market.

Battery systems, increasingly paired with photovoltaic (PV) installations, align energy generation with household demand. However, their high costs and limited seasonal storage capacity primarily confine their usage to short-term applications, such as daily or weekly energy balancing (Ochs et al., 2021; Li et al., 2023). Advanced hydrogen systems with fuel cells, while flexible, are even less cost-effective.

**Flexibility and energy storage in Austrian buildings:** Buildings equipped with heat pumps and thermal storage systems can stabilize electricity and district heating grids on a daily basis (Schöniger and Morawetz, 2022; Suna et al., 2022). Studies such as by Heidenthaler et al. (2023) and Wolisz et al. (2016) highlight thermal activation and preheating/cooling as key mechanisms for demand shifting, even over several days. Research by Tosatto et al. (2023) and Magni and Ochs (2021) projects significant load-shifting potential in Austrian regions, while Turner et al. (2015) confirms precooling benefits in lightweight structures. Overall, thermal mass insulated from indoor air proves critical for demand flexibility (Reynders et al., 2013; Masy et al., 2015; Le Dréau and Heiselberg, 2016; Luo et al., 2020).

Nationally, dynamic pricing shows potential to optimize electrified heating systems, but incentives remain insufficient for consumers (Mascherbauer et al., 2022a; Schöniger et al., 2024). Thermal inertia studies estimate 50 % of peak heating loads can be shifted to off-peak periods in post-1980 buildings (Weiß et al., 2019). By 2040, demand-response-optimized heat pump operation could achieve cost reductions of 50-75 % (Amann et al., 2023b).

**Barriers, drivers and policy needs:** Variable electricity tariffs, such as real-time pricing, could incentivize demand-side flexibility (Fitzpatrick et al., 2020). Studies suggest regulations are needed to balance retailer profits and consumer welfare (Guo and Weeks, 2022). While savings from smart systems currently only marginally outweigh their costs, future high renewable energy integration could increase their value.

For flexibility adoption to grow, policies must standardize and subsidize smart systems. By 2050, widespread heat pump use and supportive policies could significantly impact electricity grids and renewable energy integration. Challenges and opportunities in decarbonizing energy are further discussed in Sections 4.5.2 and 4.5.3.

### 3.3.2. Construction products

Population growth, increasing per capita net floor area, sustainability concerns and changing lifestyles are contributing to a significant increase in both new construction and building renovations (IPCC, 2021b). As a result, the production of construction products used for new buildings and renovations represents 11 % of total global energy- and process-related GHG emissions, with steel and cement production contributing more than half of these emissions (Röck et al., 2020). Consequently, there is growing interest in utilizing materials with low embodied environmental impacts. In addition, the reuse and recycling of materials is becoming increasingly important to reduce the demand for new resources. In Austria, 2.4 million buildings – both residential and non-residential (see Table 3.1) – are responsible for a significant portion of GHG emissions. While most of these emissions come from the operational phase of buildings, an increasing share is associated with the production of construction materials, which is typically attributed to the industrial sector or associated with electricity use and therefore falls under the emissions of the energy sector. In order to meet its climate goals, Austria aims to significantly reduce these building emissions by 2040 (see Section 3.3.1), which can only be achieved if both operational and embodied emissions reduced simultaneously.

More than half of the emissions of new buildings can be related to the embodied emissions of materials when considering the entire lifecycle (IEA, 2019; Frischknecht et al., 2020; Röck et al., 2020). In a study by Truger et al. (2022) for Austria, total GHG emissions associated with the building stock increase by a factor of 3 to 4 when the system boundaries are extended to include the entire lifecycle of buildings (including the embodied emissions of buildings), ranging from 7 $MtCO_2eq$/year (Table 3.3) of direct operational emissions (i.e., 10 % of national emissions) to 22-31 $MtCO_2eq$/year for Austria. In this sense, the most promising decarbonization measures for materials listed in the decarbonization roadmap currently developed by the EU (Le Den et al., 2023) are related to the embodied impacts of the products and materials used in buildings. They can be grouped into the Avoid-Shift-Improve (ASI) framework as follows (see also Cross-Chapter Box 4):

- **Avoid:** Focus on minimizing resource use by repurposing existing products and optimizing material efficiency. Examples include reusing building components, integrating void formers into concrete slabs, and optimizing structural designs to reduce material demand.
- **Shift:** Transition to alternative materials that are circular, low-carbon, or bio-based, thereby reducing environmental impact and supporting sustainable practices.

- **Improve:** Enhance the efficiency and sustainability of current production methods. This involves increasing the share of renewable energy used in manufacturing processes and integrating technologies like carbon capture to reduce emissions.

The recently released UN report 'Building Materials and the Climate: Constructing a New Future' (United Nations Environment Programme and Yale Center for Ecosystems + Architecture, 2023) provides a comprehensive overview of measures to decarbonize construction materials. These efforts are further bolstered by evolving EU legislation, particularly within the framework of the EU Green Deal, which aims to reduce GHG emissions across member states (COM/2019/640 final). Key directives under this framework include initiatives promoting circular economy procurement and the ongoing revision of the Construction Product Regulation (CPR) (European Commission, 2020a). These focus on enhancing environmental sustainability and establishing robust markets for the reuse and recycling of construction materials. In addition to the regulations on the European level, i.e., the Energy Performance of Buildings Directive (Directive (EU) 2023/1791) and the CPR, Austria is preparing its own directives (OIB, 2023), which align with and build on EU measures, as detailed in Section 3.3.3. In addition, more emphasis needs to be placed on equipping building stakeholders with the knowledge and skills needed to effectively implement these decarbonization measures.

Scenarios for the decarbonization of building products that align with the Austrian context include:

- Minimizing the use of new building products by leveraging existing structures. Refurbishing the existing building stock not only reduces the need for new materials but is also essential to reducing carbon emissions from older buildings. This approach is highlighted in the updated Energy Performance of Buildings Directive (EPBD, European Commission, 2024b).
- Utilizing construction products with low embodied emissions (Frischknecht et al., 2019; Röck et al., 2020).
- Improving embodied emissions in material production. Advances in production processes and improved energy mixes can lower emissions (Potrč Obrecht et al., 2021). Alaux et al. (2024) demonstrated how future material production trends may influence the sector's overall carbon footprint.
- Adopting circular economy principles, which can significantly reduce embodied emissions (Ghisellini et al., 2018; Malabi Eberhardt et al., 2020; Mirzaie et al., 2020) – see also Cross-Chapter Box 5. However, data on the potential reuse of materials from existing stocks is sparse. In Vienna, researchers are investigating the local potential (Lederer et al., 2020; Lederer and Blasenbauer, 2024), while the project 'Kraisbau', funded by the Austrian Research Promotion Agency (FFG), aims to provide further estimates (Kraisbau, 2022). In this context, more emphasis should be placed on building design to tailor new buildings for circular (re)use (Kanters, 2020; Akhimien et al., 2021).
- Reducing material use through efficient construction techniques: For example, comparing prefabricated woodframe houses with traditional solid construction methods, such as those using resource-intensive materials like reinforced concrete or masonry, and incorporating void formers to reduce the volume of concrete or other materials required, demonstrates how resource efficiency and reduced embodied carbon can be achieved in construction (Mañes-Navarrete et al., 2024).
- Incorporating carbon storage in materials: The EU's provisional agreement on a certification framework for carbon removal promotes the temporary storage of carbon in durable materials, such as wood-based construction products, that are intended to remain in the building for at least 35 years. However, when a comprehensive, system-wide boundary is applied to the analysis, it becomes clear that the promotion of wood-use in buildings is only advantageous over reduced harvesting under certain conditions (*high confidence*). Maierhofer et al. (2024) for Austria find that key criteria such as a high carbon intensity of the energy system and the efficient and sustainable use of wood building materials are critical for realizing these benefits. Similar conclusions are reached by Fehrenbach et al. (2022) and Soimakallio et al. (2022), which are in line with assessments using discounting principles (Peng et al., 2023) (see also Section 2.3.2).

Alaux et al. (2024) quantified the potential reductions in GHG emissions for various materials, taking into account decarbonization strategies such as better energy mixes, circular practices, and production advances. While a 10 % reduction seems possible for most materials, wood could even reach 35 % by 2050, but only if the extended scope is not considered, as shown by Maierhofer et al. (2024). Achieving climate goals will ultimately require decarbonizing the entire construction lifecycle, including materials (European Commission, 2020b; Toth et al., 2022) (*robust evidence, medium agreement*).

### 3.3.3. Legal reforms – barriers and perspectives

Austria is known for its high building standards, which excel in thermal quality, durability, ecological considerations, affordability, and social aspects of housing. There is a strong political commitment to meet international GHG reduction targets, aiming for net zero emissions by 2040 – ten years ahead of the 2050 global benchmark. This ambition is reflected at the federal level in the government program of the ÖVP-Green coalition (2020–2025) (BKA, 2020) and in several federal provinces, such as Vienna. Despite this commitment, experts are skeptical about the feasibility of achieving these goals with the measures currently in place (Habert et al., 2020; Steininger et al., 2024) (*medium confidence*).

#### Impact of EU legislation

Austria, a member of the EU since 1995, implements EU legislation in areas of EU competence, such as energy policy. Although housing is not directly under EU competence, related regulations have a significant impact on the sector, particularly with regard to climate targets. Key EU legislation includes the Energy Performance of Buildings Directive (first introduced in 2002, last revised in 2024) (European Commission, 2024b), as well as supporting measures such as the Energy Efficiency Directive (Directive (EU) 2023/1791), the revised Renewable Energy Directive (Directive (EU) 2023/2413), and the Alternative Fuels Infrastructure Regulation (European Commission, 2024a). The following key EU legislative frameworks are shaping Austria's energy and buildings policy:

- The European Climate Law 2021 (Regulation (EU) 2021/1119) mandates climate neutrality by 2050, a 55 % reduction in GHG emissions by 2030 compared to 1990 levels ('Fit for 55'), and outlines implementation mechanisms. Several of the twelve proposed measures target the construction, housing, and real estate sectors.
- The Energy Performance of Buildings Directive (EPBD) (draft revision, 2021): As part of the Fit for 55 package, this directive proposes a mandatory zero-emission standard for all new buildings starting in 2030 (COM/2021/802 final). It also aims to tackle inefficiency in existing buildings by progressively phasing out the 15 % of properties with the highest energy consumption through rental and sale bans. To boost renovation rates, the directive includes financial support measures to cushion the impact on low-income households, facilitating compliance while ensuring social equity.
- Inclusion of buildings in the EU Emissions Trading System as of 2026: This expansion, combined with the already existing $CO_2$ pricing mechanism, will increase the cost of heating with fossil fuels like oil and gas.
- The tightening of the Renewable Energy Directive (Directive (EU) 2018/2001) puts further pressure on national legislation to phase out oil and gas, not only with subsidies but also using regulatory measures.
- The Energy Efficiency Directive (Directive (EU) 2018/2002) sets a renovation target of 3 % for public buildings.
- The Effort-Sharing Regulation (Regulation (EU) 2018/842) tightens emission reduction targets, imposing stricter national obligations.
- The new Environmental, Social, and Governance (ESG) criteria (COM/2023/314 final) and the EU Taxonomy Regulation (Regulation (EU) 2020/852) are likely to be a game-changer for commercial real estate, as they will make it much more difficult to finance properties with poor thermal efficiency, leading to a reduction in the value of such buildings.

In response to the energy market disruptions caused by Russia's invasion of Ukraine, the European Commission introduced the REPowerEU Plan (European Commission, 2022b). This strategy focuses on diversifying energy sources, accelerating clean energy adoption, and promoting energy savings. Integrated into the EU Recovery and Resilience Facility (RRF), the plan enforces even stricter regulations under the already demanding frameworks. These developments underscore the increasing regulatory pressure on Austria's housing and energy sectors, with significant implications for achieving climate resilience (*high confidence*).

#### Existing legal regulations and measures

Austria has long pursued legal reforms in its building sector to advance climate protection, heavily influenced by EU legislation. Among the key elements of the regulatory framework is the Condominium Act ('Wohnungseigentumsgesetz') (BGBl. I Nr. 70/2002), which introduced reforms such as revised quorum rules to facilitate decision-making within condominium owners' associations. These changes make it easier to implement building decarbonization measures. In addition, mandatory minimum contributions to reserve funds ensure that more financial resources are available, allowing investments to be made without relying solely on external financing.

The Limited-Profit Housing Act ('Wohnungsgemeinnützigkeitsgesetz') (BGBl. Nr. 139/1979), provides the most supportive framework for decarbonization. Limited-Profit Housing Associations (LPHAs, 'Gemeinnützige Bauvereinigungen') benefit from strong financing mechanisms such as the 'maintenance and improvement contribution', which can be as high as $EUR_{2023}$ 2.33 per square meter per month. LPHAs can also use energy savings contracting and enforce rent increases after retrofits, making them particularly effective for large-scale energy efficiency projects.

On the other hand, the Tenancy Act ('Mietrechtsgesetz') (BGBl. Nr. 520/1981), has proved resistant to reform due to enduring ideological divisions among political parties. This is particularly problematic in the segment of older rent-protected buildings built before 1945, where energy efficiency has no impact on allowable rents. As a result, it remains difficult to recover retrofit costs through rent adjustments.

Construction law, administered by Austria's federal provinces, has significantly improved energy performance standards primarily in response to EU directives such as the EPBD (European Commission, 2024b). In order to harmonize regional building laws, the OIB has issued thematic guidelines, including guidelines on energy saving and thermal insulation ('Richtlinie 6', OIB, 2019). A new thematic guideline ('Richtlinie 7') on the sustainable use of natural resources is about to be adopted and implemented (OIB, 2023). Other relevant regulations include the Building Energy Performance Certificate Act ('Energieausweis-Vorlage-Gesetz') (BGBl. I Nr. 27/2012) and the Heating and Cooling Costs Billing Act ('Heiz- und Kältekostenabrechnungsgesetz') (BGBl. Nr. 827/1992).

In terms of financial incentives, both the federal and provincial governments offer extensive subsidies for building renovation and heating system replacement. The federal provinces provide around $EUR_{2023}$ 500 million anually (Amann, 2019; Amann et al., 2023a). Federal initiatives include the Refurbishment Initiative ('Sanierungsoffensive'), the Out of Oil and Gas Bonus ('Raus aus Öl und Gas Bonus'), and Clean Heating for All Initiative ('Sauber Heizen für Alle'), which can cover up to 100 % of the costs of replacing heating systems for households at risk of poverty. Subsidies totaling $EUR_{2023}$ 2.66 billion will be available between 2024 and 2027 (Amann et al., 2023a). In early 2024, the federal government has announced additional support from the Housing Package ('Wohnbaupaket') (Parlamentsdirektion, 2024a).

Provincial housing subsidies are based on regional laws and decrees, and federal subsidies are administered under the Law on Domestic Environmental Subsidies ('Umweltförderungsgesetz') (BGBl. I Nr. 152/2023). Recent tax incentives, although less prominent, include measures to benefit homeowners through income tax reductions and businesses through corporate tax adjustments (*medium evidence, high agreement*).

## Pending legal reforms

One of the most significant policy instruments in the Austrian political system is the Fiscal Equalization Act, which regulates the distribution of funds between the federal state, provinces, and municipalities, usually for a five-year period (see also Section 6.4.1). The latest agreement, reached at the end of 2023, introduced several changes. While housing subsidies have always played an important role in previous financial equalization agreements, almost all authorities have now been transferred to the federal provinces. As a result, the current financial equalization scheme contains few regulations on housing. Notably, a 'future fund' has been established, allocating approximately $EUR_{2023}$ 300 million per year for housing-related measures. These funds are available if certain renovation and land consumption targets are met, with an equivalent amount earmarked for increasing the share of renewable energy.

The Renewable Heat Act (BGBl. I Nr. 8/2024) prohibits the installation of oil and gas boilers in new buildings. However, it does not (yet) regulate the replacement of existing fossil fuel boilers. In addition to the Renewable Heat Act, housing law reforms are essential. A particular challenge is the Tenancy Act (or MRG, as introduced above), which has so far been largely resistant to reform. Essential reforms include the mandatory cooperation of tenants in the decarbonization of heating systems and the establishment of a fair distribution of the associated costs between landlords and tenants. The Condominium Act (WEG) also needs further reform to be aligned with decarbonization goals.

Land acquisition regulations ('Grundverkehrsrecht') could be used to reduce building-land hoarding (see Section 3.2). Housing subsidies, both for new construction and renovation, could be more explicitly linked to climate protection goals. The federal provinces have the primary responsibility for ensuring that no one is left behind on the path to climate neutrality. To stimulate climate-friendly investments in an economically sustainable way, policymakers could implement tiered incentive structures that prioritize long-term energy efficiency and carbon neutrality, as those outlined in the 'COVID-19 investment premium', while ensuring broad accessibility and minimizing deadweight effects (Weyerstraß, 2021).

### Preconditions for achieving building decarbonization by 2040

In addition to a massive reduction in the energy demand of the buildings and a switch to renewable energy sources (see Section 3.3.1), district heating systems need to be decarbonized. Simulations show that if the renovation rate is increased from the current 1.5 to 2.8 % by 2030, the entire thermally inefficient building stock could be completely renovated by 2040 (Amann et al., 2021). At the same time, nearly 700,000 oil-heated apartments will need to be converted by 2035, followed by more than one million gas-heated apartments by 2040 (in terms of registered main residences). Success in this area will depend on a significant increase in the number of buildings heated by district heating, biomass, or heat pumps (Amann, 2023; Streicher et al., 2024a).

While decarbonizing the building sector by 2040 is technically feasible, it depends on creating the right framework conditions. Key challenges include a shortage of skilled workers and the need for increased innovation. In addition, Austria's federal system, characterized by strong provincial autonomy and inadequate cooperation mechanisms, poses a significant obstacle. The current financial equalization framework is insufficient to address the scale of necessary reforms at both the federal and provincial levels. Therefore, new models of cooperation and coordination will be essential (Amann, 2023) (see also Section 6.4.1).

## 3.4. Transport and infrastructure

This section explores the role of transport and infrastructure in reducing emissions and adapting to climate change. Section 3.4.1 introduces the transport sector's emission trends and provides an overview of this subchapter. Section 3.4.2 focuses on decarbonization in the passenger transport sector, while Section 3.4.3 focuses on decarbonization in the freight transport sector. Section 3.4.4 discusses the GHG emissions embodied in road and rail infrastructure, as well as climate risks for transport infrastructure and related adaptation needs. Chapter Box 3.3 discusses the flexibility potential of electro-mobility in Austria.

### 3.4.1. Introduction

The transport sector is Austria's second largest emitter of GHGs after industry. In 2023, direct GHG emissions associated with the movement of people and goods within Austria, together with fuel sold domestically, totaled 19.8 million $tCO_2eq$, excluding international air traffic (Umweltbundesamt, 2024c). This corresponds to 29 % of Austria's total GHG emissions in 2023 (Umweltbundesamt, 2024c). Notably, transport remains the only sector where GHG emissions have not decreased since the base year 1990 (see Figure 3.8). After a continuous increase in emissions from 2012 onwards, significant reductions were observed only during and after the COVID-19 pandemic, as shown in Figure 3.8. These reductions were primarily driven by external factors: In 2020, GHG emissions fell by 13.5 % in a single year due to the pandemic and related lockdown restrictions that reduced transportation activity (Umweltbundesamt, 2024c). The low emission levels in 2022, similar to those in 2020, were largely influenced by Russia's invasion of Ukraine and the resulting European energy crisis, which drove up energy costs. The further decrease in emissions in 2023 was mainly attributed to lower economic output, which also reduced fuel exports from Austria (Heinfellner et al., 2024b).

In 2022 (the latest year available for Europe-wide comparison), renewable energy sources accounted for 10 % of energy consumption in the Austrian transport sector (European Commission: Eurostat, 2024). While this was slightly above the EU average, it remained significantly below the EU's 2030 target of 29 % (*medium evidence, high agreement*).

In 2023, roughly 34 % of total transport GHG emissions were generated by roadside freight transport, 65 % by roadside passenger transport and the remaining share by rail, shipping and domestic aviation. This highlights that transport emissions are overwhelmingly dominated by road transport. Within this category, diesel-powered passenger cars accounted for the largest share (42 %), followed by heavy-duty vehicles (26 %) and gasoline-powered passenger cars (23 %) (Heinfellner et al., 2024b).

International aviation is excluded from national emission inventories due to the lack of reporting requirements. While national domestic traffic accounted for only 0.2 % of total transport sector GHG emissions in 2023, the inclusion of international flights (originating or landing in Austria) would significantly increase this figure (Heinfellner et al., 2024b). Aviation emissions peaked in 2019 and, despite the dip during COVID-19, showed a strong upward trend af-

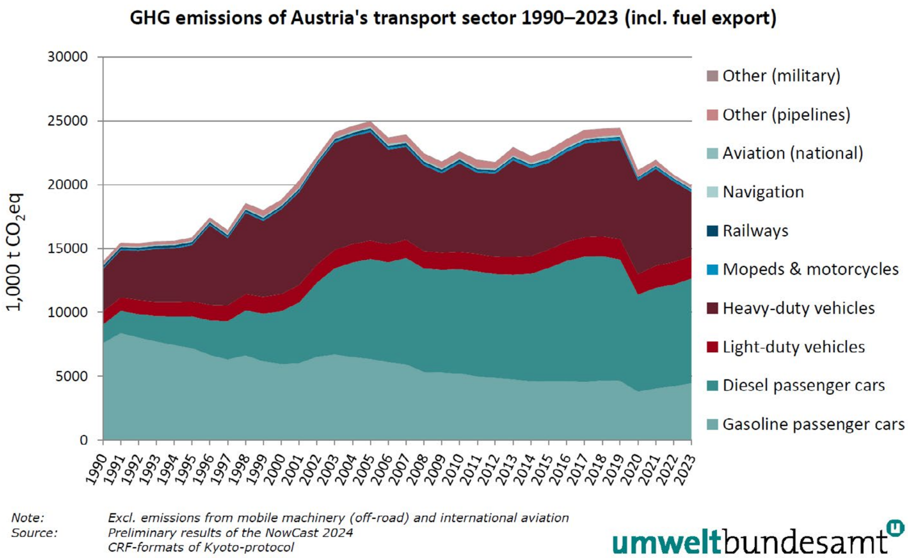



**Figure 3.8** Greenhouse gas emissions from Austria's transport sector from 1990 to 2023 (Heinfellner et al., 2024b).

ter the pandemic. By 2023, aviation emissions had already exceeded the level of 2018 (VCÖ, 2024a). Aviation affects global warming not only through GHG emissions, but also through nitrogen oxide ($NO_x$) emissions and the release of pollutants into sensitive atmospheric layers, leading to cloud formation effects. These combined factors amplify the aviation's impact on global warming, making its effect substantially greater than those of the GHG emissions alone (Lee et al., 2021) (*medium confidence*).

The intensity of direct emissions from different modes of transport is illustrated in Figure 3.9, which shows the GHG emissions per passenger kilometer for the main modes of transport using the latest available data from June 2024. There is a striking disparity between rail and road transport. This is largely due to the fact that 81 % of passenger trains run on a catenary system powered entirely by renewable electricity sources, with 95 % of the energy coming from hydropower and the remaining 5 % from other renewables (ÖBB-Holding AG, 2022). For aviation, Figure 3.9 includes the significant warming effects of GHGs other than $CO_2$ that are released into sensitive layers of the atmosphere (as explained above).

It is important to note that GHG emissions are not limited to the use of vehicles, but are also emitted during the entire lifecycle of an individual vehicle, including construction, disposal and recycling ('cradle-to-grave' emissions). For battery electric vehicles (BEVs), these indirect emissions include in particular those from energy production (De Blas et al., 2020; Owen et al., 2023) (*high confidence*). In Austria's official GHG reporting, such indirect emissions are not allocated to the transport sector, but to the industry or energy sector (if their source is in Austria). However, for most purchased vehicles, the construction phase takes place outside Austria. In addition, the construction, maintenance,

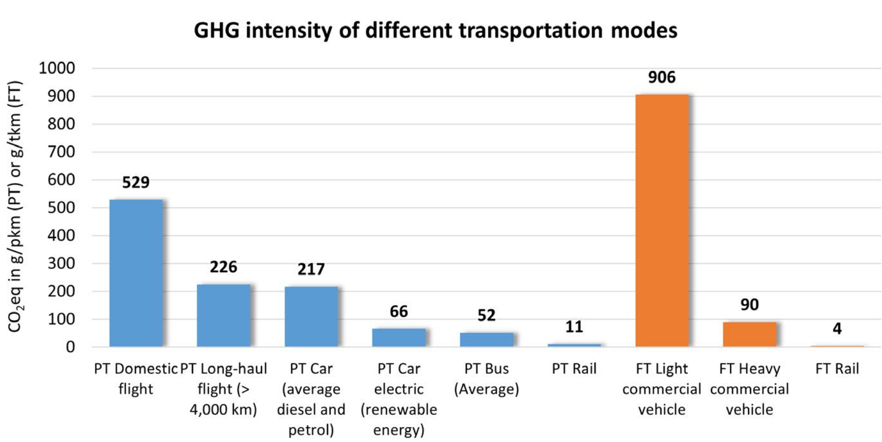



**Figure 3.9** Greenhouse gas intensity of different transportation modes in Austria as of June 2024: Passenger transportation (PT, in $gCO_2$eq per passenger-kilometer) and freight transportation (FT, in $gCO_2$eq per ton-kilometer) (Umweltbundesamt, 2024a).

and disposal of road and rail infrastructure contribute significantly to GHG emissions (see Section 3.4.4). For road infrastructure, emissions vary by road type, usage patterns, and surface material (e.g., asphalt versus concrete), adding an estimated 0.4–6.4 % to transport-related emissions (Gruber and Hofko, 2023). Rail infrastructure emits 60 % more than rail operations in Austria – this relatively large offset is due to the low operational emissions of Austrian rail systems, which are largely powered by renewable energy. From a stock-flow perspective, which assesses material stocks of existing infrastructure and the flows required for maintenance, walking and public transport are the most efficient in providing services in terms of resource use and emissions. Road transport, on the other hand, ranks lowest in this respect (Virág et al., 2022b) (*medium confidence*).

**Risks:** In the transport sector, climate change risks primarily relate to infrastructure disruptions and damage caused by extreme weather events. These lead to significant repair costs and can cause delays and uncertainty for both passenger and freight transport (*medium evidence, high agreement*) (Section 3.4.4).

**Impacts and adaptation mechanisms:** The main expected impacts of climate change on the transport sector are damage to infrastructure caused by extreme weather events. These can be mitigated through adaptation measures, such as protecting rail and road infrastructure from landslides or treefall, and using more heat-resistant surface materials (*medium evidence, high agreement*). Climate change is also expected to directly affect transport mode choices: Higher summer temperatures may reduce the attractiveness of active modes such as walking and cycling, while milder temperatures and lack of snow in winters may increase their attractiveness, leading to ambiguous and likely location-specific effects (*medium confidence*). In addition, destination preferences could shift; for example, lower altitude winter tourism areas in the Alps are likely to become less attractive (Li et al., 2024) (see also Sections 4.3.3, 7.4.2) (*medium evidence, high agreement*).

**Mitigation options:** There are numerous mitigation options for both freight and passenger transport that fit into the Avoid-Shift-Improve (ASI) framework (see also the Cross-Chapter Box 4):

- Avoid: Reduce GHG emissions by decreasing the number of trips.
- Shift: Reduce GHG emissions by shifting to transport modes with lower GHG intensity.
- Improve: Reduce GHG emissions by adopting less GHG-intensive technologies, especially in the (remaining) road-based traffic.

There is a broad consensus that no single policy is sufficient, but that comprehensive policy packages are needed to achieve the necessary reductions in GHG emissions associated with the transport of goods and people, as shown in two recent research projects (QUALITY, aPPRAISE) for the case of Austria (Thaller et al., 2021; Dugan et al., 2022; Hössinger et al., 2023) as well as in the recently published ‘Maßnahmenbericht Mobilitätswende’ (Heinfellner et al., 2024a) (*high confidence*). In particular, push policies such as pricing mechanisms and speed limits are essential. Similarly, pull policies (e.g., improvements in public transport) and technological advances alone will not be sufficient, especially as the availability of renewable energy remains a limiting factor – likely beyond 2040 (*robust evidence, medium agreement*). Rising electricity costs also pose a substantial risk to transport electrification by slowing the transition process (*medium confidence*).

Specific recommendations for Austria have been outlined in the Austrian 2030 Mobility Master Plan (MMP) (BMK, 2021b), on the basis of which strategies for different sub-areas of mobility have been developed and published. The MMP, the report ‘Pathways to Zero Carbon Transport Sector’ (Angelini et al., 2022) and the scenarios calculated by the Austrian Environmental Agency (Umweltbundesamt, 2023a) all show that a substantial modal shift away from road transport is necessary to meet Austria’s climate goals – continued growth in road-based travel (passenger-kilometers) and freight transport (ton-kilometers)[3] is considered unsustainable (*medium confidence*). Regarding infrastructure, besides limiting the construction of new infrastructure, mitigation options focused on emissions associated with the construction, maintenance and, in some cases, recycling of infrastructure are fairly limited (*medium confidence*). Some progress has been made in developing materials and technologies to reduce the embodied emissions (see also Section 4.2). Incentives to consider GHG reductions in the tendering process can be seen as a low-hanging fruit and key enabler (also for innovation) in this context (*medium evidence, high agreement*).

[3] Ton-kilometers or [tkm], measures the transportation of one ton of goods over one kilometer, a common metric unit in freight logistics.

Most mitigation options in the transport sector have significant co-benefits (see Section 8.3.1), including reduced pollution, improved public health, improved quality and availability of public spaces (as cars take up about 10 times more space than other mobility modes), and mitigation of urban heat islands (UHIs) (Sovacool et al., 2021; Maier et al., 2023) (see also Section 3.2.3 Integrated mitigation and adaptation strategies) (*high confidence*). Reducing reliance on private car ownership could not only substantially reduce material demand, including for electric vehicle batteries (see Haas et al., 2025) (see Section 4.2), but also reduce household mobility expenditures (Schönfelder et al., 2016) (*high confidence*). In addition, higher taxation on vehicle ownership or use (e.g., through road pricing) could generate broader co-benefits by allowing the redistribution of tax revenues for investment in, for example, public transport. Such measures may become essential as electrification reduces public revenues from fuel taxes, which together with associated VAT revenues currently account for about 5 % of Austria's national public tax revenues (BMDV, 2022) (*high confidence*). Finally, Chapter Box 3.3 describes the potential of electric vehicles (EVs) to address the issue of uneven renewable energy distribution and the resulting need to balance residual loads.

Many of the most effective mitigation options, which are typically fiscal and regulatory in nature, face significant implementation challenges. These difficulties stem from the involvement of multiple governance levels (see Section 6.4.1), vested material interests from industries such as automotive (Gössling et al., 2016; Pichler et al., 2021) and construction industries (see Sections 6.2, 6.4), and deeply entrenched societal norms and perceptions regarding private vehicle use and ownership (Mattioli et al., 2020) (see Sections 6.2, 5.3.1, 5.3.2), which in turn reduce public acceptance of stringent policies (*high confidence*).

Transport is a recurring theme throughout this report and is addressed from a number of perspectives. Chapter 4 examines GHG emissions embedded in infrastructure, energy demand from electrification, and emissions associated with the tourism sector. Chapter 5 looks at inequalities in emissions between socio-economic groups (5.2.2), public acceptance of policies (5.6.3), and the influence of lifestyles and norms (5.3), issues that are also related to mobility. Sections 6.2 and 6.4 discuss how the automotive industry hinders the implementation of effective policies, while Section 6.5.1 outlines the Austrian legal framework for transport. Chapter 7 deals with mobility and tourism in the Alpine region. Chapter 8 presents mitigation scenarios involving the transport sector (Section 8.4), its contribution to achieving the Sustainable Development Goals (SDGs) (Section 8.3.2), and the costs and potentials (Section 8.3.1) for decarbonizing the transport sector.

### 3.4.2. Person mobility

#### Status quo and trends

**Transport performance:** In 1990, approximately 76.7 billion passenger kilometers were traveled in Austria. By 2019, the last year before the COVID-19 pandemic, this figure had increased by 41 % to about 107.9 billion passenger kilometers (European Environment Agency, 2022), while the Austrian population grew by only about 16 % over the same period (Statistik Austria, 2022a). Mobility surveys conducted in 1983, 1995, and 2013/2014 show that the average daily travel distance of Austrians has steadily increased from 22 to 29 to 34 kilometers, respectively. Remarkably, the average daily travel time has remained almost unchanged at around 70 minutes (European Environment Agency, 2021b). This increase in passenger kilometers per capita, especially by car, correlates with several trends: The emergence of decentralized settlement structures (see Section 3.2.1), the functional segregation of livelihood functions, the expansion of 'social network geographies', and the continuous expansion of transport infrastructure (see Section 3.4.4). In addition, tourism contributes significantly to travel demand in Austria, as described in Sections 4.3 and 7.4.2.

**Modal split:** In 2022, motorized individual transport – including passenger cars and motorized two-wheelers – accounted for approximately 68 % of total domestic passenger transport performance (Heinfellner et al., 2024b). In 2018, the modal split at the trip-level was distributed as follows: 16 % for walking, 7 % for cycling, 61 % for car, and 16 % for public transport (BMK, 2021b). However, when evaluated by distance traveled, only 3 % of the total distance was covered by active modes (walking and cycling), reflecting their shorter average trip lengths, 27 % by public transport, and 70 % by car (European Commission: Directorate-General for Mobility and Transport, 2023). Despite the dominance of car travel, Austria stands out within the EU for its comparatively high use of public transport (Odyssee-Mure, 2022a).

The modal split is strongly influenced by the spatial characteristics of residential areas. For instance, car usage accounts for only 26 % of trips made by residents of Vienna (Wiener Linien, 2023). However, for commuters crossing Vienna's city limits from the surrounding regions on weekdays, the car modal share increases significantly to 77 % (Magistrat Wien, 2023). Despite the fact that many trips cover relatively short distances, car use remains prevalent: 40 % of all car trips are less than 5 km (BMK, 2016, Fig. 4.5–14). During and after the COVID-19 pandemic, the private car emerged as the 'winner' of the crisis, while active mobility gained attention as a promising alternative, especially at the expense of public transport (Hauger et al., 2022). Early data from post-pandemic years suggest that active mobility has maintained a higher modal share compared to pre-pandemic years (Bronnenmayer, 2024). The popularity of e-bikes has surged in recent years, with approximately one in two bicycles sold being an e-bike, resulting in a total stock of approximately 1.1 million e-bikes in Austria (BMK, 2023b). On the other hand, newer mobility forms such as e-scooters and car-sharing or car-pooling currently hold a small modal share (primarily in urban areas). Overall, these modes mainly tend to replace trips that would have been made by cycling, walking or public transport, especially in the absence of measures discouraging private car ownership and use (Mock, 2023). Research from Vienna and Zurich indicates that private ownership of e-bikes or e-scooters is more likely to substitute car trips than shared micromobility options (Laa and Leth, 2020; Bieliński et al., 2021; Shibayama et al., 2021; Reck et al., 2022; Mock, 2023) (*medium confidence*).

**Emissions from car travel:** Motorized individual transport accounts for nearly 65 % of Austria's total transport emissions, making it the primary source of GHGs in the sector. Domestic GHG emissions from passenger cars and motorized two-wheelers increased from 8.9 million $tCO_2eq$ in 1990 to 11.5 million $tCO_2eq$ in 2023. Taking into account price-related fuel exports (fuel purchased in Austria but consumed abroad), these emissions increase further, from 1.0 million $tCO_2eq$ in 1990 to 2.2 million $tCO_2eq$ in 2023 (Heinfellner et al., 2024b). However, the volume of price-related fuel exports dropped significantly in 2022 due to high energy costs in Austria. The growing share of EVs in the Austrian fleet is expected to significantly reduce transport-related emissions in the medium term, driven by EU regulations that aim to phase out combustion engine vehicles by 2035 (with some exceptions) (Regulation (EU) 2023/851). By the end of 2023, purely electric vehicles accounted for 20 % of newly registered passenger cars (Statistik Austria, 2024e) and 3.0 % of the total passenger car fleet in Austria (Statistik Austria, 2023b). It is noteworthy that about 80 % of these electric vehicles are company cars. In an EU-wide comparison, Austria ranked fifth in EV adoption in 2022 (EAFO, 2023).

**Car ownership:** The motorization rate in Austria has increased significantly in recent decades, rising from 391 passenger cars per 1,000 inhabitants in 1990 to 566 per 1,000 inhabitants at the end of 2022 (Statistik Austria, 2023b), a figure close to the EU average (European Commission: Eurostat, 2023). Austria's car fleet is relatively young, with an average age of 8.7 years in 2021, one of the lowest in the EU, despite a gradual increase over time, which is likely to reflect improvements in vehicle durability (ÖAMTC, 2003; ACEA, 2023b). Car ownership patterns vary significantly by settlement type. A substantial proportion of households own more than one car, especially in smaller towns and villages. In municipalities with less than 10,000 inhabitants, 38 % of households owned more than one car in 2019/20, whereas in Vienna this figure was only 7 % in the same period. Notably, car-free households are more common in Vienna, with 47 % of households reporting no car ownership in 2019/20, compared to 41 % a decade earlier. By contrast, only 12 % of households in smaller municipalities reported being car-free (Statistik Austria, 2011, 2022b).

Austria has not yet experienced a significant decline in the acquisitions of driving licenses among young adults, a trend observed in several other countries. In fact, the number of licenses issued to individuals aged 15 to 24 increased slightly from 119,789 in 2019 to 121,667 in 2022 (Statistik Austria, 2023: 'Kfz-Lenkberechtigungen'). This suggests that outside of urban areas – especially Vienna – the 'peak car' phenomenon has arguably not yet been reached in Austria. At the same time, there has been a notable shift in vehicle preferences, with the market share of SUVs increasing dramatically in recent years. The share of SUVs rose from 8.2 % in 2005 to 21.0 % in 2015, and by the first half of 2023, SUVs accounted for 44.5 % of all new car registrations (VCÖ, 2023b). This trend has substantial environmental implications, as SUVs generally have a higher carbon footprint in both production and use than smaller, lighter vehicles.

**Socioeconomic aspects:** On average, households allocate about 12 % of their net income to mobility expenditures, a share that is consistent across income groups but reflects higher absolute spending in wealthier households (Schönfelder et al., 2016; Aschauer et al., 2019). Higher mobility spending is often associated with greater GHG emissions, largely due to the ownership of more and larger vehicles. Air travel consumption is also unevenly distributed, with highly educated, young, and urban individuals in Austria taking a disproportionate share of flights (Falk and Hagsten, 2021) (*medium evidence, high agreement*) (see also Section 5.2.2).

## Chapter Box 3.3. Flexibility potential of electro-mobility in Austria

**Introduction:** The expected demand for electricity from electro-mobility has important implications for the design of the electricity market, which is undergoing a transformative shift due to the expansion of renewable energy sources (see also Section 4.5). This shift transforms the market paradigm from one where flexible generation meets inflexible demand to one where flexible demand meets inflexible generation, requiring multiple flexibility options (Gea-Bermúdez et al., 2021; Plaum et al., 2022) (see also Chapter Box 3.2). Flexibility is critical not only for balancing generation and demand (Gade et al., 2022; Saffari et al., 2023), but also for addressing the uneven distribution of renewable energy and subsequent managing of residual loads (Allard et al., 2020). Greater demand-side flexibility can reduce reliance on fossil-fuel power plants, thereby reducing GHG emissions and minimizing curtailment of renewable energy. This, in turn, can encourage further investment in renewable energy sources (Loschan et al., 2023, 2024). In particular, electric vehicles (EVs) have a high flexibility potential (i.e., the difference between the load and the available capacity during the time span of the vehicle's connection to the power grid), even surpassing heat pumps (Karimi-Arpanahi et al., 2022; Kröger et al., 2023) (*medium confidence*).

**Impact of electro-mobility on electricity demand:** In a scenario where 50 % of passenger cars in Austria are battery-electric vehicles (BEVs) (2.5 million cars) with a specific energy demand of 16.60 kWh/100 km (Desai et al., 2023) and an annual mileage of 13,900 km (VCÖ, 2023a), the total annual charging demand would be 5.8 TWh. Fleet forecasts by Angelini et al. (2022), for light- and heavy-duty vehicles indicate an additional charging demand of 0.6 TWh by 2030. This would increase Austria's annual electricity demand, currently totaling 60.7 TWh (E-control, 2023), by 10 % (*medium evidence, high agreement*).

**Flexibility potential of electro-mobility:** EV demand-side flexibility can be used at the local level for peak shaving (Ioakimidis et al., 2018; Li et al., 2020; Van Kriekinge et al., 2021; Zheng et al., 2021) and valley filling (Zhang et al., 2014a, 2014b; Jian et al., 2017; Ioakimidis et al., 2018), leading to reduced renewable energy curtailment (Haddadian et al., 2015, 2016; Schuller et al., 2015). The chosen charging strategy affects the flexibility potential: For slow charging with lower charging power, vehicles are connected to the charging station for a longer period of time, while fast charging with higher power levels is mainly used when the connection to the charging station is limited to 1–2 hours. The flexibility potential is especially high during night hours (Flammini et al., 2019; Loschan et al., 2023), when the majority of slow charging processes take place (Speth and Plötz, 2024) (*medium evidence, high agreement*). It should, however, be noted that the full flexibility potential offered by EVs is constrained by the requirement to meet transportation needs and by the temporal and spatial availability of the charging infrastructure and the vehicle (Mills and MacGill, 2018).

**Bidirectional technology potential:** In addition to the potential of demand-side flexibility, Vehicle-To-Grid (V2G) technology ('bidirectional charging') allows the vehicle battery to be used to supply electricity to the system, further expanding the range of potential interactions between BEVs and the electricity sector (Misconel et al., 2022). For example, EVs can be used to transport electricity by charging at one location, driving to a destination, and discharging there to act as an electricity supplier, thereby reducing grid use (Khodayar et al., 2012; Verzijlbergh et al., 2014; Nikoobakht et al., 2019). This flexibility can further reduce the need for the expansion of transmission capacity and redispatch measures (Loschan et al., 2023), improve the balance between generation and demand (Bibak and Tekiner-Mogulkoc, 2022), and reduce peak demand (Tan and Wang, 2017). In this way, EVs can provide ancillary services and reserves (Thingvad et al., 2019; Osório et al., 2021; Figgener et al., 2022).

**Barriers, drivers and policy needs:** While the demand-side flexibility of EVs can support the decarbonization of the electricity market, it may simultaneously lead to increased electricity consumption (Tehrani and Wang, 2015; Gilleran et al., 2021). This could be problematic because the integration of non-dispatchable renewables, combined with the electrification of multiple sectors, leads to increased power flows over the transmission grid, resulting in congestion and consequently higher redispatch costs (Loschan et al., 2023). Compared to the demand-side adjustment of load, large-scale implementation of bidirectional charging, though promising, is facing more barriers such as increased battery wear due to frequent charge-discharge cycles and limited availability of V2G-capable vehicles and bi-directional chargers, which remain expensive (Goncearuc et al., 2024).

Overall, the future flexibility potential is highly dependent on the development of preferred charging strategies for the different applications and mobility patterns of EVs, as well as expansion strategies for public charging infrastructure (*medium evidence, high agreement*). Realizing the flexibility potential of e-mobility in the electricity system will require a robust regulatory framework to address challenges while unlocking opportunities for grid stability and sustainability (Gonzalez Venegas et al., 2021; Sadeghian et al., 2022; Loschan et al., 2023).

## Mitigation strategies

The scientific consensus emphasizes that achieving decarbonization of the transport sector requires a comprehensive mix of awareness-raising, regulatory, infrastructure and fiscal measures (*high confidence*). Integrated policy packages that combine *push* measures (banning, limiting, or disincentivizing carbon-intensive travel) with *pull* measures (making sustainable alternatives like public transport and cycling infrastructure more feasible and attractive) are the most effective approach (e.g., Dugan et al., 2022; Koch et al., 2022; Hössinger et al., 2023; Heinfellner et al., 2024a) (for local policies, see Section 3.2.2).

**Avoiding travel:** The COVID-19 pandemic demonstrated the potential of teleworking to reduce commuting and teleconferencing to reduce business travel, particularly air travel. However, due to rebound effects, such as increased local errands on home-office days, existing evidence is inconclusive about the extent to which travel avoidance is feasible (Maier et al., 2022) (*medium confidence*).

Effective spatial and settlement planning (Section 3.2.2) has significant potential in the medium to long term to reduce the frequency and distance of trips, while promoting active transport modes (avoid and shift). Strategies include urban 'city of short distances'/'15-minute city' concepts in urban areas and the revitalization of town and village centers in rural or semi-urban regions. These initiatives often focus on reducing car-centric infrastructure through lanes restrictions, road closures, increased parking charges or decreased parking spaces while ensuring daily destinations (e.g., workplaces, shops, and public services) are accessible by walking, cycling, or public transport (see Jandl et al., 2024) (see Section 6.5.1). Regulatory measures such as speed limits and the elimination of minimum requirements for parking facilities further support these goals (*high confidence*). More broadly, promoting sufficiency through changes in lifestyle (i.e., consumption) and changes in social and cultural norms can enhance acceptance of these measures (see Section 5.6.2).

**Shifting away from private motorized vehicles:** Efforts to shift travel away from private motorized vehicles include reducing the cost and improving the attractiveness of alternative modes (*high confidence*). For public transport, this includes simplified and affordable fares, such as the regional/national versions of the 'Klimaticket' (BMK, 2023c), as well as improved quality (e.g., reliability, frequency, integrated schedules) and expanded spatial and temporal coverage. Demand-responsive transport (DRT) can address mobility gaps in remote areas, consistent with a 'mobility guarantee' approach that minimizes the need for car ownership (Laa et al., 2022). For international travel, advancing high-speed rail, intermodal connections, and addressing capacity constraints (e.g., night trains) are critical, although challenges remain in the medium term (*medium confidence*). Improving biking and walking infrastructure – especially for shorter trips, which make up the majority – remains vital in both urban and rural areas (e.g., ETH Zürich, 2023) (*high confidence*).

**Electric vehicles as key technological improvement option:** Travel demand that cannot be avoided or shifted must rely on low-emission technologies that are energy and cost efficient across their entire lifecycle. For passenger road transport, BEVs best meet these criteria when powered by 100 % renewable electricity (Hoekstra, 2019; Fritz et al., 2021, 2022; BMK, 2022b) (*robust evidence, medium agreement*). Financial incentives (subsidies, tax reductions), regulatory measures (low emission zones, e-taxi mandates, see also Ajanovic et al. (2021) for the case of Vienna), charging infrastructure, and policies that enable the installation of charging points in shared housing are essential (Kumar and Alok, 2020) (*high confidence*). Economies of scale are expected to further lower the purchase cost of BEVs, reducing the need for subsidies (Wicki et al., 2022). EU bans on diesel/gasoline car sales by 2035 remain the most effective lever to accelerate this shift. Alternative fuels such as e-fuels – synthetic fuels produced using renewable electricity, water, and carbon dioxide ($CO_2$) – and hydrogen are unlikely to play a significant role in passenger transport due to lower efficiency and higher costs – e.g., Morrison et al.

(2024) estimate $CO_2$ abatement costs of over $EUR_{2023}$ 600 per ton (GHG emissions reduced in $CO_2$ weight equivalent) for e-fuels versus less than $EUR_{2023}$ 150 per ton for BEVs (see Section 8.3.2). Strimitzer et al. (2022) conducted an efficiency comparison in terms of the distance that can be traveled using 10,000 kWh of renewable electricity, demonstrating the energy efficiency of BEVs at 74 %, far surpassing hydrogen fuel cell vehicles (30 %) and e-fuels (15 %). However, e-fuels are likely to play a critical role in decarbonizing air travel, particularly for large aircraft (*medium confidence*).

**Pricing and subsidies:** Pricing strategies, in line with the user-/polluter-pays principle are essential for achieving the goals of avoiding trips, shifting to sustainable modes, and relying on technological improvements (Angelini et al., 2022). For instance, the recent 'Maßnahmenbericht Mobilitätswende' shows that increasing the mineral oil tax and introducing road pricing have the highest GHG emission reduction potential among 13 policy measures examined (Heinfellner et al., 2024a). Currently, Austria's road transport cost coverage ratio – covering variable external (e.g., environmental) and infrastructure costs with tolls, taxes and fees charged to users – is only 21 %, which is one of the lowest in Europe (European Commission: Directorate-General for Mobility and Transport et al., 2019). Compared to bans, pricing policies have the advantage of generating tax revenues that can be used to counterbalance negative distributional effects, especially in rural car-dependent regions (Axhausen et al., 2021). A distinction can be made between generic pricing instruments such as carbon pricing (the ETS will be expanded to cover transport from 2027 onwards: ETS 2) (European Union, 2024), and more specific instruments such as city tolls, parking fees and taxes on car ownership. With sufficiently high prices, all of these instruments have a high potential for influencing travel behavior in such a way that substantial $CO_2$ emission reductions can be generated (*high confidence*). Removing counterproductive subsidies (e.g., for company cars, commuting, or hybrid SUVs) also has significant potential to reduce emissions (Peneder et al., 2022) (*high confidence*). Similarly, introducing taxes on kerosene or other flight charges could encourage a modal shift away from air travel and lead to innovations that benefit aircraft efficiency (*medium evidence, high agreement*).

**Exceptional challenges in reducing car modal share:** Reducing the car modal share in rural and semi-rural areas remains particularly challenging due to the perceived convenience and reliability of cars (*high confidence*). Spatial planning policies – such as minimum standards for public infrastructure, expansion of public transport, and investment in walking and cycling – can enable shifts in the modal split. Studies suggest that a significant proportion of the population is willing to switch modes under these conditions (Millonig et al., 2022; Peer et al., 2023). In the medium and longer term, these efforts could lead to a reduction in car ownership, especially among households with multiple cars (*medium confidence*).

## Scenarios

The Environment Agency Austria (EAA) presents possible trajectories for transport-related GHG emissions (Umweltbundesamt, 2023a). In the With Existing Measures (WEM) scenario, only measures (that were) bindingly implemented or legally fixed by January 1, 2022, are considered. These are insufficient to reverse unfavorable trends. The WEM scenario predicts an increase in passenger transport to 126.7 billion passenger kilometers by 2040 and an increase in motorization to 639 cars per 1,000 inhabitants. By 2040, 69 % of passenger kilometers would rely on motorized private transport, with only 56 % of the fleet electrified. This results in GHG emissions of 10 million $tCO_2eq$ in that year (Umweltbundesamt, 2023b).

In contrast, the EAA's Transition scenario models complete decarbonization of transport by 2040 using a backcasting approach. Measures are tailored in design and intensity to achieve climate neutrality by this deadline.

Motorization stabilizes at around 570 cars per 1,000 people, with the fleet almost entirely electrified by 2040. This eliminates GHG emissions from private transportation and meets climate neutrality targets. However, this requires about 23.4 TWh of renewable electricity (a 35 % increase from the WEM scenario), putting transport in competition with other sectors. Issues around equitable distribution of limited renewable energy remain unresolved, with the transport sector accounting for 20 % of energy use in the 'Transition' scenario by 2040.

## Governance and acceptability

Legal and institutional challenges – such as the insufficient design and enforcement of existing measures – often hinder effective policy implementation (Jandl et al., 2024) (see Section 6.5.1). In addition, a critical barrier to implementation remains the lack of public acceptance, especially for stringent policy instruments (see also Heinfellner et al., 2024a) (see Section 5.6.3). Public opposition is, however, not limited to strict regulations, as the debates around the '15-minute city' concept show (Caprotti et al., 2024). Strategies for improving public support include (*high confidence*):

- Policy packaging: Combining push and pull measures can mitigate negative distributional effects, such as those felt by rural residents relying on cars for commuting (Thaller et al., 2021; Dugan et al., 2022; Hössinger et al., 2023; Heinfellner et al., 2024a).
- Participatory approaches: Co-design and stakeholder engagement increase legitimacy and acceptance.
- Awareness and co-benefits: Informing the public about policies' benefits can build support (e.g., Peer et al., 2023).
- Strategic implementation: Timing, coalition-building, trials, and gradual rollouts increase acceptance. For example, Stockholm's temporary congestion charge became a permanent policy after public support increased post-trial (Schuitema et al., 2010; Heyen and Wicki, 2024).
- Address spillover effects: Avoid unintended consequences, such as Vienna's parking permit system ('Parkpickerl'), which initially shifted parking demand to adjacent districts until more comprehensive policies were enacted.
- Making sustainable travel the default: Designing sustainable travel options in such a way that they are more convenient to use than less sustainable travel options (Section 5.5.1).

Recent surveys suggest that Austrians may be more open to regulatory and pricing policies than previously thought, with a majority viewing most measures positively or neutrally (Hössinger et al., 2023; Heinfellner et al., 2024a). Lack of acceptance of technological options may also hinder progress towards decarbonization (*high confidence*). For example, a substantial portion of the Austrian population remains reluctant to adopt electric vehicles (Priessner et al., 2018).

### 3.4.3. Freight transport

#### Status quo and trends

Like passenger transportation, freight transportation is a derived demand that results from the need to move goods. As a result, economic activity, typically measured by GDP, has historically been a reliable predictor of freight volumes and flows. However, changes in the structure of the economy – such as the growth in the service sector, changes in supply chains (e.g., just-in-time logistics), and policies affecting shippers and carriers – have weakened this correlation and reduced the accuracy of forecasts (Meersman and Van de Voorde, 2013; ITF, 2023). This decoupling is evident when comparing ton-kilometers per GDP unit across EU nations; Austria is in line with the EU average, but exceeds many Western European countries (Odyssee-Mure, 2022b). Despite this trend, the consensus points to continued growth in freight demand, driven in particular by the expansion of e-commerce.

**Emissions, modal split and freight demand:** Figure 3.10 shows the evolution of transport performance for road and rail since 1990. In particular, road transport performance has increased considerably over this time period.

Table 3.4 shows the freight transport demand for inland waterways, rail and road in 2023, categorized by transport type. Road freight transport reached a record high of 56,846,395 × 1,000 tkm in 2021, accounting for 71 % of the total freight transport share. By 2023, the road share increased slightly to 72 %. Rail's role in intermodal freight

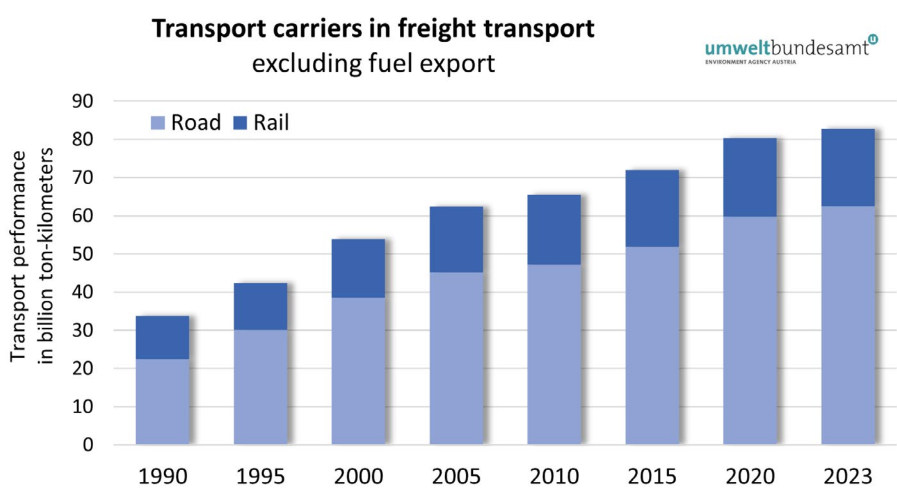



**Figure 3.10** Freight transport performance by rail and road in Austria (1990–2023) (Heinfellner et al., 2024b).

**Table 3.4** Modal split of freight transport (road/rail) by transport type (inland, import, export and transit) in Austria in the year 2023 [1000 tkm] (Statistik Austria, 2024d).

| Modal split in the year 2023 [1,000 tkm] | Inland | Import | Export | Transit | Total | |
|---|---|---|---|---|---|---|
| Inland waterway | 509,407 | 320,922 | 310,71 | 45,506 | 1,186,546 | 2 % |
| Rail | 3,948,293 | 4,921,328 | 3,516,192 | 7,819,358 | 20,205,170 | 26 % |
| Road | 18,034,181 | 8,725,596 | 8,614,571 | 19,754,058 | 55,128,407 | 72 % |
| Overall | 21,982,474 | 13,646,924 | 12,130,763 | 27,573,416 | 76,520,123 | 100 % |

transport is mainly facilitated by 14 inland container terminals across Austria (Schienen-Control, 2023; VABU, 2023).

The contribution of road freight transport to total GHG emissions from transport increased from 31 % in 1990 to 34 % in 2023, but declined significantly from 2022 to 2023 as Austria's economic output also declined. Fuel exports in commercial vehicles account for 12 % of these emissions (European Commission: Eurostat et al., 2023; Schuster et al., 2023; Heinfellner et al., 2024b). Among Austria's transport-intensive industries (e.g., mining, food, and waste), logistics activities account for about 12 % of their total GHG emissions (Miklautsch et al., 2022).

**Parcels and urban freight transport:** In 2020, approximately 290 million parcels were delivered in Austria, with parcel deliveries increasing by 9 % annually over the last decade. The Viennese chamber of commerce projects an increase to 339 million parcels by 2030 (WKO Wien, 2022). Despite this large volume, the associated GHG emissions have not been explicitly measured. Urban freight accounts for 10 % of urban road transport in Europe, with deliveries estimated to contribute 20 % of freight emissions – the same as maritime transport, although it represents only 3 % of freight activity compared to 70 % for shipping (ITF, 2023).

**Technological advancements:** There have been significant technological changes in the light- and heavy-duty vehicle markets in recent years. For heavy-duty electric trucks, recent studies show that electrified highways are economically feasible, but feasibility depends on international adoption, which seems unlikely. In addition, the construction of such electrified highways is expected to result in large GHG emissions (Qiu et al., 2022; Colovic et al., 2024) (*medium confidence*).

Battery-operated freight vehicles have been advancing in recent years: In 2024, battery trucks reached a 4 % market share among light-duty vehicles, which are often used for distribution and especially urban freight delivery, and a 1.6 % share among heavy-duty vehicles (i.e., larger truck classes) in Austria (AustriaTech, 2024). Scaling up this adoption will require improved charging infrastructure, especially along highways and at loading sites (*limited evidence, high agreement*).

Hydrogen-powered heavy-duty vehicles offer greater range than (existing) battery-operated vehicles and faster refueling (similar to diesel and gasoline). However, high hydrogen prices and limited filling stations (four in Austria) make them economically and logistically unattractive, and this is unlikely to change in the short to medium term (*medium confidence*).

Hydrotreated vegetable oil (HVO) is gaining traction as a transitional fuel due to the limited availability of heavy-duty battery electric trucks and related charging infrastructure. A 220-fold increase in HVO sales compared to 2022 levels occurred following Austria's new national fuel regulation in 2023, which promotes the use of renewable energy (Heinfellner et al., 2024b).

**Energy efficiency:** Low-carbon fuels, including biofuels and synthetic fuels, significantly reduce GHG emissions compared to standard diesel for heavy road vehicles (Benajes et al., 2024). However, compared to battery electric trucks, biofuels require 2–3 times more cumulative energy input (i.e., the sum of all primary energy inputs), while synthetic fuels (or e-fuels) require 5.5–6.5 times more, due to their energy-intensive production processes that use electricity to convert hydrogen and carbon dioxide into a usable energy source (Fritz et al., 2022). This is a major challenge given the expected increase in demand for renewable energy across all sectors (*medium evidence, high agreement*). Lifecycle assessments also indicate that battery electric trucks have the lowest cradle-to-grave GHG emissions (O'Connell et al., 2022) (*medium confidence*).

**Adaptation:** As discussed in Section 3.4.4 on infrastructure, the increasing likelihood of extreme weather events – such as landslides, floods, and tree falls – and their impacts on infrastructure negatively affect network connectivity and thus accessibility and reliability. With higher global warming levels, such events are expected to become even more frequent (see Section 3.2.3, Sections 1.4.1, 1.6.2, 1.7, and Cross-Chapter Box 1). Particularly in mountainous areas, where alternative routes or modes are not available, prolonged network disruptions can lead to high economic costs if goods are not delivered on time (e.g., Fikar et al., 2016) (*medium evidence, high agreement*). Supply chain diversification offers some potential to mitigate these risks (*medium confidence*).

## Mitigation strategies

The medium-term mitigation potential for freight transport is considered to be relatively high (*high confidence*). This potential can be divided into three key areas: Avoiding unnecessary freight movements, shifting to more sustainable transport modes, and exploiting technological improvements. A comprehensive policy addressing all three dimensions could include a dynamic road pricing system that takes into account usage, location, time of day and vehicle type and internalizes negative externalities, including not only GHG emissions but also local air pollution, accidents, noise and infrastructure costs (Marcucci et al., 2023) (*high confidence*). In Austria, less than one-fifth of these costs are currently covered by charges and tolls, despite the existence of a motorway toll system (European Commission: Directorate-General for Mobility and Transport et al., 2019).

**Avoiding and shortening trips:** Optimizing logistics and supply chains (e.g., reducing empty backhauls) can play a key role in reducing freight movements (*medium confidence*). Regionalization of production and distribution can also lead to shorter transport distances (*medium evidence, high agreement*). Adopting circular economy principles, which promote resource efficiency and product reuse, can help minimize the need to transport new goods (*medium confidence*). In urban areas, tailored approaches such as parcel boxes can further contribute to GHG emission reductions (*limited evidence, medium agreement*). However, while these measures could moderate the projected growth in freight volumes, an overall reduction would require strong pricing and/or regulatory measures (*medium confidence*).

**Shift from road to rail:** Shifting long-haul freight movements from road to rail has significant GHG emissions-savings potential given the low emission factors of railway operations in Austria (see Section 8.3.2 and the recent 'Maßnahmenbericht Mobilitätswende') (Heinfellner et al., 2024a). Despite the relatively high share of rail freight in Austria (27 %), increasing this share to the political target of 40 % by 2040 poses considerable practical challenges. These include the rigidity and limited capacity of the rail system, as well as first and last mile issues. Accessibility and expansion of rail infrastructure, terminals and sidings are critical, with the latter even declining in recent years. Strong policies, such as bans on road freight along corridors with sufficient rail capacity (limited to certain types of freight, times of day, or truck types), could enforce this shift. Improvements in rail speed, reliability, and predictability are also critical. To compensate for rail's higher costs, subsidies – e.g., for personnel or infrastructure usage fees – could be effective, especially in the absence of road freight charges that fully internalize the corresponding external costs (*medium evidence, high agreement*).

Rail modal shift is generally viable for trips over 250–300 km; shifts for shorter distances are usually unattractive for shippers and carriers. Due to Austria's geography, approximately 80 % of the longer trips start or end abroad. Achieving the 40 % modal share is therefore highly dependent on improving international connectivity, without which only a 34 % share is considered achievable (BMK, 2021b). Cross-border rail operations remain inefficient, hampered by waiting times, limited capacity, and unattractive, difficult-to-schedule services.

In addition, interconnectivity gaps also exist between rail networks and airports, seaports, and major inland waterways. The EU's efforts to address these issues are pronounced, as evidenced by initiatives such as the 'Fourth Railway Package' (European Commission, 2016) and the multimodal Trans-European Transport Network (TEN-T) 'core network' targeting major European axes by 2030 (and a more comprehensive network by 2050) (European Commission, 2020b). It is estimated that failure to complete the TEN-T would result in a loss of 1.8 % of potential economic growth and 10 million person-years of employment across the EU (Schade et al., 2015) (*medium evidence, high agreement*).

**Technological options:** There is great potential to shift road freight vehicles to low or zero emission technologies. EU regulations, including a Directive on the deployment of alternative fuel infrastructure (Directive 2014/94/EU), the 'Clean Vehicles Directive' (Directive (EU) 2019/1161), and a Regulation on $CO_2$ emission performance standards for new heavy-duty vehicles (Regulation (EU) 2019/1242), require manufacturers to reduce the fleet-wide average $CO_2$ emissions of their newly registered trucks per calendar year by 15 % by 2025 and 45 % by 2030 (compared to 2019 levels). These measures have already reduced the $CO_2$ intensity of the freight vehicle fleet, although growing freight demand has largely offset these gains (*medium evidence, high agreement*) (see Figure 3.8 and Figure 3.10).

The relatively young truck fleet in Austria (average age: 6.6 years (ACEA, 2023a), possibly a result of significantly lower toll fees for less polluting vehicles) underlines the potential for a rapid change in propulsion technology, which would lead to considerable GHG emission reductions. This can be seen as low-hanging fruit, and vehicle manufacturers can be seen as enablers of a faster transition. Battery-electric systems, particularly for distances under 300–500 km, offer feasible near-term solutions if supported by regulatory and infrastructure advancements. A key barrier is limited range and long charging times, which could be mitigated by systems that allow battery swapping (e.g., a 'stagecoach' model), especially for international routes (*medium confidence*).

Emissions from urban freight transport can be significantly reduced by establishing zero-emission zones in cities, effectively enforcing $CO_2$-free logistics in urban centers. Light-duty electric vehicles (range ~500 km, charging time ~30 minutes) have already already entered the market and could be complemented by (e-)cargo bikes for short-distance and special deliveries (*medium evidence, high agreement*).

### Scenarios

For the Austrian context, there is little evidence on decarbonization scenarios for the freight sector. Sedlacek et al. (2021) calculate two scenarios for the road freight sector, one corresponding to a WEM scenario and one that achieves carbon neutrality by 2040. The scenarios emphasize the role of technological progress in all vehicle categories. A Europe-wide strategy and policy framework is considered essential due to the international nature of freight transport. Despite significant transformation efforts, they conclude that the macroeconomic impact on Austria's GDP is expected to be small (*low confidence*).

## 3.4.4. Transport infrastructure

Infrastructure supports the physical mobility of goods and people and includes fixed structures (e.g., roads, railways, bicycle and pedestrian paths, inland waterways), access points (e.g., train stations, airports), and parking facilities (both on- and off-street). In 2022, Austria's transportation infrastructure included approximately 128,000 km of roads, 4,965 km of railways, 1,033 railway stations, 6 commercial airports, 8 inland waterway terminals, and 538 rail sidings. Statistics for local infrastructure, such as bicycle paths and parking spaces, are difficult to obtain, but notable examples include 280 km of tram lines and 80 km of subway networks.

Infrastructure can be characterized in terms of its capacity and technical specifications, which in turn affect its (perceived) quality, safety and resilience. Changes in infrastructure alter accessibility, typically affecting the flow of people and goods across routes and transport modes. Especially over time, infrastructure developments can reshape spatial patterns, such as residential and business locations and supply chain structures. For example, the expansion of (high quality) road networks has repeatedly been shown to induce urban sprawl and suburbanization (*robust evidence, medium agreement*) (see also Section 3.2).

The provision of transport infrastructure is associated with significant embodied GHG emissions (see also Section 4.2), which are often underestimated or ignored, leading to a severe undervaluation of the environmental impacts of transport (Facanha and Horvath, 2007; Chester and Horvath, 2008). A distinction can be made between direct and indirect effects:

- **Direct effects** result from energy consumption and associated GHG emissions for raw material extraction (mining) and production, transportation, production and construction of the transport infrastructure itself, maintenance and eventual disposal. Infrastructure construction requires substantial amounts of material (Haas et al., 2024) (*medium evidence, high agreement*).
- **Indirect effects** include increased fuel consumption of vehicles due to road surface irregularities, but also changes in travel behavior and freight transport movements induced by infrastructure improvements: In general, infrastructure improvements often increase travel activity, potentially increasing GHG emissions, especially in the case of road infrastructure expansions, where on average a 1 % increase in road kilometers leads to a corresponding 1 % increase in vehicle kilometers traveled (e.g., Garcia-López et al., 2022) (*medium confidence*). Similarly, the availability of convenient parking greatly increases the likelihood of car ownership and use (e.g., Hess, 2001) (*medium confidence*).

Infrastructure can exacerbate the effects of global warming, particularly in urban areas, by reinforcing the UHI phenomenon as described in Section 3.2.1, which is particularly relevant in densely populated areas. In addition, infrastructure covers a significant area of land, contributing to soil sealing and potentially increasing the negative impacts of extreme weather events such as heatwaves and heavy precipitation (see Section 3.2.3). Land-based infrastructure occupies 6.7 % of Austria's permanent settlement area (Umweltbundesamt, 2020). Among transportation modes, rail infrastructure uses 7 m² of land per passenger, compared to 100 m² per car user.

In addition to being a source of GHG emissions, infrastructure is also strongly affected by climate change and associated weather events – see also Section 3.2.3 for the urban context and Section 7.4.3 for infrastructure in alpine areas. The main weather hazards requiring adaptation are high temperatures and (excessive) precipitation (Fian et al., 2021; Palin et al., 2021) (*medium evidence, high agreement*).

In the following subsections, rail and road infrastructure, the dominant types in Austria, are analyzed in detail. Other infrastructure types also contribute to GHG emissions, but have a comparatively smaller network size and therefore a limited reduction potential. Nevertheless, some statistics and considerations for rail and road infrastructure can be adapted to broader application. For example, trams and subways share characteristics with rail infrastructure due to their rail-bound systems, while on-street parking is consistent with emission factors for road surfaces. A discussion on urban infrastructure planning can be found in Section 3.2.2.

Although local variations and dependencies make it challenging to generalize the need for infrastructure investments, adaptations, or even removal, evidence suggests that welfare benefits of additional infrastructure diminish at high levels of infrastructure availability (Virág et al., 2022a) (*limited evidence, medium agreement*).

## Railway infrastructure

As of 2023, Austria's rail infrastructure network covers 4,935 km, of which 2,262 km are double track (ÖBB-Holding AG, 2024). Among European countries, Austria ranks second in per capita investment in rail infrastructure, surpassed only by Switzerland (ITF, 2022). The investment plan of the Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology allocates $EUR_{2023}$ 21.1 billion for the period 2024-2029 for new line construction, line expansion and electrification, freight terminals, digitalization, efficiency improvements, and park-and-ride facilities. The annual budgets include $EUR_{2023}$ 780 million for maintenance and $EUR_{2023}$ 838 million for reinvestment. Major cost-intensive ongoing projects include the Brenner Base Tunnel, the Koralm Tunnel and Semmering Base Tunnel, while further investment plans are guided by Austria's long-term expansion strategy, the 'Zielnetz 2040' (BMK, 2023a, 2024b).

Existing rail capacity is heavily utilized. In 2023, the Austrian Federal Railways 'ÖBB' handled 12.6 billion traveled passenger kilometers, which corresponds to 7,026 trains operated daily (ÖBB-Holding AG, 2024). In addition, freight transport accounted for 26.1 billion ton-kilometers. Maintenance work limits the extent to which freight transport movements can be shifted to night hours. Expanding rail capacity is complex and cost-intensive, especially for routes that cross mountains or urban areas, requiring costly tunnels and infrastructure. Austria's central location in Europe means that its trans-European connectivity relies heavily on investments from neighboring countries. Without adequate foreign investment, the shift of freight from road to rail is constrained, as intra-Austrian distances often fall below the 300 km threshold typically considered uneconomic for rail freight (see also Section 3.4.3).

The majority of the environmental impacts of railway infrastructure are caused by the rails, ballast, sub-ballast, and civil engineering structures (de Bortoli et al., 2020), with the track substructure being a critical factor (Cheng et al., 2020; Pons et al., 2020). The GHG emissions for ballasted railway tracks reported in this section are calculated based on a detailed bottom-up approach that considers all related upstream and downstream processes, including local conditions (traffic loads, radii, and elevation), used track components, specific supply chains, and emissions from trackwork machinery (Landgraf and Horvath, 2021; Landgraf et al., 2022). In addition, supply chains, asset lifetimes, and maintenance requirements throughout the infrastructure lifecycle are considered (Landgraf and Horvath, 2021) (*medium evidence, high agreement*).

In Austria, the focus is on maintaining and renewing the existing network rather than building new lines. In 2023, for example, 216 km of track were renewed, which corresponds to an annual rate of 2.3 % (ÖBB-Infrastruktur AG, 2024), while new track construction has averaged 12 km per year since 2008 (ÖBB-Holding AG, 2022). This continuous renewal rate offers high potential for innovation, as new solutions can be integrated swiftly into the existing network (*medium evidence, high agreement*).

Annual cradle-to-gate GHG emissions from rail infrastructure – based on the current infrastructure network, asset distribution and renewal rates – amount to 234,730 $tCO_2eq$, compared to 144,900 $tCO_2eq$ from passenger operations and 149,500 $tCO_2eq$ from freight operations in 2019. Tunnels and aerial structures (bridges) remain the largest contributors to emissions per kilometer (Chang and Kendall, 2011; Landgraf and Horvath, 2021) (*medium evidence, high agreement*).

Track construction and maintenance account for 55–60 % of GHG emissions within the Austrian rail network (Landgraf and Horvath, 2021). This share is relatively high compared to other countries (Banar and Özdemir, 2015; Jones et al., 2017) because, unlike most other foreign rail operators, ÖBB uniquely sources its traction power from renewable energy sources – 95 % hydropower and 5 % other renewables (ÖBB-Holding AG, 2022). This significantly reduced operational GHG emissions, but increases the relative share attributable to infrastructure.

*Mitigation strategies*

**Planning for future rail demand:** Overall, the shift towards rail is crucial to avoid environmental impacts in the transport sector, as emphasized by the European Green Deal's strategy to 'accelerate the shift to sustainable and smart mobility' (ERA, 2020). However, the development of transport infrastructure development should be limited to what is necessary, based on in-depth traffic volume simulations, which the ASI framework promotes.

**Shift to low-emission materials and fuels in rail infrastructure construction and maintenance:** The main further mitigation potential lies in shifting to low-emission materials and fuels (ÖBB-Holding AG, 2022). Key areas include steel and concrete production, the adoption of circular economy principles, and the use of fossil-free propulsion for heavy maintenance machinery and transport. In particular, as the extraction and processing of raw materials account for 18 % of the EU's total GHG emissions associated with the consumption of goods and services, climate-friendly procurement and processing practices are crucial (European Environment Agency, 2021a). In addition to further research and support (subsidies, financing) for the market entry of sustainable products, this can be achieved by quantifying and integrating environmental impacts into the public procurement process (BMK, 2021a; UNEP, 2021). This, in turn, may encourage contractors and manufactures to invest in environmentally efficient production processes and services (*medium confidence*).

**Efficiency improvements in rail infrastructure design, usage, and maintenance:** Railway infrastructure can be improved by increasing efficiency within the system. The further implementation of the 'European Train Control System' (ETCS) according to Austria's 'National Implementation Plan' (BMVIT, 2017) will increase the efficiency and capacity of the existing railway infrastructure. In addition, ÖBB has already taken a number of measures to mitigate lifecycle costs and GHG emissions (ÖBB-Holding AG, 2022). For example, ballast cleaning allows about 50 % of material to be reduced when reinvesting in existing rail infrastructure (Zeiner et al., 2021). Optimized maintenance planning and improvements in railway infrastructure design can also extend the service life of existing infrastructure (Landgraf and Horvath, 2021).

## Road infrastructure

In 2022, the Austrian road infrastructure consisted of 2,260 km of high-level roads ('Autobahnen' and 'Schnellstraßen'), 33,800 km of intermediate-level roads ('Landesstraßen' 'B' and 'L'), and about 92,000 km of low-level roads ('Gemeindestraßen'). Overall, more than 95 % of roads are built with asphalt pavements (bituminous bound, hot mix asphalt (HMA)) and less than 5 % with concrete pavements (cement bound, portland cement concrete (PCC)). However, about one third of the high-level road network is cement-bound. In comparison, Austria has a high-level road network that is 50 % larger per capita than the EU average and about 55 % larger than Germany's (VCÖ, 2024b).

In 2020, $EUR_{2023}$ 1,291 million were spent on the high-level road network, 46 % on new construction and 54 % on maintenance. For this, 7.4 million tons of asphalt mixture were produced, a decrease of 10 % from the peak year (2010), while 1.26 million tons of reclaimed asphalt were recovered for recycling. Of the recycled material, 70 % was reused in HMA, while 30 % was diverted to other uses or landfills (Blab et al., 2012; BMK, 2022c; EAPA, 2023).

GHG emissions from road infrastructure vary by material type. This can be assessed using a production-based material flow analysis, which includes the production of (raw) materials (bituminous binders, cement, mineral aggregates, additives), and the transport of materials. HMA production results in 40–50 $kgCO_2eq/t$, while PCC emissions range from 75–100 $kgCO_2eq/t$, as shown by Gruber and Hofko (2023) with calculations based on Gruber (2023). For HMA, raw materials contribute approximately 50 %, transportation 5 %, and production of asphalt mixture about 45 % of total GHG emissions. In contrast, PCC raw materials account for 95 % of the emissions, with transportation and production accounting for the remainder.

Overall, the impact of asphalt paved roads on GHG emissions is 0.4 % to 4 % of traffic-related emissions for the low- and high-level road network, respectively, while concrete roads contribute 0.6 % to 6.4 %, respectively (calculations based on Gruber, 2023). Due to continuous dynamic loading of road infrastructure by vehicle traffic, the road surface and structural properties deteriorate over time. As a result, top-layer lifetimes are typically 10-15 years before replacement. This deterioration includes increased surface roughness and increased longitudinal unevenness, leading to increased activation of vehicle damping systems, resulting in energy dissipation and thus increased fuel consumption. Recent studies estimate the potential GHG emission savings from improving the evenness of road surfaces to be between 5–15 % (Louhghalam et al., 2019). For example, road traffic on a 1 km long section of a 3-lane road with 27,000 vehicles per day, of which 10 % are heavy goods vehicles (HGVs), causes approximately 3,000 $tCO_2eq$ of GHG emissions per year. With a theoretical, rather pessimistic savings potential of 2.5 % by improving longitudinal evenness, 74 $tCO_2eq$ could be saved per year, which is roughly equivalent to the GHG emissions caused by the rehabilitation of the surface layer. Thus, in this case, the emissions from asphalt production could be offset by reduced fuel consumption already within the first year (Roxon et al., 2019). Even with an 30 % overall share of electric vehicles (cars and HGVs), the corresponding emissions savings potential would still be 59 $tCO_2eq$ per year (calculations based on Gruber and Hofko, 2023).

*Mitigation strategies*

**Avoidance of road infrastructure expansion:** Current planning and design standards for road infrastructure drive the need to expand the network and cross-sections of existing roads due to: (a) Future traffic volume growth – mandatory assumptions of a 2–3 % annual traffic growth result in larger, thicker structures, wider cross-sections, and sometimes additional lanes; (b) Design speed requirements – minimum design speed thresholds set for various road classes, increase space and material requirements, as speed limits affect the required curvature radii and lane widths; (c) Capacity thresholds – in periodic checks of existing roads, current capacity overload thresholds prioritize high user service levels over efficiency. Therefore, critically reviewing and adapting all standards and guidelines to minimize future expansions can not only reduce the need for material- and production-based GHG emissions, but also reduce land use and indirect emissions from further traffic attracted to overly capacious infrastructure (Anupriya et al., 2023) (*high confidence*).

**Shifting to low-emission materials in the construction and maintenance of road infrastructure:** Incentives in tendering processes can drive reductions in GHG emissions by incorporating best bid criteria that optimize road production and products not only economically and technically, but also ecologically (*medium evidence, high agreement*). Calculation tools to assess emission reduction potential based on material mix designs and production parameters are already available for the tendering process of the high-level road network operated by ASFINAG (an Austrian public corporation that plans, finances, builds, maintains and collects tolls for the Austrian highways) (ASFINAG, 2024). Dry storage of mineral aggregate, reclaimed asphalt pavement (RAP), and short transport distances have a significant positive impact on the GHG reduction potential of HMA, increasing its importance in achieving minimum overall energy consumption (Hofko et al., 2020) (*high confidence*). While the addition of RAP to HMA can reduce emissions, excessive RAP content can affect the durability of the road, reducing its service life while increasing the need for rehabilitation and therefore long-term energy consumption. There is currently no consensus on safe RAP limits, highlighting the need for further research to establish reliable thresholds and improve lifecycle analysis.

**Optimization of surface quality:** High surface quality (i.e., longitudinal evenness) improves not only the structural quality (technical lifetime) but also, as discussed above, fleet fuel consumption. Incorporating surface quality models into pavement management systems can therefore further reduce traffic-related GHG emissions (*high confidence*). Continuous assessment of longitudinal evenness is possible with simple means, as recent studies have shown (Gruber and Hofko, 2024).

## Risks and adaptation possibilities

Adaptation to increasing global warming levels is essential for transport infrastructure due to the risks posed by changing weather patterns and their consequences (see also Cross-Chapter Box 1), including infrastructure unavailability and reduced network resilience (*high confidence*). Temporary or prolonged unavailability can result in significant economic costs due to delays and necessary adjustments in routes and modes of transport caused by reduced travel time reliability, supply chain disruptions, and other logistical challenges. Urban areas face higher impacts due to denser populations and freight demand, while rural areas – although less affected (with the exception of tourism hotspots; see also Section 7.4) – may suffer severe disruptions due to the lack of alternative routes and modes (no redundancy) (*medium evidence, high agreement*). The complexity of infrastructure operations means that the response of the infrastructure to hazards is rarely linear (*medium evidence, high agreement*). Infrastructure damages can also increase the risk of accidents and potentially lead to loss of property (vehicles, cargo, etc.) if not detected in time, or if warnings are ignored.

In general, proactive adaptation safeguards infrastructure and ensures functionality under increasing global warming levels. Moreover, adaptation of rail and road infrastructure to climate change usually results in net macroeconomic benefits by balancing direct benefits and indirect benefits such as employment, even at rather low damage reduction potentials (Bachner, 2017) (*limited evidence, medium agreement*). So far, Austria's adaptation targets for climate change – as outlined in König et al. (2014) – have not been met in any of the relevant transport and infrastructure dimensions (see Table 48 in Balas et al., 2021) (*high confidence*).

**Heavy rain events:** Increased likelihood of shorter (*high confidence*) and longer (*low confidence*) heavy rainfall events can trigger pluvial and riverine flooding, rock falls, avalanches (rock and snow), and shallow slides, especially in narrow valleys (Huttenlau et al., 2010; Olsson et al., 2012; Löschner et al., 2017; Schlögl and Matulla, 2018; Unterberger et al., 2019). Consequences include infrastructure damage, disruption, and potentially safety issues. Prolonged heavy rain events can increase surface runoff due to increased soil saturation and cause structural failure of unbound base layers, necessitating premature reconstruction (*high confidence*). In addition, landslides can result from rain-induced deconstruction. Bridge scour and water damage to electronic equipment are other specific consequences associated with heavy rain events. Adapting standard practices with porous surface layers, slightly tilted surfaces (for water drainage), and slope stabilization increases resilience (see also Section 3.2.3 Urban water impacts). Surface elevation in vulnerable areas, such as valleys, creates safe escape routes during floods. Infrastructure improvements such as water retention basins manage excess water. In flood-prone areas, soil monitoring combined with an automatic warning system provides additional safety (see also Sections 1.4.1, 3.2.3 and 7.4.1). Urban water management concepts, such as the 'sponge city' concept, can improve safety during short heavy rain events and retain water from precipitation in soils under sealed surfaces by allowing water to locally percolate through porous surface layers (see also Section 3.2.3).

A recent example of such a heavy rain event occurred in Eastern Austria in September 2024. In addition to an estimated EUR 1.3 billion in damages to businesses and households, immense infrastructure damage occurred, the cost of which cannot yet be determined (as of 2024) (WIFO, 2024). It led to the closure of Austria's main railway line between Vienna and Salzburg ('Weststrecke') for nearly two months due to flooding that damaged tunnels, stations, and electronic systems. Despite being designed in the 1990s according to standards to statistically withstand 100-year flood extremes, the 2024 rainfall exceeded these magnitudes, with water levels equivalent to a 500- or 1000-year event. An example for which infrastructure costs have been quantified are the several heavy rain events in Styria in the summer of 2024, with a total estimated damage of $EUR_{2023}$ 34 million (ORF, 2024).

**Acute heat:** Increased acute heat can cause significant material damage. For road infrastructure, this includes premature failure of asphalt pavements due to excessive softening and permanent deformation (rutting) (Zhang et al., 2022) and failure of concrete pavements due to slab buckling (Kerr, 1994). Acute heat increases the risk of rail buckling, with thermal expansion being particularly problematic in narrow curves such as those often found in mountainous areas. These risks can be partially counteracted by changes in product design and construction techniques. Speed and weight restrictions on roads and railways, and the design of rail infrastructure to avoid narrow curves (e.g., tunnels) are other suitable short- and long-term adaptation measures.

In urban areas, adaptation strategies to reduce UHIs are of utmost importance (see Section 3.2.3 Integrated mitigation and adaptation strategies). Surface adaptations such as lighter-colored pavements and permeable structures are currently being studied to gain experience. Lighter colored surfaces increase reflection and reduce energy dissipation, resulting in faster cooling after sunset. However, during the day, higher reflectance can lead to higher local temperature maxima. Permeable structures contain less mass to act as a heat carrier, and water can be applied and partially stored during extreme temperature events to shift energy conversion from heating to evaporation (Myrup, 1969; Qin et al., 2024) (*high confidence*). However, changes in road surfaces can only provide partial solutions. Preserving and increasing the amount of natural shade is necessary and provides the most significant improvements to UHIs.

**Lack of precipitation:** Risks associated with a lack of precipitation primarily affect waterways, as lower water levels reduce freight carrying capacity. However, waterways are only a small part of the Austrian transportation network. In exceptional cases, dry soils can cause shrinkage cracks or even landslides, leading to infrastructure failures. Cost-effective adaptation options for these risks are limited.

*Regulation, governance, and planning aspects*

Beyond the physical adaptation of infrastructure, regulatory and governance frameworks will also need to evolve to meet the demands of building and operating transport infrastructure under changing climate conditions (e.g., see Table 48 in Balas et al., 2021). The acute need for action is underscored by the fact that infrastructure assets built today are expected to remain operational well beyond 2100, a timeframe that is often overlooked in current legislation (see, e.g., Siefer et al., 2019, on railway infrastructure regulations in Germany). Forward-looking scenarios and risk assessment tools, such as maps detailing changes in minimum and maximum surface temperatures and extreme precipitation probabilities, can guide the design of resilient infrastructure to accommodate changing climate patterns (Fasthuber, 2019; Esterl et al., 2022). In particular, the urgent need to re-evaluate flood risk statistics was further illustrated by the extreme flood event in the fall of 2024, which revealed significant gaps in existing predictive models and preparedness measures.

## Conclusion

Climate change is already impacting Austria's built environment and transport sector, with rising temperatures and extreme weather events threatening infrastructure. To ensure resilience and protect public welfare, adaptation strategies are essential, including improved water management, flood and landslide protection, and greening measures to mitigate heat stress. Soil sealing and excessive land take exacerbate these challenges, highlighting the need for permeable surfaces, sustainable drainage systems, and nature-based solutions. Resilient urban planning must incorporate these elements to ensure long-term sustainability.

Meanwhile, Austria's building and transport sectors remain major contributors to climate change, accounting for 70 % of national energy consumption and 38 % of greenhouse gas emissions in 2023, excluding emissions from electricity and district heat generation, which are attributed to the industrial sector. Electrification, driven by heat pumps and electric vehicles, is key to decarbonization, but its full potential depends on defossilizing and decarbonizing both electricity generation and district heating. Maximizing the benefits of the transition requires deep renovations of buildings, widespread adoption of heat pumps, and the use of low-emitting materials alongside circular design principles to minimize environmental impacts and resource consumption.

Compact urban development and reduced car dependency are also critical to reducing emissions, but urban heat island effects and strong preferences for single-family homes and car ownership pose challenges. Mitigation options include urban greening, prioritizing mixed-use neighborhoods, and improving public transport and active mobility infrastructure. Freight transportation is another hurdle, with rising demand and limited low-carbon alternatives delaying full decarbonization. Solutions include optimizing logistics and shifting long-distance transport to rail, while improving cross-border rail connectivity in line with EU transport policy. Dynamic road pricing and stronger incentives targeting the advancement of sustainable transport technologies, including low- and zero-emission trucks, could further accelerate emissions reductions.

Achieving a low-carbon future will require a combination of pull and push measures, including incentives for behavioral change, renewable energy adoption, and efficiency improvements. With a 43 % reduction in GHG emissions from 1990 to 2022, the building sector is already making progress. However, continued emphasis on emission avoidance, renewable solutions, and efficiency gains will remain critical to meeting climate goals. Through integrated planning, technological innovation, and behavioral shifts, Austria can foster more resilient, sustainable, and livable communities.

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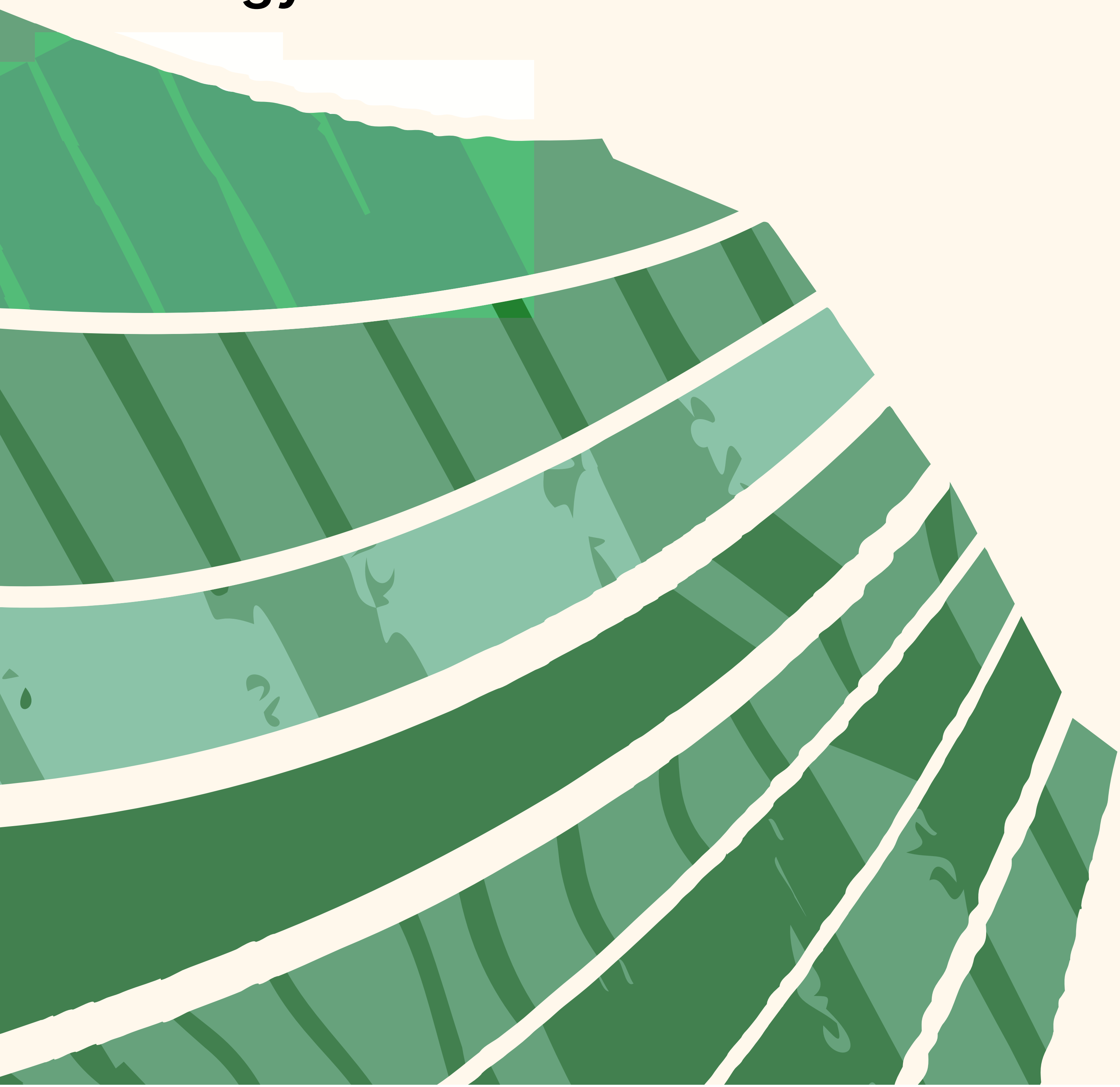
## Chapter 4

# Provision of goods and services in a climate-resilient economy via materials, energy and work



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# Chapter 4
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## EXECUTIVE SUMMARY

**Several mitigation pathways are available after 2030 to reach net-zero $CO_2$eq emissions in 2040 (*medium evidence, high agreement*).** First, it is evident that the infrastructure necessary for energy storage, grids, and public transport will differ from the current infrastructure. This implies the need for swift and determined decisions today so that the necessary infrastructure is available in time, given the considerable construction time for energy and rail infrastructure. Second, the discrepancy in energy service demand, industrial output, and energy efficiency measures causes a large range of primary energy use (237–337 TWh) across the scenarios, underscoring the significance of measures reducing demand. Third, energy import dependency varies considerably (5–39 %). Fourth, wind power and solar PV constitute the backbone of the power sector in all scenarios, satisfying demand, but the respective shares differ (wind: 5–25 %; PV: 6–20 % of gross domestic consumption). Fifth, biomass remains a highly important resource in the energy sector, but to varying degrees (ranging from 14–28 % of gross domestic consumption). {4.4, 4.5}

**Unabated fossil liquid fuels and gases are partly substituted by varying amounts of biogenic fuels, synthetic fuels and fossil fuels with CCS in 2040 in the scenarios (*medium evidence, high agreement*).** While electrification is the most cost-effective mitigation technology in many applications, there is still a substantial need for carbon-neutral fuels and gases in 2040. Their use ranges from to 91–156 TWh in 2040. These fuels are mainly used in industry (35–59 % of all liquid fuels, and gas, and solid use), in transport (8–33 %), in households, services and agriculture (20–34 %) and in power generation and district heating (4–21 %). Legacy effects cause the continued use of fossil fuels or the build-up of synthetic fuel use in land transport and heating. Due to delayed action in these sectors, a significant stock of assets based on liquids or gases may remain, causing the costly and inefficient use of these fuels in sectors where electrification could provide emission reductions at lower cost. As an example, a high proportion of liquid fuels in the transport sector will only be necessary if the electrification of land transport remains at its current low level. Sensitivity scenarios show that the phase-out of internal combustion engines in land transport is crucial if climate neutrality is to be achieved quickly. Efficient scenarios show that liquid fuels are only used for aviation and shipping, and that, after overcoming the legacy of the past, no liquid fuels or gases are used for heating. {4.4, 4.5}

**The Austrian economy is already at risk due to climate change related impacts. Future climate change as well as socioeconomic development will further intensify these impacts (*limited evidence, high agreement*).** International studies provide quantitative climate change impact assessments at national and supranational levels. Subnational and sector-specific assessments are rare, but needed to broaden the evidence base for potential climate change-related impacts in Austria, focusing on the Austrian energy generation and transmission infrastructure, services and industrial sectors. {4.3.3, 4.5.2}

**Current provisioning of goods and services is a key driver for high levels of energy and material demand and thus domestic and upstream greenhouse gas emissions (*high confidence*).** The Austrian economy rests on growing infrastructure and building stocks to provide services in transport, housing, communication, and finance (*high confidence)*. The continued accumulation of infrastructure and buildings and the increased service and activity levels have largely offset technological efficiency gains and inhibited structural shifts towards a service economy (*high confidence*). {4.2.1}

**A needs-oriented circular economy that focuses on reducing energy and material use through optimized space and building use, improved spatial planning that halts urban sprawl, shifting motorized private transport to public and active modes of transport, sharing, eco-design, increasing durability, reuse, and repair provides multiple benefits (*high confidence*).** Shifting from material-intensive production and construction processes to services (e.g., rental, sharing) has the potential to avoid rebound effects and increase value-added and employment (*medium confidence*). The provisioning of goods and services thereby can become significantly more climate-friendly and -resilient while maintaining high levels of service quality and well-being (*high confidence*). {4.2.2}

**Achieving a net-zero-emissions and resilient provisioning system requires changes at multiple levels: End-use technologies, the infrastructures that underpin everyday life, and in the local provisioning systems that shape people's modes of living (*high confidence*).** Important decarbonization technologies such as electric vehicles and photovoltaics increase demand for electricity and critical raw materials, which need to be compensated by energy and material efficiency measures that reduce both the volume of material stocks in use and their energy requirements (*high confidence*). This aids decarbonization across all sectors, reduces dependencies on critical raw materials, reduces land consumption, and aligns with the government's circular economy targets (*medium evidence, high agreement*). {4.2.3}

**Tourism is of high economic significance for Austria and is associated with substantial emissions (*high confidence*).** With about 4.15 % of $CO_2$ emissions in Austria originating from tourism, and up to 34.1 % when transport-related emissions between origin and destination of foreign and domestic visitors to Austria are included, the sector is a relevant driver of emissions (*medium confidence*). Due to the economic significance of tourism in Austria (7.5 % of GDP in 2019), tourism is an important sector to be considered on the path to a carbon-neutral economy (*high confidence*). {4.3.2}

**The impacts of climate change will substantially alter some of the supply and demand in the tourism sector (*high confidence*).** Changing overall climate conditions (e.g., increase in average temperatures, shift in precipitation, shorter snow cover duration) and increasing extreme weather events (e.g., number of heat days, precipitation intensity, storm frequencies/intensity) will change the supply conditions for tourism services and thus require an adaptation of tourism (*high confidence*). The adjustment will need to take place along several dimensions and include seasonal adjustment of supply and demand, changes in the type of products offered and a reduction in the frequency of travel combined with longer stays (*high confidence*). {4.3.3}

**A modal shift to public transport and the greening of the destination transport systems are key in mitigating emissions in tourism (*high confidence*).** The largest share (75 %) of global total tourism-induced greenhouse gas (GHG) emissions is generated by transport to, from and at the destination (mostly by air and road) (*high confidence*). In Austria, too, the single most important source of GHG emissions related to tourism is personal transport, which makes up 92.2 % of the sector's GHG emissions (*medium confidence*). Consequently, to reduce tourism-related GHG emissions, a higher share of transport to and from as well as at the destination must be carried out by trains and busses and, as public transport capacities are limited, in particular in sub-urban and rural regions, by low (zero-) emission private vehicles (*high confidence*). {4.3.4}

**The industry and manufacturing sector is particularly emission intensive, contributing 18 % to GDP and 35 % (26 $MtCO_2eq$) to emissions in 2020 (*high confidence*).** Emissions are highly concentrated in the iron and steel, chemicals, pulp and paper, and non-metallic minerals industries, which account for 82 % (21 Mt) of the sector's and 29 % of national emissions. From 2014–2020 emissions of this sector fell by 1 % per year, while value added has grown by a rate of 2 % per year (*high confidence*). {4.4.1}

**Many technological options are already available to support the defossilization of Austria's industry and manufacturing sector, but key technologies such as hydrogen-based steelmaking and the integration of CCUS require further research and development. Future systems will heavily rely on electricity; thus, the availability of low-carbon electricity is key to prevent outsourcing emissions to the energy sector (*high confidence*).** If current production levels are maintained, electricity demand for the direct use in emission-intensive industries will more than double (*high confidence*). {4.4.2}

**The defossilization of industry and manufacturing requires an integrated and coordinated economy-wide strategy, as individual incremental improvements are insufficient (*high confidence*).** In addition to sufficiency measures (avoid), the key levers are fuel switching (shift), energy/material efficiency and carbon capture (improve). These changes involve new investments and will generate major new challenges, such as securing sufficient renewable energy supply and restructuring global value chains (*medium confidence*). {4.4.4}

**The Austrian energy system is mainly based on fossil fuels and is a large emitter of greenhouse gas emissions (*high confidence*).** The Austrian energy system (serving various economic sectors) was responsible for 70 % (44.5 $MtCO_2eq$) of all greenhouse gas emissions in Austria in 2023 and fossil fuels had a share of 62 % in energy supply. A major share of fossil fuels is imported (96 % in 2023), implying a high import dependency in terms of primary energy. {4.5.1}

**A carbon-neutral and climate-resilient energy system is electrified, hosts high shares of renewables, and is prepared for climate change impacts to maintain system security (*medium evidence, high agreement*).** A future carbon-neutral energy system will show significantly higher shares of electricity in end use and larger shares of renewables (*medium evidence, high agreement*), but many different technology mixes allow carbon neutrality to be achieved, e.g., focusing on wind power or on solar PV, or allowing for higher shares of carbon capture and storage versus using green hydrogen (*medium evidence, high agreement*). Systems with high shares of wind and/or solar PV will have a higher degree of exposure and vulnerability to weather-related variability and hazards (*limited evidence, medium agreement*). Therefore, the design of energy systems needs to consider long-term climate trends in addition to weather variability, exposure, and vulnerability to reduce future risks (*limited evidence, medium agreement*). {4.5.2}

**The net costs of transitioning to a carbon-neutral energy system are low to negative (*limited evidence, medium agreement*), most of the necessary technologies are available, and there are in principle sufficient land resources for most pathways to successfully transition to a carbon-neutral energy system (*medium confidence*).** However, major barriers in terms of infrastructure development, including flexibility options to balance intermittent renewable supply and coupling energy-demanding sectors, policy design, technology acceptance and supply-chain bottlenecks, need to be overcome to implement a carbon-neutral energy system (*medium evidence, high agreement*). In all scenarios, import dependency on energy carriers is reduced, but reductions vary and depend on assumptions about the development of energy demand, in particular in the industrial sector, on assumptions about domestic renewable energy potential and on the expansion of fossil fuels with carbon capture and storage. {4.5.3}

**Carbon Capture, Utilization, and Storage (CCUS) technology chains are mature and can be employed to bind $CO_2$ and thus prevent the release of emissions into the atmosphere (*high confidence*).** CCUS refers to technology chains for reducing $CO_2$ emissions on a relevant scale through geological storage underground or through utilization in industrial processes and products. While geological $CO_2$ storage (CCS) is a large-scale and permanent-reduction option, $CO_2$ utilization (CCU) is limited by demand and final product lifetime. {4.6.1}

**During the transition to a climate-neutral society, especially regarding hard-to-abate industrial emissions, CCUS will play a crucial role in decarbonizing the Austrian economy (*high confidence*).** CCUS can enable emission-critical industries in Austria to achieve $CO_2$ reduction goals. This requires a national and European transportation network of $CO_2$ sources and sinks. Combined with bioenergy and direct air capture, geological $CO_2$ storage can contribute to achieving negative emissions (Carbon Dioxide Removal, CDR) (*medium confidence*). Mineral carbonation and closed $CO_2$ utilization loops can contribute to the $CO_2$ reduction goals in the transition to climate neutrality (*medium confidence*). CCUS also comes with new challenges, as it is energy and water intensive and puts pressure on the supply systems. {4.6.2}

**The development of CCUS in Austria requires overcoming geological, technological, and societal challenges (*high confidence*).** Using the geological subsurface for permanent storage requires public acceptance based on relevant information and a broad societal consensus. Technological feasibility requires that $CO_2$ emitters and sinks are connected by a transport network, that geological fields are developed while minimizing risks, and that innovative solutions for utilizing $CO_2$ are found that permanently remove $CO_2$. With Austria's estimated capacity, CCUS can contribute to national decarbonization on a relevant scale (*high confidence*). {4.6.3}

**Work, including unpaid care and paid employment, dominates daily life in Austria, and the structural dependence of persons and welfare systems on paid work currently tends to impede climate-neutral provisioning as well as climate-friendly living (*high confidence*).** High-productive, energy-intensive work is well-paid and structurally linked to low-productive, energy-light, unpaid or low-paid, very essential work (including care) (*limited evidence, medium agreement*). The work-mode of living poses a structural barrier for climate-friendly mobility, food, housing and leisure practices, and encourages energy- and fossil-fuel-intensive practices (*medium confidence*). 46 % of Austrians believe that their current job does not contribute to the green transition (*limited evidence, high agreement*). {4.7.1}

**A transition to a climate-friendly society will end the requirement for greenhouse gas emissions from paid employment or unpaid care (*limited evidence, high agreement*).** The greening and sharing of paid employment and unpaid care will ensure a high quality of life, good work and climate-friendly living, work-life balance and adequate provisioning of care (*medium confidence*). Under the current business-as-usual scenario, work will be severely affected by the unfolding of the climate crisis, requiring sectoral shifts towards the provisioning of basic goods such as health, care, food, and housing (*limited evidence, medium agreement*). {4.7.2}

**To avoid climate-damaging production and to overcome labor supply constraints, climate-friendly regulation of labor markets can enable a shift from excess production to climate-friendly provision of essential services (*medium confidence*).** A redistribution of paid work and unpaid care and the relocation of jobs to people's living place through economic and labor market policies, can enable climate-friendly work-life patterns (*medium confidence*). More equal distribution of wealth and income, job guarantee and public provision of basic goods (e.g., housing, food and health care) can increase economic security and thus enable green labor market transformations (*medium confidence*). {4.7.3}

## 4.1. Chapter introduction

Chapter 4 of the AAR2 discusses the role of the Austrian economy in a climate-neutral 'Provisioning System', with the objective of satisfying anticipated human needs and fostering human well-being (see, e.g., Fanning et al., 2020). In conjunction with the Avoid-Shift-Improve framework (see Cross-Chapter Box 4), this demand and service-provisioning perspective (see Cross-Chapter Box 3) allows to identify leverage points, such as a Circular Economy (see Cross-Chapter Box 5), to achieve a climate-neutral and low material footprint economy along the resource conversion chain.

### 4.1.1. The provisioning system

Here, in Chapter 4, we focus on the provision of goods and services (capital and consumer goods and from other sectors including tourism) and of energy to meet diverse human needs. Figure 4.1 illustrates this understanding of the economy as a provisioning system and how specific elements of it are represented in the AAR2. The provisioning system is embedded in the broader societal sphere and fulfills the ultimate goal of satisfying human needs and thereby generating human well-being, which requires appropriate governance and financial arrangements. The provision of goods and services, for example through manufacturing processes, involves a certain demand for resources (for materials, energy, and work). In doing so, the provisioning system interacts closely with the ecological sphere through the demand for natural resources and as a source of greenhouse gas (GHG) emissions (with mitigation potential through Carbon Capture Storage and Utilization, CCS/CCU, see Section 4.6) and other pollution and impacts on ecosystem health (which plays a key role in land-based Carbon Dioxide Removal, CDR, see Cross-Chapter Box 4). In addition, the provisioning system is affected by climate and global change, presenting opportunities and challenges for adaptation to climate change.

Other chapters of the AAR2 discuss other aspects of the Austrian provisioning system in the context of a climate neutral economy, in particular Chapter 2 (agriculture, land use, ecosystem services) and Chapter 3 (buildings and mobility), Chapter 5 (human needs and wellbeing and individ-

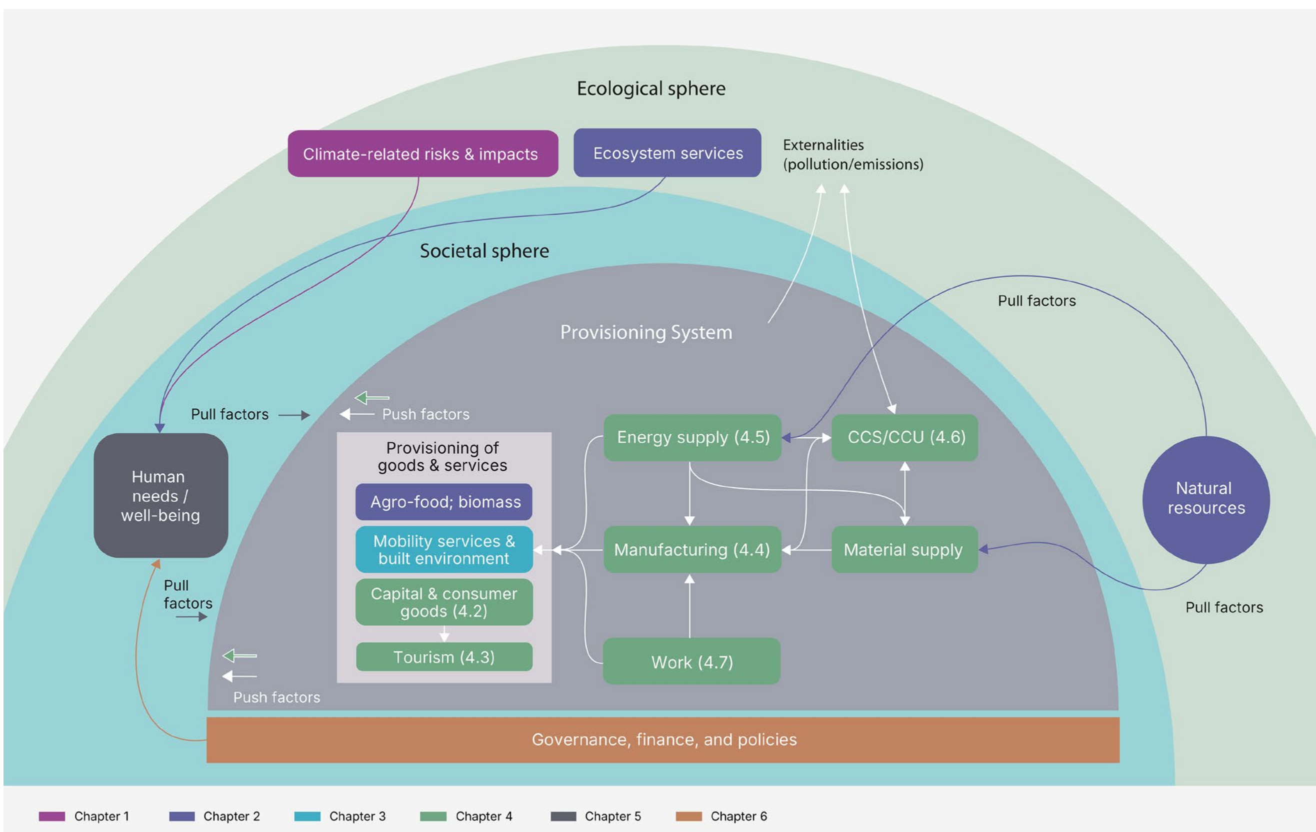


**Figure 4.1** The economy as a 'Provisioning System' as represented in the AAR2.

ual decision making at household and company level) and Chapter 6 (governance, finance and policy).

After a brief presentation of Austria's historical GHG emissions at the sectoral level (Section 4.1.2), the provisioning of goods and services (Section 4.2) is the starting point of this chapter. As tourism is an important sector within the Austrian economy, we assess tourism as a driver of climate change but also as a highly affected sector, with significant adaptation needs in the future (Section 4.3). We assess the industrial and manufacturing sectors that provide goods and services for final demand (Section 4.4), with a particular focus on Austria's hard-to-abate industrial sectors and the opportunities and challenges of a more circular economy for material supply. In addition, we assess the scientific evidence on energy supply (Section 4.5) and focus on decarbonization through the storage and use of $CO_2$ from carbon-intensive industries (Section 4.6). We also review the literature on the framework conditions for work, which are not only shaped by economic development, but are also crucial for the development of low-carbon pathways in production and consumption. Both paid work and unpaid but socially necessary work and activities are important for climate-friendly livelihoods (Section 4.7). Each of these sub-chapters reflects on the respective status quo, the constitution of a potential future climate-resilient and carbon-neutral sub-system, and the transformations needed to get there.

## 4.1.2. Sectoral emissions

GHG emissions in Austria have been fairly stable over the last five decades at 80 $MtCO_2eq/yr$, excluding sinks such as land-use, land-use change and forestry (LULUFC). Looking at Austrian sectoral emissions, the transport sector and industry are the largest contributors, with the latter's emissions

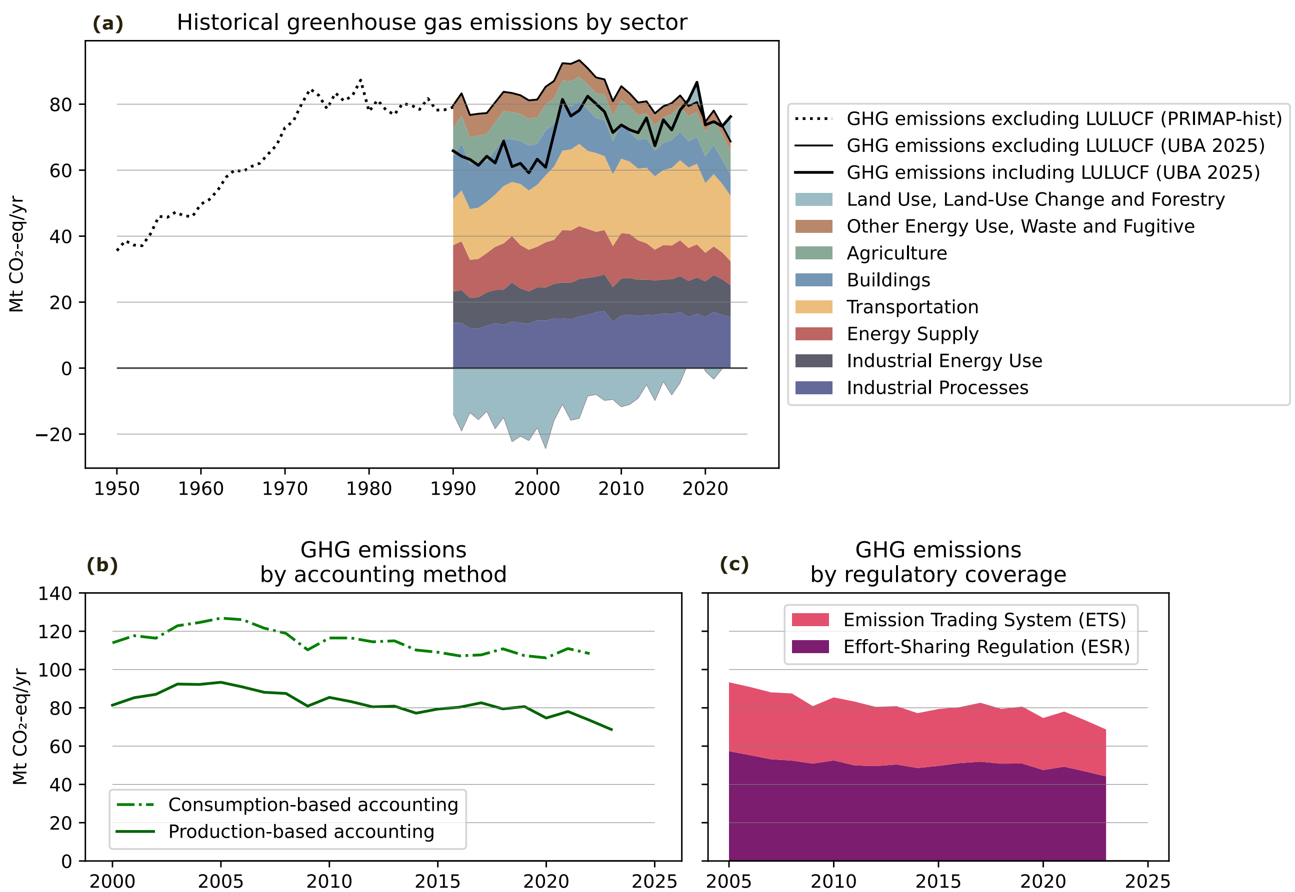


**Figure 4.2** Panel (a) Greenhouse gas emissions in Austria by sector (production-based accounting) since 1990 (Umweltbundesamt, 2025) (solid thick line including LULUCF; solid thin line excluding LULUCF; GHG emissions excluding LULUCF since 1950 (dotted line, Gütschow et al., 2016, 2024). Panel (b) Production- vs. consumption-based accounting of GHG emissions excluding sources and sinks from LULUCF (Dorninger et al., 2025). Panel (c) GHG emissions in Austria by regulatory coverage, excluding sources and sinks from LULUCF (Umweltbundesamt, 2024c, 2025). The reference data shown in this figure is available at aar2.ccca.ac.at/explorer.

split into those from industrial processes (the larger share) and those from energy use in industry (Figure 4.2).

When carbon emissions are adjusted for emissions associated with foreign trade in goods and services, Austrian imports are much more carbon-intensive than Austrian exports, making these so-called 'consumption-based' emissions about 50 % higher than the emissions generated within Austrian borders, so-called 'territorial' or 'production-based' emissions. Per-capita emissions in Austria are 10 % higher than the EU27 average and more than 50 % higher than the global average (Ritchie et al., 2024).

Only the last few years show a noticeable decrease in GHG emissions (Nowcast 2024, Umweltbundesamt, 2024b). This reduction of emissions was at first mainly due to effects of the COVID-19 pandemic-induced lockdowns, and in 2022 and 2023 due to a combination of the fossil fuel price increases due to the war of aggression by Russia against Ukraine and climate policy measures by the Austrian government (see Chapter 6) (Eibinger et al., 2024).

## 4.2. Provisioning of goods and services

This section considers the GHG intensity and climate resilience of the goods and services provided to meet individual and societal needs. Provisioning systems define the range of options available to individuals to meet their needs and thus have a significant influence on the adopted technologies, daily routines, and lifestyles (Plank et al., 2021b; Wieser and Kaufmann, 2023). The provisioning of goods and services contributes to well-being, but it requires both human labor and material stocks such as buildings, transportation infrastructure, and the energy production system, the expansion and maintenance of which can consume large amounts of energy (i.e., fossil fuels) and materials. In addition, access to services, such as thermal comfort in a living space or access to a particular destination, generally requires energy (Haberl, 2018; Kalt et al., 2019).

The goods and services that are made available for final consumption and use, and the way in which they are provided, thus have a major impact on resource demand and the climate footprint of a society. Furthermore, goods and services are essential for meeting needs that are distributed across space, time, and society (Chapter 5). Transforming goods and services to be climate-neutral and adapting them to changing climate conditions is therefore critical to ensuring adequate levels of service for all. In addition to decarbonization measures in 'supply-side' energy and manufacturing systems, which will be discussed below, changes in the volume (avoid), composition (shift), and quality (improve) of goods and services offer a wide range of options for 'demand-side' reductions in GHG emissions (Creutzig et al., 2022b) (see Cross-Chapter Box 4).

### 4.2.1. Status quo in the provisioning of goods and services

Material flow analyses provide a comprehensive overview of the number of resources that have to be extracted each year for the provisioning of goods and services. In Austria, the annual demand for processed materials amounts to 242 Mt, of which 51.2 % are extracted domestically, 40.5 % are imported, and 8.3 % are derived from secondary materials (see Figure 4.3) (BMK, 2024b). Nearly half of these processed materials (46 %) are used for durable goods and infrastructures, following their continued expansion in the recent decades (Jacobi et al., 2018; Wiedenhofer et al., 2021; Schug et al., 2023). The processed materials consist of 74 Mt of biomass, 27 Mt of metals (incl. extractive waste), 105 Mt of non-metallic minerals, and 37 Mt of fossil energy carriers. The expansion, replacement, and maintenance of the *built environment* in particular has become a major source of material demand (101 Mt), overshadowing the material requirements for technical equipment (4 Mt), transport vehicles (3 Mt), and non-technical products (3 Mt) used by households and firms. Today, the total mass of infrastructures and buildings in Austria is estimated at 540 t/capita, compared to 450 t/capita in Germany (Haberl et al., 2021), and per capita stocks are particularly high in sparsely populated areas (Schug et al., 2023). Important drivers of the expansion of infrastructures and buildings include the growth of the service economy (Deetman et al., 2021; Plank et al., 2021b), their significance for contemporary financial investments (Schaffartzik et al., 2021; Pineault, 2023; Wieser et al., 2023), and spatial development (see Chapter 3).

Increasing material demand for building and maintaining materials stocks (Wiedenhofer et al., 2021; Schug et al., 2023) and high growth rates in some service sectors (especially real estate, information and communication technologies, finance) (Plank et al., 2021b) have largely offset positive contributions to the decarbonization of provisioning systems made possible by structural shifts towards a more service-oriented economy. As a result, the total material footprint decreased only marginally between 2000 and 2015 in Austria (Plank et al., 2021b). A study found that out of 11 high-income countries that were able to reduce consump-

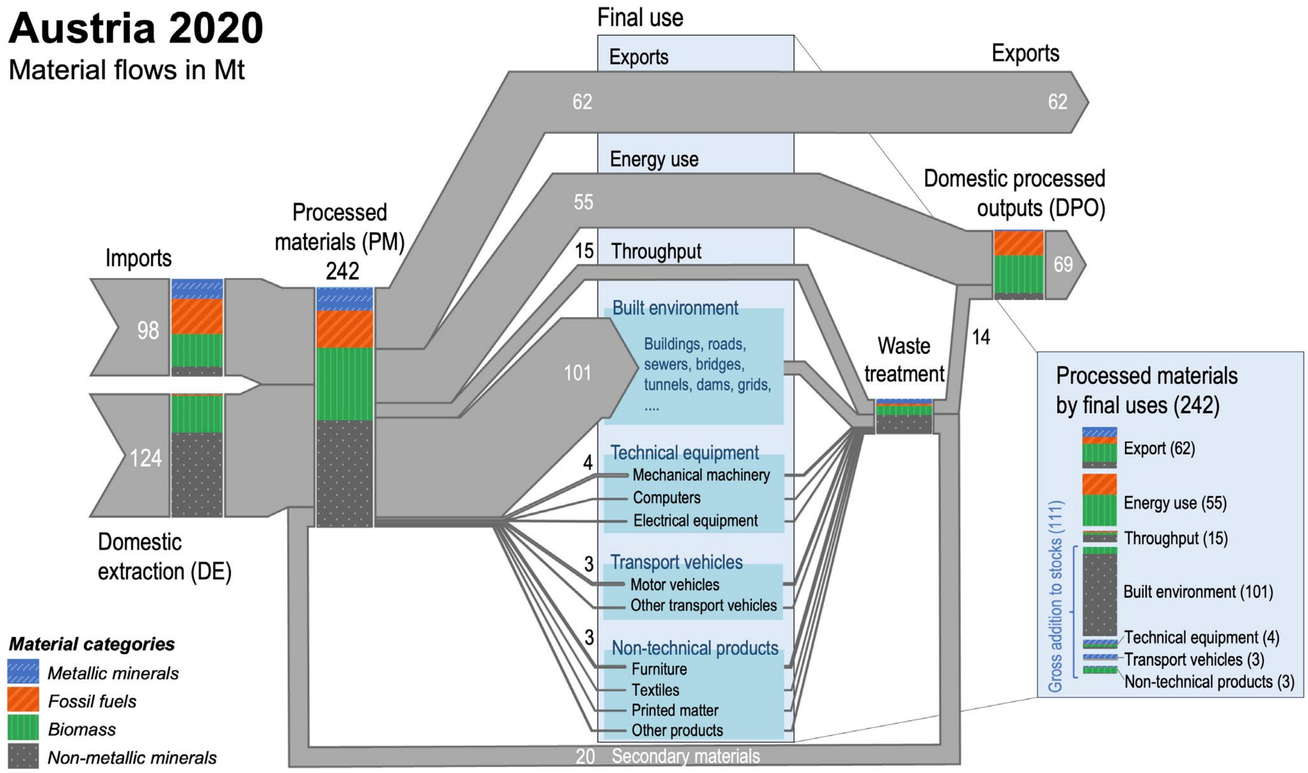


Figure 4.3 The material flows through the economy of Austria from inputs (extraction and imports) to final use (stock building) to outflows of exports and domestic processed outputs (DPO) (waste and emissions excluding oxygen from air) in 2020 (BMK, 2024b).

tion-based $CO_2$ emissions between 2013 and 2019 (achieving absolute decoupling from their GDP), Austria had the second slowest rate of reduction in consumption-based $CO_2$ emissions (-0.87 %/yr), which, when extrapolated into the future, is far from sufficient to stay below the temperature limit of the Paris Agreement (Vogel and Hickel, 2023).

Despite the importance of material stocks such as buildings, infrastructure, and machinery in driving material demand and GHG emissions, their expansion has received little attention in Austrian climate policy and discourse to date (cf. Theine et al., 2023) (see Chapter 6). Instead, efforts towards more climate-friendly goods and services have traditionally focused on the development and diffusion of technologies (Aigner et al., 2023b; Haas et al., 2023) (see Chapter 6). Today, 4.6 % of Austria's GDP is related to the production of environmental goods and services. Since 2008, this sector has grown largely in line with the Austrian economy, with comparatively high growth rates in export products, especially in renewable technologies, industrial products (chemical, machinery, information and communications technologies), and waste management. The Austrian economy has been shown to be particularly competitive in the provision of technologies for low-carbon buildings and rail transport (Steininger et al., 2021). However, most firms have so far focused on process innovations, with less attention being paid to the climate-friendliness of goods and services and how they are delivered to customers (Schöggl et al., 2022). The portfolios of Austrian manufacturing firms remain predominantly product-centric, with complementary services (e.g., repair, maintenance) and alternative, service-oriented business models (e.g., contracting, rental) making up only a small share of company revenues and added value to date (Dachs et al., 2014; Mastrogiacomo et al., 2019; Friesenbichler and Kügler, 2022; Wieser et al., 2023). The provisioning of energy-efficient technologies has thus been largely detached from wider concerns about material demand.

Public and non-governmental organizations are core pillars of the provisioning of goods and services in Austria. Public provisioning tends to be significantly more energy and material efficient due to a stronger focus on services and collective needs (Giljum et al., 2016; Vogel et al., 2021; in relation to public transport, see Virág et al., 2022). However, in the private sector, the focus has so far been on improving procurement and internal processes for resource efficiency (see Klien et al., 2023), rather than on the implications of public infrastructures and services for climate-friendly living (Aigner et al., 2023b; Haas et al., 2023). Significant decarbonization potential exists in several areas of public provisioning, including transport, housing, energy, and land use (Bröthaler et al., 2023).

In addition to challenges in cutting material demand, it has proven difficult to reduce the demand for energy needed to process and utilize goods and services. Energy demand is a key driver of GHG emissions in Austria, stabilizing at a level of around 1,280 PJ final energy (BMK, 2023b). The residential, industrial, and transport sector (Chapter 3) each account for around 30 % of final energy demand (Section 4.5). Despite improvements in energy efficiency, so far only *relative* decoupling (resource use grows more slowly than GDP) has been achieved for energy to date (BMK, 2023b). *Absolute* decoupling (declining energy use independent of GDP growth), which would be necessary to achieve ambitious climate goals with the current energy mix and without negative emission technologies, has not yet been achieved in Austria (Figure 4.4a). Reasons for this can be found in the residential and transport sectors and include the rebound effect (Seebauer, 2018), increasing activity and service levels, and the expansion of material stocks in buildings, infrastructure, and vehicle fleet which have outpaced energy efficiency improvements (see Chapter 3). In Austria, for example, higher heating energy demand (Figure 4.4b) is associated with behavior (Kulmer and Seebauer, 2019; Venturi et al., 2023) and an increase in floor area (Holzmann et al., 2013; Narula et al., 2022), despite recent climate- and price-induced reductions in energy demand for heating (WIFO, 2024). Heterogeneous effects across income groups have been observed (Kulmer and Seebauer, 2019), with, for example, energy-poor households compensating for previously unmet thermal comfort needs when insulation leads to lower energy bills for heating (Berger and Höltl, 2019). Similarly, the number of kilometers traveled in passenger cars, which are still predominantly powered by fossil fuels, has increased almost twice as much in Austria (+11.3 %) compared to the EU average (+6 %), while some EU countries have managed to achieve a decrease since 2010 (e.g., The Netherlands -3.8 %) (Eurostat, VCÖ, 2019) (Section 3.4.2). With their high dependence on fossil fuels and increasing demand for thermal comfort (mainly heating) and mobility, these sectors pose challenges for Austria's decarbonization, but several Avoid-Shift-Improve options are available (see Cross-Chapter Box 4 and Chapter 3).

Both private and public provisioning systems are exposed to extreme weather events, particularly floods and droughts, which can cause significant economic damage (Steininger et al., 2016; Unterberger et al., 2019). Empirical evidence on climate adaptation in the private sector is scarce but indicates that levels of awareness are low (Balas et al., 2021) and that the implementation of climate risk management measures is underdeveloped (Meinel and Höferl, 2017; Mitter et al., 2019; Hanger-Kopp and Palka, 2022), with public authorities considered as responsible for the management of physical climate-related risks (Rauter et al., 2020).

### 4.2.2. Future systems for the provisioning of goods and services using circular economy principles

Provisioning systems can become significantly more climate-friendly and -resilient while maintaining high levels of service quality and well-being (Barrett et al., 2022; Creutzig et al., 2022a). Energy services needed for a decent life (Grubler et al., 2018; Rao and Min, 2018; Kikstra et al., 2021) (Section 5.2.1) are substantially lower than the ener-

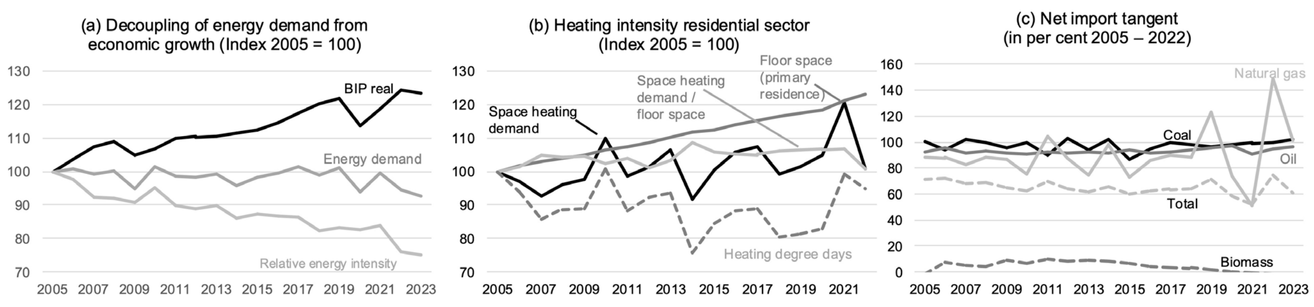


**Figure 4.4** (a) No absolute decoupling of energy demand from GDP growth in Austria as service levels increase; (b) heating demand (example), linked to energy; (c) import dependency. Source: Redrawn Figures 34, 36, 43 (BMK, 2023b).

gy footprint of the current provisioning system. For example, the carbon footprint of the Austrian healthcare system (0.8 $tCO_2$/capita) is significantly higher than in most European countries (0.52 $tCO_2$/capita in France or 0.42 $tCO_2$/capita in Sweden), suggesting significant GHG mitigation opportunities in the provision of high-quality healthcare services (Pichler et al., 2019; Weisz et al., 2020) (see Cross-Chapter Box 2 and Section 5.2). Reducing energy and material demand through changes in provisioning systems can deliver multiple co-benefits, most notably with respect to health and clean air (Creutzig et al., 2022a, 2022b), and system security and import dependence (see Figure 4.4c) (Bento et al., 2024), and enable low-carbon transformations of upstream supply systems (Grubler et al., 2018; Barrett et al., 2022; Creutzig et al., 2022b).

The recent decades have seen a sharp increase in material extraction from the environment, which has multiplied by a factor of 12 from 1900 to 2015. This acceleration of material use can be observed for all major material categories: Biomass, metals, non-metallic minerals, and fossil fuels (Krausmann et al., 2018). This unprecedented growth in resource use has implications for the climate, the environment, and the global supply chain. In this context, the Global Resource Outlook (UNEP IRP, 2024, p. 46) states prominently: "Given that resource use is driving the triple planetary crisis, sustainable resource management is urgently needed".

To mitigate the increase in resource use, the concept of the circular economy has become increasingly popular in recent years (see Cross-Chapter Box 5 and Cross-Chapter Box 4, for more details on circular economy principles). Material Economics (2018) investigated the climate potential of the circular economy in relation to industries in the European Union for 2050. They model (a) the material recirculation opportunity and assume that 75 % of steel, 50 % of aluminum and 56 % of plastics could be recirculated, saving 33 % of $CO_2$ emissions. Next, (b) their model results show that materials efficiency increases through avoiding losses in production processes (e.g., for aluminum or building materials) could save another 11 % of $CO_2$ emissions. Finally, (c) circular economy business models are identified as another lever that could reduce 12 % of emissions, particularly through sharing of vehicles (utilization of cars is currently about 2 % in the EU) and buildings (European offices' utilization is only about 40 %). Overall, 56 % of $CO_2$ emissions in heavy industries can be saved by these circular economy strategies.

A review article (Cantzler et al., 2020) screened more than 300 English-language papers in the fields of industry, waste, energy, buildings, transport, and agriculture that explicitly referred to both circular economy or closely related concepts and climate change mitigation potential. Only 10 % of the studies provided insights into how the circular economy can support climate change mitigation. The highest abatement potentials are found in industry, energy, and transport, medium abatement potentials in waste and buildings, and the lowest abatement potentials in agriculture. In conclusion, substitution of material and process substitution in cement, steel, and vehicle production, together with a shift to renewable energies, are core and essential strategies to decarbonize economies. This study shows that the existing literature provides a rather fragmented picture. Circular economy strategies of lower priority seem to be favored, while refuse, reduce, and rethink strategies are only poorly represented in the applied literature (see Cross-Chapter Box 5).

The most recent Global Resource Outlook (UNEP IRP, 2024) developed scenarios for a sustainability transition to 2060. It focuses on four policy packages, including (1) resource efficiency measures, (2) climate and energy, (3) food and land, and (4) a just transition. The packages address, for example, a resource tax, efficient and sustainable settlements with a compact urban form, and sustainable transport modes (ad. 1), carbon pricing, electrification, and renewable energy (ad. 2), nature protection and restoration, healthy diets, and less food waste (ad. 3), and net carbon revenues to provide a carbon dividend payment that supports reduced inequalities and no net economic loss due to the transition (ad. 4). These policy packages achieve a 30 % reduction in resource use and a 90 % reduction of GHG emissions by 2060 compared to a continuation of historical trends.

For Austria, a recent study models the biophysical economy for the period 2018 to 2040 to investigate how circular economy strategies in the building, transport (passenger and freight) and electricity sectors interact with decarbonization (Haas et al., 2025). For this purpose, two economic projections (moderate growth (1) and no growth (2)) are used in combination with four scenarios. One scenario (R) is a continuation of historical trends with no clear decarbonization, while the second scenario (A) is a decarbonization in the three sectors with strong recycling activities and a weak modal split shift representing circular economy strategies by 2040 (see details for all scenarios in Figure 4.5). A third scenario (B) adds to the decarbonization weak circular economy strategies, which are mainly a moderate reduction of passenger kilometers (p-km) and ton kilometers (t-km) and a moderate reduction of per capita floor area in new building construction. The strong circular economy scenario (C) includes a strong modal split shift and strong reduction in traffic volume, increased car sharing, a complete halt to the expansion of the road network, a halt to new construction on unbuilt land, and a higher share of wood construction in new buildings. The reduction in construction activity allows for a significant reduction in ton kilometers as, in addition to eliminating the transportation of fossil fuels, a large proportion of construction materials no longer need to be transported.

The weak circular economy scenario is based on assumptions found in official documents and studies during the modeling exercise (e.g., Kranzl et al., 2018; BMNT, 2019; Krutzler et al., 2023). The strong circular economy scenario is designed to achieve decarbonization and the targets set out by the Austrian government's circular economy strategy (BMK, 2022).

Methodologically, this research is based on international predecessor studies (Haas et al., 2015; Mayer et al., 2019a; Haas et al., 2020; Wang et al., 2020; Miatto et al., 2024) but goes beyond them in modeling all stocks in the building, transport and electricity sectors. End-use explicit material stocks are essential in modeling, as a transition will sooner or later need to replace societal stocks from heating systems, vehicles, to power plants.

The results in Figure 4.5 are presented for a smooth economic recovery projection after the crises since 2019 (COVID-19 pandemic, Russian war on Ukraine, assuming an annual GDP growth of 1.6 %, projection indexed 1) and a slow recovery with zero GDP growth (projection indexed 2). Reducing domestic material consumption (DMC) from 18.4 t/capita in 2018 to the targeted 14 t/capita in 2030 and about 6 t/capita in 2050 (based on the proclaimed 7 t/capita material footprint target of the government's circular economy strategy) (BMK, 2022) is unachievable with pure decarbonization (yellow line, A1). A combination of decarbonization and weak circular economy (B1) measures based on loop-closing (blue line), would still lead to a material consumption significantly above the official target and much closer to the reference value with continued trends (see Figure 4.5a). The strong circular economy scenario (C1) can contribute its share of the buildings, transport, and electricity sectors to government's circular economy targets. It should be emphasized that the measures needed to achieve these targets are highly controversial amongst policymakers. A halt to new building construction on unbuilt land is highly debated, as is a significant reduction in car use (derStandard, 2024).

The phasing out of fossil fuels through fleet electrification and non-fossil fuel heating systems (e.g., heat pumps), as well as the decarbonization of the electricity sector (green power), will contribute significantly to the achievement of the targets. The combination of a phase-out of new constructions of buildings in the period until 2030 and a strong modal split shift assists to reduce both processed materials and final energy use. While some measures have a strong impact on reducing both energy and material demand (e.g., no construction on unbuilt land), others mainly reduce final energy (fleet electrification) or materials (no new roads). Collectively, they contribute to a reduction in final energy of more than 50 %. The direct final energy use in these three sectors is completely based on renewable energy sources (mainly wind, solar and hydro at present levels). The reduction of material of more than 70 % by 2040 is in line with a reduction of the material footprint of Austria from 22 t/capita in 2018 to 7 t/capita in 2050.

The transition to a carbon-neutral economy can be facilitated if accompanied by strong circular economy strategies (Creutzig et al., 2024). The electrification of transport and, to some extent, heating (especially through heat pumps) is increasing demand for electricity. In 2018, electricity generation was 244 PJ, of which 158 PJ was based on renewable energy sources. In 2040, when all electricity generation is to be based on renewable sources, the demand is 378 PJ in the decarbonization scenario A1 (2.4 times the demand in 2018). The weak circular economy scenario (B1) requires 354 PJ of renewables (2.2x), while the strong circular economy scenario (C1) requires 308 PJ (2.0x). At the same time, as renewable energy sources increase, the demand for rare earth elements (REEs) increases from 84 t in 2018 to 722 t in the decarbonization scenario (A1) in 2040 and 181 t in the strong circular economy scenario in 2040. In particular, the transition will require REEs for electric vehicles and wind turbines. The availability of REEs is potentially challenging, depending on the global increase in renewable energy (Valero et al., 2018; Li et al., 2020; Klimenko et al., 2021) and potentially complicated by geopolitical tensions and negative social impacts in extraction locations (Creutzig et al., 2024). Similarly, a strong increase in electricity demand, as seen in the decarbonization scenario (A1), will require a significant increase in storage capacity, for example in the transport sector, associated with batteries containing scarce raw materials such as lithium (Diouf and Pode, 2015). This material demand can be mitigated by the strong circular economy scenario (C1), as it significantly reduces the number of battery-driven vehicles, for example through less road transport and car sharing.

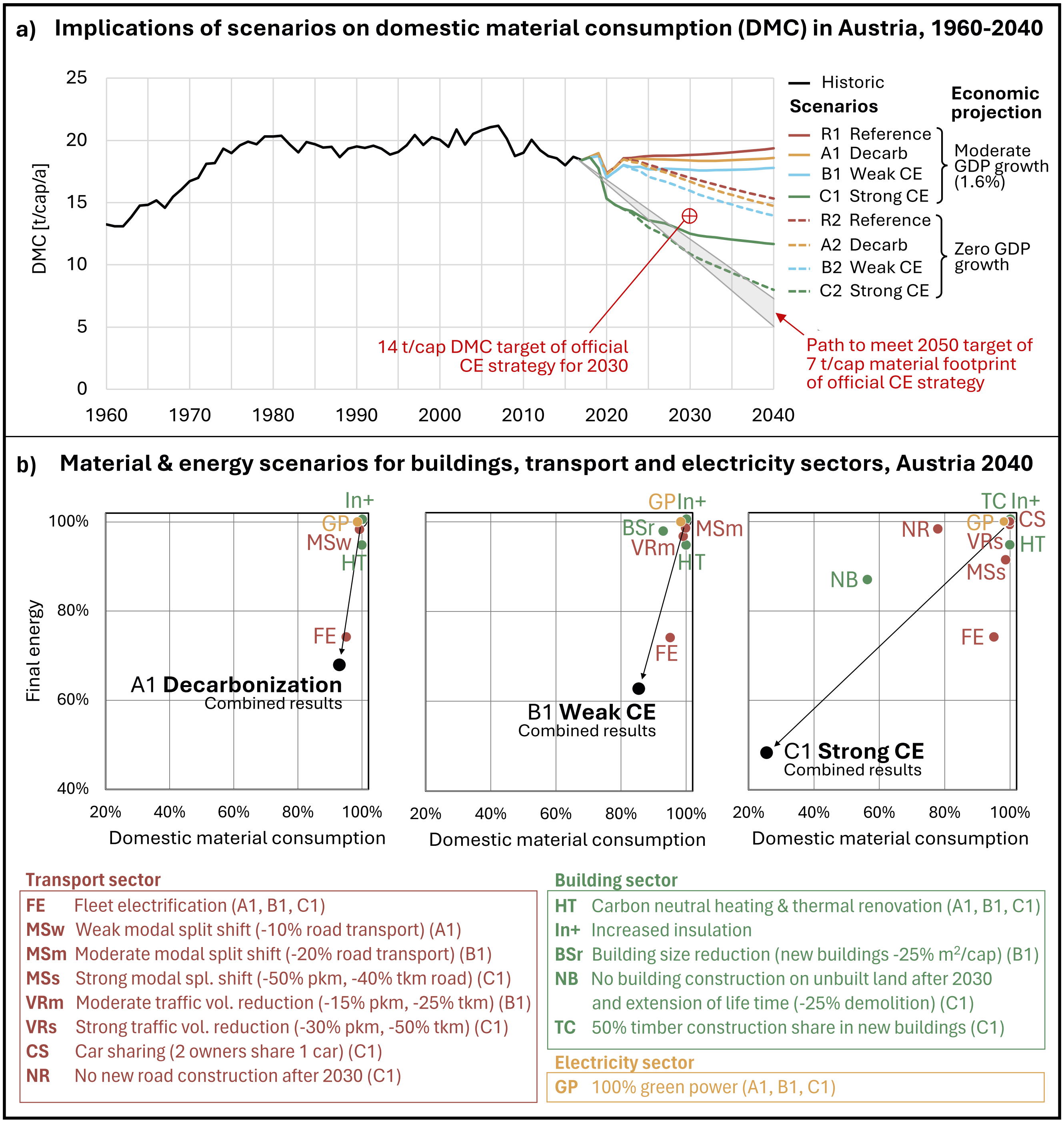


**Figure 4.5** (a) Domestic material consumption (DMC, all material extraction + imports – exports) for different decarbonization and circular economy scenarios towards the 2030 and 2050 targets of the Austrian Circular Economy Strategy. Scenarios were applied for two different economic projections, a moderate growth (GDP growth after recovery of 1.6 % and a slow recovery and growth of 0 %). (b) Below, a list of measures for decarbonization and circular economy is presented. These measures were applied in a decarbonization and loop closing (material recovery through recycling) scenario (A1), a decarbonization and weak circular economy scenario (applying officially reported measures) and a decarbonization and strong circular economy scenario (C1) that aims for contributing to the government's circular economy targets, which is summarized in processed materials (PM = DMC + secondary materials) but also reduces the demand for final energy. See assumptions for measures in the legend (Haas et al., 2025).

Although some circular economy measures in scenario C1 may seem extensive, the actual impact on quality of life will be rather low. While the car ownership rate is drastically reduced in a strong circular economy scenario (due to modal split shifts and an increase in car sharing), the distance traveled per capita would be reduced by 6 % compared to 2018. This is reasonable given the recent increase in the popularity of teleworking arrangements that reduce the need for work-related car-based commuting (Hartwig et al., 2022), and since the phasing out of new buildings in the C1 scenario stops further urban sprawl.

Another impact of the transition can be seen on floor space and land consumption. The decarbonization scenario (A1) would imply a continuation and thus an increase in land consumption from 11.5 to 12.4 ha/d in 2040. However, such an increase could be mitigated in the C1 scenario because no new roads and no new buildings on unbuilt land have the potential to stabilize land use without further land-consuming stock additions. In terms of floor space, this means that while we have 72 $m^2$/capita for residential and office space in 2018, this would increase to 78 $m^2$/capita in 2040 in the decarbonization scenario (A1), but decrease to 67 $m^2$/capita in the strong circular economy scenario (C1). Among the older population (60 years and older), there is an openness to reducing per capita floor space. For example, a German study found that 29 % of homeowners and 11 % of tenants are overburdened and assess their housing conditions as too spacious (Kitzmann, 2023). The Global Resource Outlook estimates a utilization rate of 40 % for office buildings (UNEP IRP, 2024). Numerous non-representative case studies show that office, public and educational buildings stand empty for between 90 to 95 % of their service life (including non-working time like weekends or holidays). Factors like low occupancy of seminar rooms, home office, part-time jobs and high proportion of field service can play a significant role here (Wiegand, 2012) (see also Section 3.3). Another Swedish study finds in a specific case a utilization rate of meeting rooms between 14 and 36 %, with meeting rooms mostly larger than needed, and an office attendance of less than 50 % on weekdays and during working hours, with no overcrowding up to 68 % office attendance (Holmin et al., 2015). Thus, a 7 % reduction in heated floor space for residential buildings and offices does not seem unrealistic. Further potential can be found in improved spatial planning that counteracts urban sprawl (Brenner et al., 2024).

From an economic point of view, an assessment of these scenarios shows that the average GDP growth rate for the period 2018–2040 would increase from 1.35 % in the reference scenario to 1.44 % in the C1 scenario. This change is due to the re-investment of savings from reduced construction activity in services, as services have a relatively low import intensity and high domestic wage intensity. For the same reason, employment also shows positive effects (Meyer et al., 2024).

An investigation of 18 individual measures with the overall aim of reducing the consumption of mineral raw materials in line with the sustainability strategies (consistency, efficiency, and sufficiency) from exploration through material processing to semi-finished production finds many positive effects for SDG 12 and its targets (Trummer et al., 2022) (see also Chapter 3). An interaction assessment of the measures related to the individual SDGs to better understand the many synergies and trade-offs between SDGs/targets was not conducted and is still lacking. The Global Resource Outlook finds that 13 SDGs are directly, and 4 are indirectly linked to natural resource use (out of 17 SDGs) (UNEP IRP, 2024).

The transition to a carbon-neutral economy offers both benefits and transition risks, depending on how it is implemented. A narrow implementation of measures for buildings, transport, and electricity sector, as in the A1 decarbonization scenario, could risk being highly vulnerable to supply chain disruptions, as REE demand would steeply increase. In addition, the high demand for electricity from renewable energy sources carries the risk that it is highly dependent on the smooth approval of projects, with little room to participate and respond constructively to public opposition and the availability of a sufficiently skilled workforce. Such a scenario would imply further land consumption, exceeding the long-discussed target of 2.5 ha of land consumption per day. It would fail to meet the targets set out in the government's circular economy strategy and to address the triple planetary crisis of climate change, biodiversity loss, and pollution. In contrast, the strong circular economy scenario (C1) has great potential to achieve circular economy goals, reduce land consumption, and facilitate the transition to renewable energy sources, as energy consumption and demand for REE are significantly lower. In summary, especially if a strong circular economy strategy in combination with demand-side measures is implemented, both the magnitude of the climate challenge and the need for material resources relevant to biodiversity and pollution will be reduced (see Creutzig et al., 2024; Haas et al., 2025).

## Cross-Chapter Box 3. Needs orientation in provisioning systems

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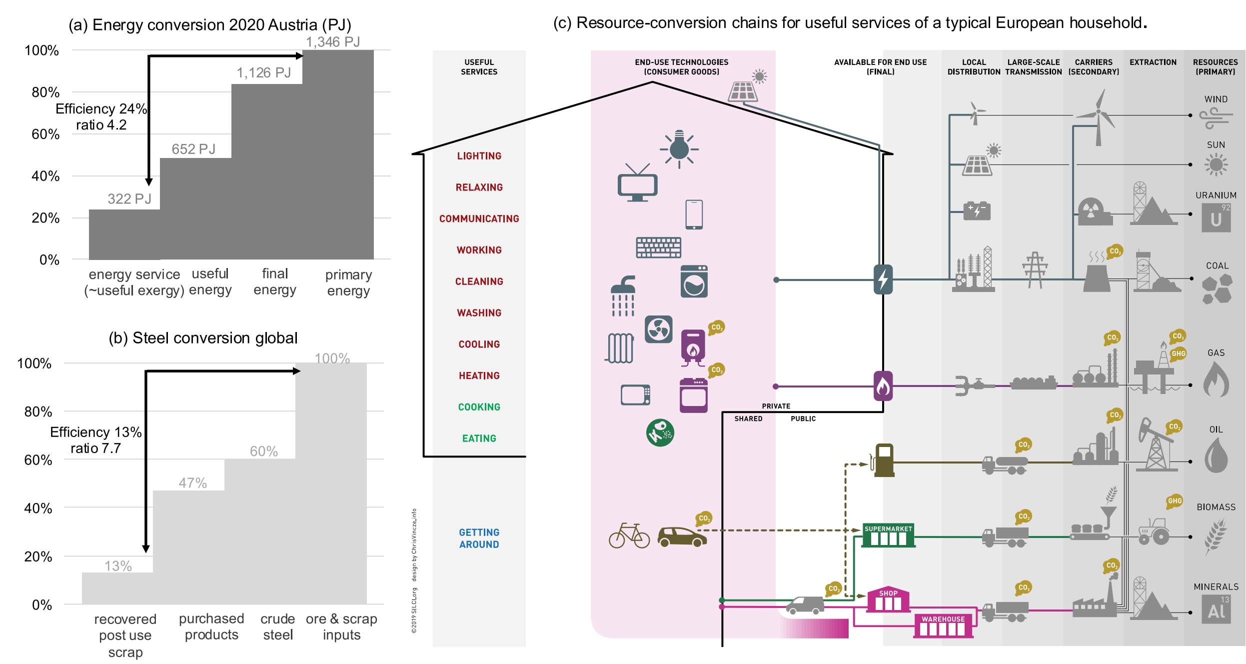
A demand-side perspective that focuses on the provisioning of services can help (i) identifying large leverage opportunities along the resource conversion chain and (ii) shifting focus on human needs and well-being.

Conversion losses occur, for example, when energy is transformed from one form to another, such as from primary energy (e.g., crude oil) via final energy (e.g., gasoline) to useful energy (e.g., power to the wheel of the car) to the energy service level (e.g., mobility for a certain distance). First, in the current energy system dominated by thermal combustion (e.g., internal combustion engines, boilers), service energy (i.e., useful exergy as a proxy) accounts for 24 % of primary energy input in Austria (CCBox 3 Figure 1a), up from 11 % in 1960 (Marshall et al., 2024). This means that each unit of energy that is avoided or not needed at end-use levels translates to around four units of primary energy that do not need to be provided (Marshall et al., 2024). When we move towards more (renewable) electricity-based systems, these conversion losses will be reduced substantially. The conversion losses also occur in materials processing, where Austria is connected to global material chains (Section 4.2). Globally, steel production from primary ore shows high conversion efficiency losses (CCBox 3 Figure 1b), even though steel is one of the easier-to-recycle materials and a respective market exists. Challenges related to materials will increase with the need for high-quality materials, which are often not available through recycling, and increasing shares of compound materials used, which cannot be recycled easily. Actions reducing demand have great potential in terms of overall resource implications and other co-benefits, e.g., for energy, GHG reduction potential, costs, well-being, reduced air pollution, supply security, flexibility, positive impact on the trade balance of energy importers (Finn and Brockway, 2023; Bento et al., 2024) (see Figure 4.4c and Cross-Chapter Box 2).




**CCBox 3 Figure 1** (a) Resource efficiency cascades throughout the provisioning system for energy in Austria and (b) for steel globally. Each step of the cascade shows the percentage of the extracted primary resource remaining after conversion losses, starting from primary energy on the right. Arrows indicate the efficiency ratio between primary input and the last conversion step. (c) Resource conversion chains (gray shades) linking energy services (e.g., heating, cooking, and mobility) with primary energy for a typical European household (Source: Adapted from Wilson et al. (2023) based on TWI2050 (2018). Estimates for energy in Austria from Marshall et al. (2024), for global steel from De Stercke (2014)).

Moreover, demand for goods and services can be met with different levels of energy or material input. By shifting the focus away from primary resource inputs (e.g., tons of oil) to services that meet human needs and enable human well-being (e.g., thermal comfort), diverse provisioning opportunities of different resource intensities arise. Energy or materials are not demanded for their own sake, but for the goods and services they enable (CCBox 3 Figure 1c). The design of services and the associated user experience is highly relevant to managing demand (Lovins, 2010; Polaine et al., 2013). This is critical for just energy transitions, as human well-being should not be compromised, or at least maintained, but ideally be improved in the transition process. Focusing on service levels rather than on energy or material inputs can facilitate the achievement of decarbonization and distributional objectives, such as those related to affordability (Sections 5.6, 6.7), energy poverty (Sections 5.3.4, 6.8) and decent living (Sections 5.2.1, 6.8), but a focus on the demand side also helps to achieve improvements in health (see Cross-Chapter Box 2), jobs, and energy security (Bento et al., 2024).

## Cross-Chapter Box 4. Avoid – Shift – Improve: The ASI-framework

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Avoiding, shifting and improving are different entry points for achieving **reductions in emissions and resource use** which have been systematized in the so-called A(void)-S(hift)-I(mprove)-framework (Creutzig et al., 2018). In many ways, the ASI-framework is complementary to a framework based on efficiency, consistency and sufficiency. Here, efficiency (i.e., improve) refers to 'doing things better', consistency (i.e., shift) refers to 'doing things differently' and sufficiency (i.e., avoid) to 'doing less' (Fuchs et al., 2023). The ASI-framework represents a hierarchy, with concerns for 'Avoid' and 'Shift' preceding those of 'Improve' (Arnz et al., 2024), as improve strategies so far have not led to the required GHG emissions reductions (Haberl et al., 2020), while national climate action plans in the EU still hardly use sufficiency-oriented measures (Fuchs et al., 2023).

***Avoid*** refers to mitigation options that aim at **reducing or refraining from activities** that are using products and services that are unnecessary in meeting basic human needs (see Cross-Chapter Box 5) (Fuchs et al., 2023). 'Avoid' refers to the reduction of energy and materials either through behavioral change and/or through the redesign of associated *service provisioning systems*, such as the redesign of infrastructures and institutions by means of laws, regulations, nudging, etc. (Aigner et al., 2023b). Sometimes structures enable needs satisfaction without producing goods or using energy and materials (e.g., a compact city) (Aigner et al., 2023b). Examples of mitigation options of 'Avoid' comprise reducing unused living space, calory consumption or transport needs by working from home (or remotely), thereby avoiding the production and consumption of energy and material-intensive harmful and unhealthy food (Lampl et al., 2024).

***Shift*** describes a change through substitution of one option for another. This entails a **switch to another cleaner option or service provisioning system.** This could be the switch from car to public transport due to new infrastructural arrangements or price incentives (e.g., climate and repair bonus), replacing fossil fuels by renewables in the energy mix (e.g., gas boiler to heat pump), or moving towards a more plant-based diet.

***Improve*** refers to enhancing the efficiency of existing technologies or practices improving their environmental performance. This often means optimizing the efficiency of existing products, services and production processes. Examples are better building insulation, reducing food losses, or higher efficiency in internal combustion engines.

In line with multi-perspectivity, avoid, shift, and improve measures are not mutually exclusive, but **need to be combined in portfolios of measures**, to increase their effectiveness (Fuchs et al., 2023; Novy et al., 2023) (see Sections 6.5.4, 8.6.1). Transport systems that provide the service of accessibility and mobility can combine compact cities with a shift to public transport and ridesharing (see Section 3.4.2, CCBox 4 Table 1).

As all ASI mitigation options entail synergies and trade-offs (e.g., rebound effects), a careful approach is required that takes into account the interactions between ASI options in order to utilize synergies and mitigate trade-offs (Haas et al. (2023); for a discussion on digitalization, see Santarius et al. (2020)) (see Section 8.3, 8.6).

The ASI-framework is also relevant for GHG-emissions stemming from consumption in general (e.g., GHG emissions from process emissions in the concrete production as part of housing provisioning) (Aigner et al., 2023a, 2023b).

While avoid and shift measures often depend on **changes in infrastructure, institutions and prices**, improve measures are often compatible with incumbent habits and practices and can therefore be implemented more quickly. However, improve options alone often bear a small mitigation potential compared to avoid and shift measures to achieve decarbonization. They may also lead to rebound effects when efficiency gains induce an increase in production and consumption (Alcott, 2008; Sachverständigenrat für Umweltfragen, 2024).

The ASI-framework aims at reducing environmental pressures rather than solely favoring efficiency gains, acknowledging the absolute biophysical limits of the Earth system and the non-substitutability between different dimensions of sustainability. It is grounded in theories of provisioning, exploring the interplay between production, consumption and distribution. While a 'provisioning system approach' does not examine the material throughputs (Fine, 1994; Bayliss and Fine, 2020), a 'social provisioning perspective' studies the organization of livelihoods and places provisioning at the center of feminist and (social) ecological economics, investigating who provides services (paid and unpaid), by what means, and with what material impacts (Nelson, 1993; Jo, 2011; Jo and Todorova, 2019; Spash, 2024). Human well-being depends on the specific institutional-normative organization of the socio-economic system embedded in biophysical systems with diverse planetary boundaries (O'Neill et al., 2018). Therefore, gender, inequality and power relations affect the potential to mitigate emissions and resource use (Brand-Correa et al., 2018; O'Neill et al., 2018; Schaffartzik et al., 2021). In such a broad understanding of provisioning, actors including households, business, civil society and (semi-)public institutions form provisioning systems (Plank et al., 2021b). They evaluate, judge, and decide on whether and how to modify framework conditions of service-provisioning systems – and in consequence – forms of life (Creutzig et al., 2022a). Structures of supply (e.g., available portfolio of goods) and infrastructures (e.g., village centers with a high quality of livability) interact with social and cultural norms for service choices (i.e., diet choice, modal split).

The ASI framework encourages a more systematic way of thinking about different measures by **directly targeting well-being** and needs satisfaction when formulating and comparing mitigation strategies. The underlying eudaimonic understanding of a good life puts human needs at the center, including thermal comfort, nutrition, or mobility (Creutzig et al., 2016, 2018) (see Cross-Chapter Box 3). It aims to change supply structures and modify infrastructures and choice architectures to change demand for goods and services, thereby differentiating between the overall amount of resource use (e.g., liters of fuel), the required *service level* (e.g., the use of energy for heating or cooking) and the related *provisioning systems* (e.g., the energy, food or mobility system covering production, consumption and distribution) that are available to provide the different services (Creutzig et al., 2022a).

The ASI framework, interested in what people need for a good life, has labeled its policy proposals as demand-side solutions, i.e., service provisioning systems with the specific objective to conceptualize **demand, preferences and choices not as given but as malleable** (Creutzig et al., 2018). Globally, demand-side solutions could collectively reduce emissions by 40–70 % by 2050 (IPCC, 2023a). Demand-side solutions widen the available portfolio of measures. First, they nudge behavioral changes within given infrastructures and institutions by exploring consumer preferences and deriving feasible (often incremental) solutions under given framework conditions (see Chapter 5). Second, they aim at deeper transformations of norms and objectives due to different infrastructures, institutions and prices (Meadows, 1999; Abson et al., 2017; Aigner et al., 2023a) (see Section 8.6.3).

Some examples to guide the categorization of options are provided in CCBox 4 Table 1.

**CCBox 4 Table 1** Selected examples of measures across sectors categorized according to the ASI framework (assessment by authors based on Creutzig et al., 2018, 2022a, 2024; Aigner et al., 2023; Arnz et al., 2024). For a systematic list of measures and their assessment, see the respective chapters, as well as Table 6.2.

| | Service | Avoid | Shift | Improve |
|---|---|---|---|---|
| Transport | Accessibility<br>Mobility | Compact cities<br>Integration of transport and land-use planning<br>Teleworking<br>Workplace near to place of residence | Electric two-, three- and four-wheelers<br>Mode shift from car to cycling, walking, or public transit | Eco-driving<br>Light-weight vehicles<br>More efficient gasoline engines<br>Ride sharing |
| Buildings | Shelter | Avoid empty living space<br>Change temperature set-points<br>Efficient floor space allocation and reuse of existing buildings<br>Passive house (avoiding demand for heating/cooling)<br>Shading and solar radiation aware architecture<br>Smaller houses | Combined heat and power<br>Heat pumps, district heating and cooling<br>Invertor air conditioning<br>Solar thermal | Building insulation<br>Improved raw materials sourcing practices<br>Condensing boilers<br>Incremental insulation options<br>Energy-efficient appliances<br>Other building materials |
| Manufactured products and services | Clothing<br>Appliances | Prohibition of certain fast fashion business practices (e.g., throwing away non-used goods in online-shopping)<br>Reuse and repair (that is: Not producing new goods, thereby avoiding emissions and material)<br>Sharing economy | Shift to recycled materials, low-carbon materials for buildings and infrastructure | Long-lasting fabric, appliances<br>New manufacturing processes and equipment use<br>Use of low-carbon fabrics |
| Food | Nutrition | Calories in line with daily needs<br>Smaller fridges and freezers | Healthy fresh (seasonal) food to replace processed food<br>Shift from ruminant meat to other protein sources where appropriate | More efficient fridges and freezers<br>Reuse food waste and food waste reduction |
| Work | Commuting | Limit the availability of car parking lots<br>Reduce the number of days worked per week to avoid non-needed commuting<br>Work-places nearby the living places | Provide sharing options at workplace<br>Shift to public transport or cycling | Shift to electric mobility for commuting<br>Subsize the electrification of company cars |

## Cross-Chapter Box 5. Circular economy

*Willi Haas, André Baumgart*

Steadily increasing extraction and processing of material resources (fossil fuels, minerals, non-metallic minerals and biomass) are the main drivers of the three planetary crises climate change, biodiversity loss and pollution (Geissdoerfer et al., 2017; UNEP IRP, 2024). To better deal with these increasing resource flows, the concept of circular economy has gained popularity in the past two decades and is being continuously developed (Kirchherr et al., 2023). The importance of and interest in circular economy concepts derive primarily from the fact that they can be used as a basis for developing solutions to environmental and climate policy concerns that will also provide economic opportunities, while relying on key economic principles such as the efficient use of resources. Increased resource efficiency through a circular economy essentially means striving for higher value creation with lower use of natural resources (Geng et al., 2019). The definition of the circular economy matters for circularity assessments and prioritizing measures. In the last two decades, according to Korhonen et al. (2018), practitioners have been the dominant driving force behind the circular economy concept. Thus, policymakers, businesses, business consultants, business associations, and business foundations play a key role in this field (People's Republic of China, 2008; Ellen Macarthur Foundation, 2013, 2015; COM/2015/0614 final; McKinsey & Company, 2016; Japanese Ministry of the Environment, 2018; de Wit et al., 2019). Consequently, these actors promote definitions that serve their interests with little attention to consistency across products, supply chains, materials, or scales, and in the worst case risk greenwashing and image loss (Nobre and Tavares, 2021). But also within the scientific community, circular economy "means many different things to different people" (Kirchherr et al., 2017, p. 229). In a follow-up article, Kirchherr et al. (2023) found 221 definitions in 6,566 studies in a review of circular economy conceptualization.

A definition that received broad recognition (more than 3,800 citations) comes from Korhonen et al. (2018, p. 39): "Circular economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical materials flows, renewable energy sources and cascading-type energy flows. Successful circular economy contributes to all the three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilizes ecosystem cycles in economic cycles by respecting their natural reproduction rates".

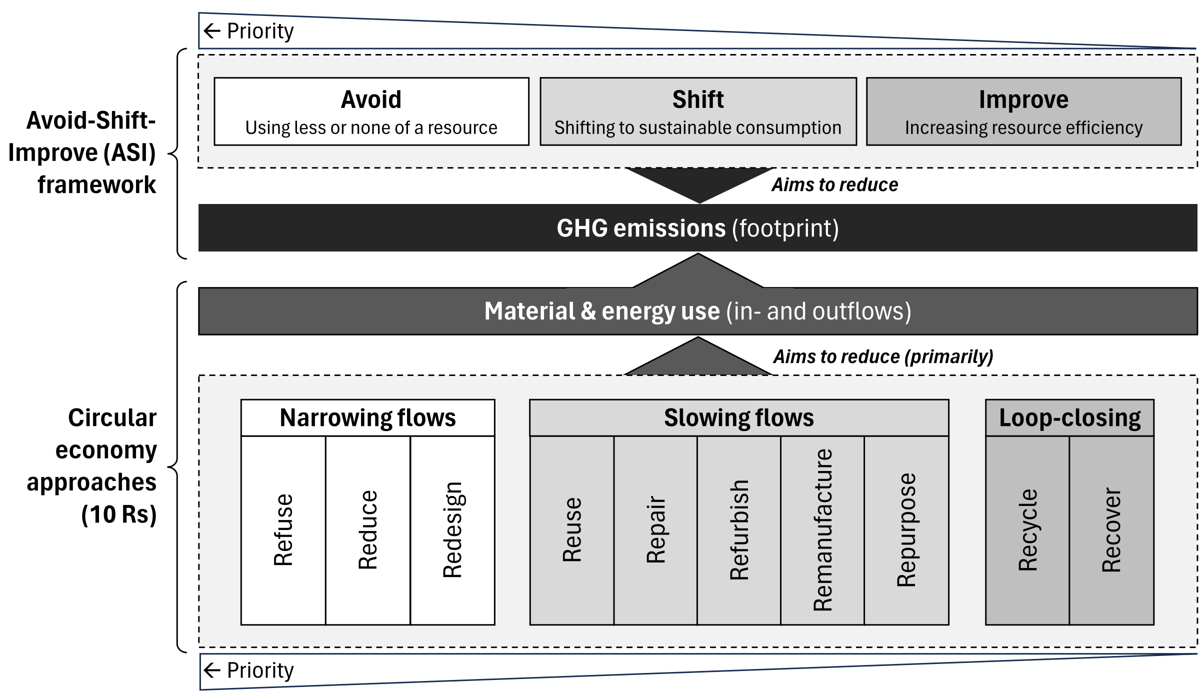
In line with this definition, there are several circularity strategy frameworks, often referred to as 10R (Potting et al., 2017; Blomsma et al., 2019; Morseletto, 2020) – because of the ten strategies all starting with an 'R' – which aim to minimize the consumption of raw materials and the generation of waste and emissions. The 10R strategies (sometimes referred to as 9Rs due to different counting) range from narrowing (refuse, reduce, redesign), slowing (reuse, repair, refurbish, remanufacture, repurpose), to closing loops (recycle, recover) of material flows. Strategies are prioritized according to their levels of circularity, with smarter product manufacturing and use, such as product sharing, generally being preferred over extending product lifetime because more users can be served by one product (narrowing strategy with high circularity). Next in order is lifetime extension (slowing), followed by material recycling (closing loops), in which product integrity is lost. Last is incineration, in which energy is recovered with the highest quality material reduction (Potting et al., 2017).

Thus, the 10R strategies follow the same guiding principle as the Avoid-Shift-Improve framework (Muñoz et al., 2024). While Avoid-Shift-Improve is primarily focused on reducing GHG emissions, the 10R strategies are focused on reducing raw material inputs from nature and waste (Reike et al., 2018). However, the two concepts are inherently linked, as the material perspective of the 10R framework, which includes energy materials (fossil and biomass fuels) and the extraction, processing, and use of materials as products and infrastructure, is a major cause for energy use and GHG emissions (see CCBox 5 Figure 1). As a direct result of material and energy use reduction, the circular economy approach also reduces land consumption and biodiversity loss.

The circular economy is thought to contribute to resource security and resilient value chains by redirecting resource flows from waste management to the productive economy (IEA, 2022). However, there is a risk that circular economy strategies focus too narrowly on closing loops, respectively recycling, as this promises a zero-waste world and thus allows unrestrained growth of stocks and flows, rendering circular economy impossible and failing to address the enormous strain to reduce and slow material and energy use (Haas et al., 2025).

While circular economy offers strategies to reduce material and energy use as well as waste and emissions, it encounters surmountable thermodynamic limits. According to the first law of thermodynamics, mass and energy are constant in a closed system (Fischer-Kowalski et al., 2011). Therefore, if the global socio-economic system is a circular economy that does not draw on the resources of the biosphere, this is not feasible with growing stocks of materials. Materials cannot be created out of nothing, so any system with growing stocks will need inputs of primary materials, even if it were possible to completely reuse or recycle all old materials and waste. As stocks, even if constant, have to be maintained due to deterioration, wear and losses, a fully circular economy is impossible. The second law of thermodynamics on entropy means that material qualitative characteristics are altered in irreversible production processes (Giampietro, 2022). Further, energy and material requirements for recovery, processing and recycling rise disproportionally the more dispersed and mixed end-of-life wastes are. This is because waste materials of all households for example need to be returned to the specialized production sites and have to comply with quality and purity requirements of high-tech production processes or for performance reasons, e.g., in construction (Ayres, 1999; Reck and Graedel, 2012; Cullen, 2017).

All these limitations need to be seriously considered when discussing circular economy potentials against the backdrop of material and energy use dynamics at different levels. According to the latest Global Resources Outlook report (UNEP IRP, 2024), global domestic material consumption (DMC) amounted to 96 Gt/yr in 2019. With 9.5 Gt/yr of secondary materials having re-entered the production chain, global input circularity was about 9 % (UNEP IRP, 2024). Since 1900, non-circular input flows have increased 16-fold, while the global input cycling rate has decreased from 43 to 27 % (Haas et al., 2020). At EU level, with a DMC of 6.4 Gt/yr and a recycling of 0.8 Gt/yr in 2022, the circularity rate was about 11 % (Eurostat, 2023).




CCBox 5 Figure 1 Comparison of two overlapping but different frameworks: The Avoid-Shift-Improve framework sets priorities between three strategies to reduce GHG emissions while the circular economy approaches set priorities for 10R strategies to reduce material and energy in terms of their related inflows of raw materials from and outflows wastes and emissions to nature. Source: Own visualization.

To increase circularity, circular economy concepts have been integrated into various international policies and strategies, including the Sustainable Development Goals (SDGs), where SDG 12 'Responsible consumption and production' is primary concerned with sustainable use of natural resources and waste reduction. Likewise, the European Union adopted the 'EU Action Plan for the Circular Economy' in 2015 (COM/2015/0614 final), which has gained new impetus in the wake of the Green Deal to achieve climate neutrality (COM/2019/640 final), but has also been criticized for being holistic in words but 'end-of-pipe' in action (Calisto Friant et al., 2021), with fragmented and competing goals reducing effectiveness (Domenech and Bahn-Walkowiak, 2019), and finally for a lack of high-quality data to assess progress towards a far-reaching circular economy (Morseletto and Haas, 2023).The Austrian government has set the ambitious goal to achieve climate neutrality by 2040 at the latest (BMK, 2023a). The 'Austrian Circularity Strategy' aims to reduce resource use and waste by promoting circular economy strategies (BMK, 2022). The strategy envisions an annual per capita DMC of 14 t in 2030 and a per capita material footprint (MF=DMC including upstream material requirements) of 7 t/yr in 2040, which corresponds to a DMC of roughly 5–6 t/capita. However, Austria, as a country with a high per capita stock level (Haberl et al., 2021), had a DMC of around 18 t/capita in 2018, of which 28 % was used in the building sector, 19 % in the transport sector, and 2 % in the electricity sector (Haas et al., 2025). This leaves more than half for other sectors, including manufacturing and agriculture (see Section 4.2.2 and Chapter 5).

Circular economy can support climate policy and the transition to carbon neutrality, as the accumulation of material in societal stocks in particular is key to energy reduction, since the expansion, maintenance and operation of stocks are major drivers of energy use. Since green energy will remain a bottleneck for at least the next decades (see challenges discussed in Ang et al., 2022), the circular economy's reduction potential is urgently needed.

The goals of the Austrian Circularity Strategy are interwoven with goals from other national strategies: Soil sealing remains an issue in Austria, with the average daily increase in hectares of land taken being significantly above the official 2.5 ha/d target formulated as part of the Master Plan Rural Development 2017 (Prokop, 2019). Reducing the amount of land sealing implies a reduction in newly constructed houses or a slowdown in further transport network expansion and consequently puts a restraint on resource use. Reductions in material and energy use lead to reductions in GHG emissions. Together, a reduction in land sealing and associated land fragmentation and mitigation of GHG emissions benefit biodiversity and the climate (Wiedenhofer et al., 2015; Koemle et al., 2018).

### 4.2.3. Necessary transformation in the provisioning of goods and services

Considering the large stocks of materials in use in infrastructures, buildings, and appliances, major investments are required to reduce fossil fuel consumption needed for their use and to adapt these stocks to changing climatic conditions (Bachner, 2017; Bachner et al., 2019a; Bröthaler et al., 2023). At the same time, the modernization and replacement of existing material provisioning structures, alongside necessary investments in new manufacturing facilities (see Section 4.4) and energy supply infrastructures (see Section 4.5), would significantly increase electricity and material demand in the short- to medium-term. Furthermore, an overemphasis on the diffusion of low-carbon technologies can create long-term dependencies on critical raw materials such as lithium. This calls for a balanced approach to transformation that accounts for the different timeframes within which net reductions in GHG emissions can be achieved. Energy and material efficiency measures in the provisioning of goods and services with high potential for short-term reductions in demand, thus play a vital role in the transformation process (Barrett et al., 2022; Creutzig et al., 2022a; Langevin et al., 2023). Avoid measures come with both short- and long-term potential, thus focusing on them offers great transformation opportunities. Within all Avoid-Shift-Improve options, the interplay between individual actions and existing structures can hamper the potential (see Chapters 5 and 6; Cross-Chapter Box 4).

To realize the potential for reductions in energy and material demand outlined in the previous section, and to improve the resilience of provisioning systems to climate-related shocks, provisioning systems would need to undergo transformative change at multiple levels: Shifting to local provisioning systems that enable climate-friendly modes of living, establishing infrastructures and buildings that facilitate climate-friendly practices in everyday life, and deploying more climate-friendly end-use technologies. To date, the latter have received most attention in climate mitigation strategies (see Section 4.2.1). Integrative frameworks such as the circular economy can support actions across all three levels and thereby contribute to more systemic and needs-oriented responses (see Cross-Chapter Box 5 and Cross-Chapter Box 4) to climate mitigation.

**Local provisioning systems for climate-friendly modes of living:** Provisioning systems can play an important role in giving rise to daily needs in the first place. The quality, design, and spatial organization of provisioning systems can influence decisions as diverse as starting a family, relocating, or choosing a certain lifestyle – decisions that can have long-term repercussions for both climate mitigation and adaptation (Schäfer et al., 2012; Greene, 2018). Compact city design, polycentric provisioning systems, and multifunctional areas can reduce dependencies on unsustainable technologies and practices (e.g., car dependency) (Svanda and Zech, 2023). Design aspects need to go beyond spatial planning to include institutional arrangements with regards to, for example, work or decision making (Sections 4.7 and 8.5.4). Within the design of systems that cater to certain needs lies the largest power for avoid and shift activities that reduce the overall system size (see Cross-Chapter Box 4).

**Infrastructures and buildings for everyday life:** At the level of everyday practices, the circular economy, the sharing economy, and digitalization are three interrelated 'megatrends' that offer cross-sectoral opportunities to improve more infrastructures and buildings more efficiently (Creutzig et al., 2022b). Synergies may exist between the circular economy and resilience, but evidence is limited to date (Kennedy and Linnenluecke, 2022). New, digitally-enabled and more service-oriented business models are at the center of many circular economy and sharing economy initiatives, although assessments of their mitigation potential still remain fragmented. Despite the greater service orientation, there is still a significant gap between the focus on business models and specific product lifecycles in these economic models on the one hand, and the broader solution space considered in energy and material services perspectives on the other (Carmona et al., 2017; Whiting et al., 2022; Wieser et al., 2023). Less attention is paid, for example, to public provisioning and inequalities in access to goods and services. The mitigation potential of circular and sharing business models is therefore contingent on the careful management of rebound effects (Kjaer et al., 2019; Castro et al., 2022; Metic and Pigosso, 2022). As a regulator, procurer, and owner of large infrastructure providers, the public sector can play a key role in supporting the transition to climate-neutral and -resilient infrastructures and buildings (Kubeczko and Krisch, 2023). It has been shown that policies to meet Austria's circular economy strategy (BMK, 2022) and the formulated targets for land take (Prokop, 2019), have to limit the construction of road infrastructure and buildings, as they are major consumers of materials and are related to increasing energy consumption (see Figure 4.5). Thus, a strong circular economy strategy focused on narrowing material resource flows and essentially targeting infrastructures and buildings in the transport, building and electricity sectors, can reduce material consumption in these sectors by more than 60 % and their energy consumption by more than 50 % (Haas et al., 2025).

**Environmental end-use technologies:** The diffusion of climate-friendly end-use technologies has been critical to climate mitigation to date (Geels, 2023). As the development of important end-use technologies such as electric cars, heat pumps, photovoltaics, and biomass district heating in Austria shows, innovation and diffusion processes typically take several decades, frequently have an infrastructure component, and involve significant changes in user practices (Geels and Johnson, 2018; Kulmer et al., 2022). Supporting such non-incremental innovation requires a balanced combination of supply-side 'technology-push', demand-side 'market-pull', and systemic intervention measures (Pitelis et al., 2020; Aflaki et al., 2021). Where technologies have reached a high level of maturity and become available in markets, coordinated efforts to improve cost-performance ratios, coalition building, and market shaping can create self-reinforcing positive feedback effects to accelerate technology diffusion (Roberts et al., 2018; Victor et al., 2019; Kulmer et al., 2022; Andersen et al., 2023; Geels and Ayoub, 2023). Cost-performance improvements can be achieved through economies of scale, learning-by-doing, and increased availability of complementary technologies (Victor et al., 2019). Shared visions and targets, public procurement, empowerment of actor coalitions, visibility of frontrunners, and economic incentives for adoption can increase support for climate-friendly technologies (Roberts et al., 2018; Termeer and Dewulf, 2019). End-use technologies lie at the core of improve and also shift activities (Cross-Chapter Box 4).

## 4.3. The case of tourism and climate change

### 4.3.1. Overview of the Austrian tourism sector

The Austrian tourism sector is of considerable importance to the Austrian economy. Prior to the COVID-19 pandemic, Austria recorded more than 46.2 million guests with around 152.7 million overnight stays in 2019 (Statistik Austria, 2022). In 2019, the direct value-added effects of tourism amounted to $EUR_{2023}$ 26.45 billion according to the Tourism Satellite Account (TSA), which corresponds to a share of 5.5 % of the gross domestic product in 2019 and $EUR_{2023}$ 36.2 billion (7.5 % of GDP in 2019) if the indirect value-added effects of tourism are also included; direct tourism employment in 2019 accounted for 6.2 % of total nationwide employment (Fritz et al., 2021).

As peripheral Alpine regions in particular are economically dependent on the tourism sector, a failure to successfully implement adaptation and mitigation strategies to climate change in the immediate future will pose significant economic risks (Pröbstl-Haider et al., 2020).

### 4.3.2. The contribution of tourism to GHG emissions

Tourism is a significant contributor to global warming. According to Lenzen et al. (2018), global tourism emitted approximately 4.5 $GtCO_2eq$ in 2013, accounting for about 8 % of total GHG emissions. This includes direct emissions from visitor consumption (2.9 $GtCO_2eq$) and indirect emissions from the upstream supply chain (1–2 $GtCO_2eq$). Notably, about half of the emissions are attributed to transport, with a higher share originating from high-income countries due to increased air travel consumption. Gössling et al. (2023, p. 2) note that "adding aviation's non-$CO_2$ contribution to climate change … increases tourism's contribution to global warming to 10 % in 2013".

For Austria, estimates of tourism-induced emissions are provided by three sources: Lenzen et al. (2018), Neger et al. (2021), and Prettenthaler et al. (2021).

- **Lenzen et al. (2018)**: The authors provide (so far unpublished) estimates indicating that GHG emissions from the Austrian tourism sector amounted to 12.85 $MtCO_2eq$ in 2013. The accounting relies on Tourism Satellite Account data and is destination-based (DBA), i.e., it includes emissions from domestic tourism, inbound tourism, and local services for outbound travel (e.g., travel from home to the airport). For international air transport, only emissions from national carriers for inbound, outbound, and stop-over services are included, as well as emissions from other transport providers registered in Austria.

  Additionally, Lenzen et al. (2018) apply a residence-based accounting (RBA) approach that considers all direct and indirect travel-related emissions (transport, accommodation, food, etc.) generated by Austrian residents. These emissions are estimated at 15.63 $MtCO_2eq$, indicating that Austria is a 'net origin' country: Emissions caused by Austrian residents traveling abroad exceed those induced by international travelers visiting Austria by 2.78 $MtCO_2eq$ (21.7 %).
- **Neger et al. (2021)**: This study uses a destination-based accounting (DBA) approach. They estimate that the Austrian tourism sector directly emitted 4.3 $MtCO_2eq$ in 2016, which corresponds to 4.15 % of total Austrian $CO_2eq$ emissions. Notably, this estimate does not include indirect emissions from tourism activities (scope 2 and 3 emissions). Thus, the reported direct emissions are significantly lower than the estimates of Lenzen et al. (2018).

  For the year 2018, the authors also calculate transport-related emissions from foreign visitors to Austria which amount to 35 $MtCO_2eq$ (and thus more than eight times the DBA emissions, corresponding to a share in total $CO_2eq$ emissions of 34.1 %). Almost 95 % of these emissions are generated by visitors arriving in Austria by air from outside Europe. Together with the DBA estimates of 4.3 $MtCO_2eq$ for 2016, this implies that about 99 % of all emissions directly caused by visitors to Austrian destinations are related to transport. However, such a high share of transport-related emissions may depend on the estimation method used (e.g., if international air carriers are included), but also on the share of international visitors arriving mainly by car or air. Other studies have found much lower shares: For Norway, Sun et al. (2022) estimate that 56 % of total carbon emissions are transport-related, the same share was reported by Kitamura et al. (2020) for Japan.
- **Prettenthaler et al. (2021)**: This study reports direct transport-related emissions from residents traveling to destinations within and outside Austria (RBA) at 11.5 Mt $CO_2eq$ for 2016, with 95 % of these emissions concerning travel abroad. However, as this estimate does not include emissions from accommodation and food, it is not directly comparable with the estimates from other studies.

As the estimates by Lenzen et al. (2018) and by Neger et al. (2021) differ not only in scope (direct and indirect emissions for the former, only direct emissions for the latter), but also in magnitude, a high degree of uncertainty regarding tourism-induced emissions for Austria is evident. The challenges of estimating tourism emissions' footprint are also highlighted by Gössling et al. (2023). An emissions inventory for Austrian tourism is needed, which must shed light on tourism-induced emissions from different perspectives (DBA, RBA, producer-based accounting) and the emission sources.

### 4.3.3. Future systems: Impact of climate change on tourism

Austria's tourism industry is particularly vulnerable to climate change due to its dependence on the natural environment, which is one of the most important factors motivating international tourists to visit the country (Nature Reloaded, 2015). Rising temperatures, shifting weather patterns, and extreme weather events are reshaping tourism offerings and demand. This will consequently change tourism employment, both in terms of regionality and seasonal shifts, which may require different skill sets, training and education (Scott et al., 2019). Shifts in tourism employment will depend on changes in tourism product offerings. A detailed analysis of the impacts of climate change on the Austrian tourism industry is provided in the *Austrian Special Report 2019* 'Tourismus und Klimawandel' (Pröbstl-Haider et al., 2020), which discusses the demand- and supply-side effects of climate change.

Higher temperatures could make summer vacations in the Austrian alpine regions more attractive for both domestic and international visitors seeking cooler destinations, thus shifting their choice of destinations away from southern European destinations suffering from intense heat waves, rising sea temperatures, wildfires and water scarcity. In addition, more moderate temperatures in the shoulder months of the summer season will extend the season. On the other hand, winter tourism in the Alps is expected to lose demand due to higher average temperatures and less precipitation in the form of snow (Steiger et al., 2021). Consequently, the main adaptation strategy will be to at least partially compensate for the loss of income from alpine snow-related winter tourism by increasing tourism revenue from spring to fall (Pröbstl-Haider et al., 2020).

Austrian cities and rural, non-alpine tourism regions are also experiencing various impacts of climate change, particularly rising temperatures, but also extreme weather events. These changes affect the environment, local economies, and overall quality of life for residents and visitors alike.

- More frequent and intense heat waves in cities can exacerbate the urban heat island effect, making them significantly warmer than surrounding rural areas (Loibl et al., 2014). This can lead to increased energy demand for cooling, higher health risks for vulnerable populations, and a greater strain on infrastructure. Additionally, higher temperatures can worsen air quality by increasing the formation of ground-level ozone, which poses health risks, particularly for individuals with pre-existing health conditions (European Climate and Health Observatory, 2021; Mayer et al., 2022; Umweltbundesamt, 2024a).
- Rising temperatures may initially appear to benefit rural tourism, but extreme heat may deter visitors. Rising air temperatures lead to higher water temperatures in lakes, which can negatively affect aquatic ecosystems (Dokulil et al., 2021). Warmer temperatures can disrupt local ecosystems, leading to changes in species composition and loss of biodiversity. Further, changes in water quality and levels can affect recreational activities such as swimming, boating, and fishing; thereby reducing the attractiveness of tourist destinations. Rising temperatures can lead to more intense and frequent precipitation events, increasing the risk of flooding that damages infrastructure, homes and businesses, and deters tourists.

In winter, the Austrian ski industry is expected to be negatively affected by rising temperatures (see Section 1.3 on snow coverage). Studies on the impacts of climate change on ski tourism show a significant shortening of the ski season, less precipitation, lower snow depth, increased need and difficulty for artificial snowmaking, and a decrease in glaciers in Austria (Olefs et al., 2017; Helfricht et al., 2019; Steiger et al., 2020; Steiger and Scott, 2020; Abegg and Mayer, 2023; François et al., 2023a; Salim et al., 2023; Mayer and Abegg, 2024) (see Section 7.4 for details on climate change impacts on ski destinations). Visitors may also be deterred by the lack of snow-covered landscapes. In this respect, guest numbers in ski resorts fluctuate more than the number of overnight stays (Steiger, 2010; Falk, 2013), presumably because day visitors can react more spontaneously to weather and snowfall than vacation guests (Steiger, 2011). Many Austrian ski resorts, especially those at lower altitudes, will therefore have to find alternative solutions for increasingly difficult winter operations, as it may no longer be technically possible, economically viable, or preferable/acceptable to guests and local communities to provide sufficient snow cover in some places (see Section 7.4). However, there are also challenges in high-altitude ski resorts, particularly related to the retreat of permafrost and glaciers (Mayer and Abegg, 2024).

Furthermore, the climate crisis could significantly reduce the importance of the tourism industry in the context of a general loss of prosperity (Scott and Gössling, 2022).

### 4.3.4. Needed transitions in the Austrian tourism sector

#### Avoid

A reduction in the **number of trips** would decrease overall GHG emissions. In the case of business trips, digitization facilitates such a reduction, as meetings are increasingly organized online (Kagermann, 2015). The COVID-19 pandemic provided incentives for firms to invest in equipment for online videoconferencing, thereby saving on travel costs. Furthermore, an increasing number of conferences are organized online or in a hybrid mode (Lenzen et al., 2018; Hanaei et al., 2022). A reduction in the number of holiday trips, accompanied by an increase in vacation duration to compensate for the loss of recreational value, could help to curb tourism-induced emissions (Pröbstl-Haider et al., 2020; Gössling and Higham, 2021).

Furthermore, as the largest share of emissions originates from mobility (Dubois et al., 2011; Pröbstl-Haider et al., 2020), visitors from **long-distance markets** traveling by air could be discouraged to spend their holidays in Austria, e.g., by refraining from marketing activities in these countries. However, global net emissions benefits are only achieved if long distance trips to (Austrian) destinations are not substituted by long distance trips to other destinations outside Austria.

#### Shift

In line with the above, climate change mitigation efforts may take the form of a shift in the target groups of the Austrian tourism industry, for example by focusing on guests that have more opportunities to travel by sustainable means of transport. This is essential, as air traveling produces 31 times more $CO_2$ emissions than train travel, and traveling with a combustion engine car produces about 15 times more $CO_2$/km compared to the train alternative (VCÖ, 2022). Touristic service providers and tourism operators may encourage the proposed shifts by guiding guest behavior, for example by introducing price or convenience incentives (Gössling and Higham, 2021; Bursa et al., 2022; Blättler et al., 2024). Such substitution could also be incentivized by internalizing the environmental costs of carbon emissions.

Public transportation networks, active mobility options (including bike and e-bike rental systems) or car sharing systems can be an attractive and more sustainable option for mobility within destinations (Pisoni et al., 2022; Edberg, 2024) (see Chapter 3 on spatial planning and mobility). However, this can only be achieved through infrastructure investments.

A shift in the mode of transport is also key to reducing emissions from outgoing tourism: Reducing the number of long-haul trips by plane and increasing domestic travel by train, for example, already drastically reduces GHG emissions (Umweltbundesamt, 2018; VCÖ, 2022, vacation in Austria by train: 15 kg $CO_2$/capita/d vs long-haul trip by plane: 454 kg $CO_2$/capita/d).

#### Improve

In addition to avoiding emission-intensive tourism and shifting to a less carbon-intensive mode of the tourism production function, the current supply of tourism services, including transport to and from the destination, needs to be improved to reduce emissions (Gössling and Higham, 2021; Gössling et al., 2023). If individual travel cannot be fully shifted to public transport (both because of the mobility preferences of the travelers and insufficient rail transport capacities), the use of electric cars should be promoted by investing in charging infrastructure. If, at the same time, electricity generation is shifted to renewable energy, $CO_2$ emissions will be reduced (Holmberg and Erdemir, 2019). Numerous other transition measures have been listed and discussed for the different segments of the tourism industry (accommodation, restaurants, transport, summer and winter outdoor activities, events etc.).

Suggested improvements focus on energy efficiency (related to tourism buildings and infrastructure), waste reduction and recycling concepts, water management, intensification of natural planting to limit ground erosion, and greening of buildings to create natural shade and cooling systems (see, e.g., Pröbstl-Haider et al., 2020; Gössling and Higham, 2021). In the accommodation sector, building insulation can be improved and measures can be taken to increase energy efficiency in terms of room temperature, hot water use, and lighting (Energieinstitut der Wirtschaft GmbH, 2012). This is particularly important in city destinations, as energy demand for cooling buildings will increase as climate change continues (Prettenthaler et al., 2008; Dowling, 2013; Berger et al., 2014a, 2014b). In addition, measures such as increasing green spaces, creating green roofs, and improving urban planning can be proposed to reduce the urban heat island effect (Aram et al., 2019).

In recent years, the Austrian tourism industry has already made a considerable shift away from non-renewable energy sources (Umweltbundesamt, 2023b): Between 2008 and 2019, the share of renewable energy in the accommodation and restaurants sector has increased from 36 to 54 %, which is above both the Austrian average of 34 % and the Austrian government's target of 50 % for 2030 (Pröbstl-Haider et al., 2020). This ongoing shift to renewable energy is necessary at the expense of non-renewable sources (see Federal Statistics Office, 2023, for where this is not the case). In Austria, several federal government programs offer financial support for companies to encourage this shift.

In winter tourism destinations, technological innovations are needed to find new ways to intensify snowmaking due to lower precipitation and higher winter temperatures, while improving the efficiency of water storage and other processes to reduce the growing demand for energy. The economic benefits should be carefully weighed against potential ecological impacts and problems associated with snowmaking, such as energy consumption, resource scarcity, and biological degradation (Aigner et al., 2024) (also see Section 2.2 on ecosystem services).

However, the potential for adaptation is limited. Due to regional climate conditions, businesses and skiing resorts, especially at lower altitudes (Marty, 2013), have already closed due to economic unviability (Falk, 2013). As climate change progresses, regional 'tipping points' will be crossed, making alpine skiing impossible in certain (mostly lower-lying) alpine regions (Ginkel et al., 2020). The exact point at which skiing becomes impossible depends on several factors, including the intensity and pace of warming, the availability of technological adaptations, local geography, and snowmaking capacity (Damm et al., 2014; François et al., 2023a).

## 4.4. Industry and manufacturing

### 4.4.1. Status quo

The industry and manufacturing sector[1] covers a wide range of production processes needed for the transformation of materials and energy into intermediate and finished goods. Manufacturing firms in Austria tend to use state-of-the-art technology, but energy intensity is relatively high compared to other Western European countries due to the high share of energy-intensive metal and paper industries (Diendorfer et al., 2021). Between 2014–2020, the sector contributed 18 % to Austria's value added, growing by 2 %/yr. Due to its high emission intensity, the sector's share of Austrian emissions was significantly higher over the same period, but stable (fluctuating between 32–35 %), with absolute emissions of 26 $MtCO_2eq$ in 2020 (Statistik Austria, 2023a, 2023c). Despite increasing output, absolute emissions in industry have remained relatively stable since 2005, mainly because of energy efficiency improvements (Umweltbundesamt, 2023a), indicating a relative decoupling from economic growth.

Emissions are highly concentrated in a small number of sectors and firms. In 2020, more than 80 % of the sector's emissions (or 29 % of total national emissions) came from four groups of products (see Figure 4.6): Basic metals (12 $MtCO_2eq$, 16 % of national emissions), other non-metallic mineral products (5 $MtCO_2eq$, 7 %), chemicals and chemical products (2.2 $MtCO_2eq$, 3 %), and paper and paper products (1.9 $MtCO_2eq$, 2 %) (Statistik Austria, 2023f, 2023e, 2023c).

### 4.4.2. Current and future systems

The following sections present sectoral perspectives and economy-wide effects in the Austrian context. More details on mitigation options and emission reduction potentials per sector are given in Table 4.A.1. Global trends for each sector can be found in the appendix as well.

#### Steel

In Austria, the metal sector is relatively large, with steel being the most important product. In 2020, the sector 'manufacture of basic metals' generated 1.1 % of the economy's value added ($EUR_{2023}$ 4.45 billion) and employed more than 37,000 people (Statistik Austria, 2023a, 2023b). Emissions come mainly from the use of coal/coke as a reducing agent and from the high temperatures required for steel production (see Figure 4.6 for details). Steel output has been stable since 2018, between 7–8 Mt/yr (WSA, 2023a), of which 90 % is produced via the blast furnace-basic oxygen furnace (BF-BOF) route (WSA, 2023b). The specific energy demand of crude steel in Austria is 4.9 MWh/t, its emission factor is 1.7 $tCO_2eq/t$ which is below the global and EU averages

[1] In this section the industry and manufacturing sector is defined as NACE sectors 10–32, if not stated differently.

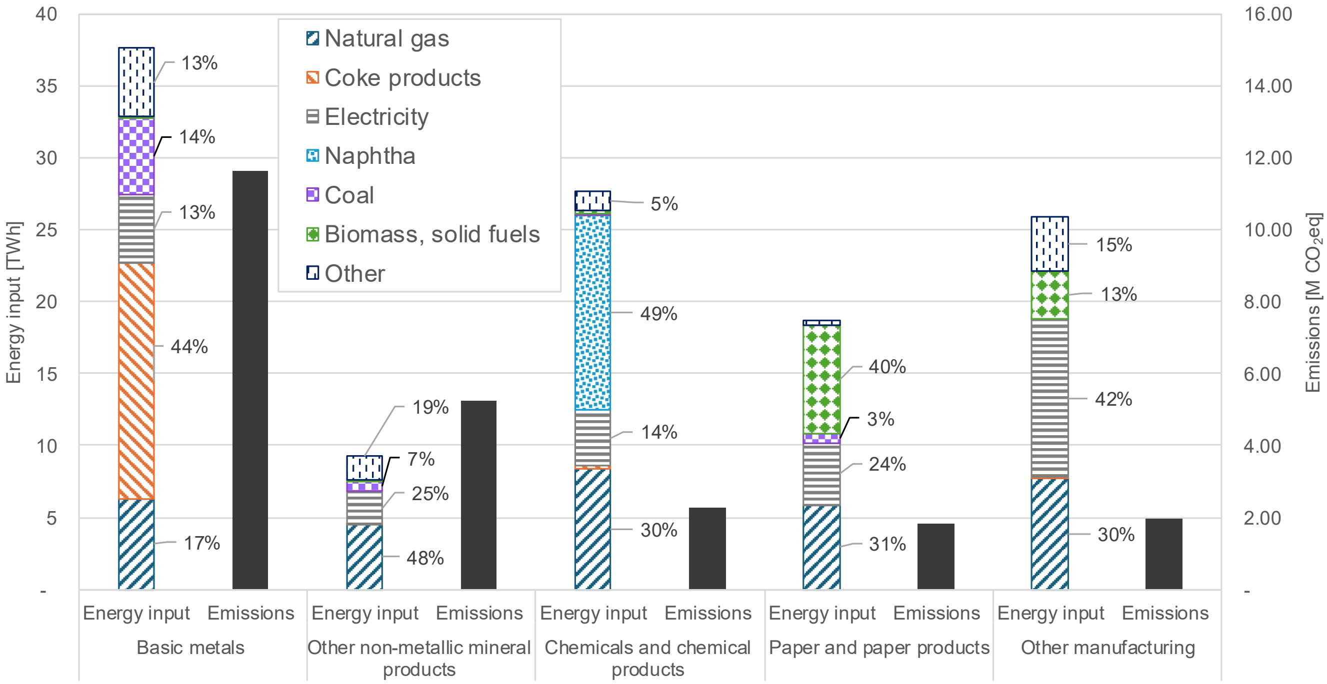



Figure 4.6 Production-based direct GHG emissions and energy inputs by energy product (covering also feedstocks) and sector. The sector 'manufacture of coke and refined petroleum products' was excluded from 'other manufacturing'. Sources: Physical Energy Flow Accounts (Statistik Austria, 2023f) and Air Emissions Accounts (Statistik Austria, 2023c).

(5.5 and 1.9 respectively) (Alton et al., 2022; Rahnama Mobarakeh and Kienberger, 2022). 88 % of emissions are process-related and 12 % are combustion-based (Rahnama Mobarakeh and Kienberger, 2022).

Emissions can be reduced by increasing circularity, especially by increasing the proportion of secondary steel (avoid). It is estimated that scrap-based steel production emits only one-eighth of the carbon compared to the conventional BF-BOF route (Wang et al., 2021). In the long term, the Austrian steel sector plans to switch to a hydrogen-based direct reduced iron-electric arc furnace (DRI-EAF) route (using natural gas as a bridging fuel until hydrogen becomes economical; shift). At constant output, this would require an additional 30–33 TWh of electricity (50 % of today's demand in Austria) (Mayer et al., 2019b; Alton et al., 2022). Efficiency improvements (improve) can further reduce emissions, but emissions are already close to the best available technology (BAT) of 1.6 $tCO_2eq/t$ (Material Economics, 2019).

Mayer et al. (2019b) derive Austria-specific unit costs of $EUR_{2023}$ 551/t of steel for a low-cost specification (Plasma Direct Reduction) and $EUR_{2023}$ 760/t for a high-cost specification ($H_2$ based DRI), compared to the current BF-BOF route at $EUR_{2023}$ 500/t. However, these figures are highly sensitive to electricity price assumptions. Other estimates range between $EUR_{2023}$ 460–1,020/t, covering (in order of increasing cost): Recycling via EAF, gas-based DRI-EAF, gas-based DRI-EAF with carbon capture and storage (CCS), hydrogen-based DRI-EAF, smelting reduction with CCS as well as material efficiency and circularity (Material Economics, 2019; IEA, 2020).

Austria-specific 'greenfield' investment requirements for carbon-neutral steel production technologies are about $EUR_{2023}$ 1,340/t of annual capacity (corresponding to capital expenditures (CAPEX) of about $EUR_{2023}$ 120/t) (Mayer et al., 2019b). In the international literature, the range is $EUR_{2023}$ 670–1,050/t (Chiappinelli et al., 2021). Investment requirements are estimated to be 60–65 % higher for the implementation of new processes or CCS, but only 25 % higher (or even below baseline levels in the long term) for a circular economy pathway (Material Economics, 2019).

## Cement

In Austria, the sector 'manufacture of other non-metallic mineral products' directly generated 0.8 % of the value added in 2020 ($EUR_{2023}$ 3.1 billion), employing 30,500 people (Statistik Austria, 2023a, 2023b). Emissions come mainly from geogenic process-emissions and the combustion of gas and waste for high-temperature heat in cement production (Rahnama Mobarakeh and Kienberger, 2022) (see Figure

4.6). In 2020, Austria produced 5.2 Mt of cement and is equipped with highly efficient dry kiln factories, producing at 0.84 MWh/t of cement, generating 0.5 $tCO_2$/t cement (Rahnama Mobarakeh and Kienberger, 2022).

In the Austrian context, short/medium term solutions are improve-measures such as circular economy (including recycling) and material efficiency increases, further increases in energy efficiency, the use of waste fuel with higher heating value content as well as biomass. Specifically, the share of biomass in alternative waste fuels (AWFs) could be increased (depending on availability; see Section 2.3.2) until AWFs are replaced by biomethane or hydrogen (fuels with higher calorific values) by mid-century. However, this would only reduce heat-related emissions. Since a large share (60 %) of $CO_2$ emissions are process-related (coming from the chemical reaction to decompose limestone ($CaCO_3$) into lime (CaO) and $CO_2$), CCS/CCU (improve) is currently seen as an option to reach carbon neutrality in the long term (Plaza et al., 2020; Bashmakov et al., 2022; Rahnama Mobarakeh and Kienberger, 2022) (see also Section 4.6). Specifically, 'cement electrolysis' with CCUS is currently being researched (mostly in the US), indicating both technical and economic viability (Mowbray et al., 2023). Energy demand for the non-metallic minerals sector in Austria is expected to increase by 25–90 % (2–9 TWh), mainly due to higher electricity demand for CCS. Natural gas and coal are expected to be replaced by hydrogen (Alton et al., 2022).

Production costs of carbon-neutral cement are estimated to be 70–115 % higher than the reference technology when using CCS (Material Economics, 2019). The cheapest alternative technology is oxyfuel CCS with cost estimates between $EUR_{2023}$ 100–110/t clinker. Other technologies range between $EUR_{2023}$ 130–150/t clinker. In general, higher CAPEX, higher fixed operating costs, and the higher electricity and steam requirements drive the cost increase (Gardarsdottir et al., 2019). Investment requirements are estimated to increase by 22–49 %, with a circular economy pathway demanding the lowest additional investment (Material Economics, 2019).

## Chemicals

In Austria, the sector 'manufacture of chemicals and chemical products' contributed with 0.9 % ($EUR_{2023}$ 3.85 billion) to total value added, employing 18,600 people in 2020 (Statistik Austria, 2023a, 2023b). Energy demand and emissions are mainly driven by low and high temperature heat provision via natural gas (for details, see Figure 4.6).

Specifically for Austria, the methanol-to-olefin (MTO) process appears to be a promising option (Alton et al., 2022), which could replace naphtha (i.e., a fossil resource) as feedstock (improve). However, this requires methanol, which could be produced from biomass (depending on availability; see Section 2.3.2 on a sufficiency oriented bioeconomy) or hydrogen and captured $CO_2$ from other sectors (e.g., cement). Such production of the feedstock would increase energy intensity, but (within the system boundaries of the chemicals industry) the process could become a carbon sink, by absorbing captured carbon from other sectors. Ammonia could be completely synthesized from hydrogen. Following the decarbonization pathways described in (Alton et al., 2022), the total energy demand of the Austrian chemicals sector (28 TWh in 2020) is projected to increase strongly, reaching between 53–63 TWh in 2050, of which 8–9 TWh will be electricity, the rest hydrogen and biofuels as feedstock. This is due to the higher energy intensity of the processes compared to the status quo (particularly the MTO process). Taking into account the electricity required for hydrogen production, electricity demand would increase by 42 TWh.

Switching to low-carbon production routes in the chemicals sector is estimated to increase costs as the feedstock has to be synthesized. For plastics, cost increases are estimated at 20–43 % (Material Economics, 2019). For ammonia and methanol, cost increases are expected to range from 25–90 % depending on the technology and feedstock, with electrification options being the most expensive and CCU-based options less so (IEA, 2020). Investment requirements in the plastics industry are estimated to increase by 122–199 % (Material Economics, 2019).

## Pulp and paper

In Austria, the sector 'manufacture of paper and paper products' accounted for 0.7 % ($EUR_{2023}$ 2.76 billion) of national value added in 2020 and employed 17,000 people (Statistik Austria, 2023a, 2023b). Direct emissions mainly come from natural gas combustion for low-temperature heat for drying processes (Figure 4.6 gives details). In 2020, 1.6 Mt of pulp and 5.6 Mt of paper and board were produced in Austria (CEPI, 2023).

Short to medium term mitigation options in Austria are efficiency improvements and fuel switching (to electricity) (improve). The emission intensity can still be decreased, which is currently 0.38 $tCO_2$/t paper (compared to the EU average of 0.33). In addition, heat management (recovery of waste heat) can be further improved and alternative drying technologies used. Natural gas in boilers could be replaced by biofuels (depending on availability, see Section 2.3.2 on a sufficiency oriented bioeconomy), or non-electric boilers could be replaced by electric boilers (improve). In the long term, further electrification and installation of heat pumps and an increase in the share of biofuels in combined heat and power (CHP) can replace natural gas (the only source of direct emissions). The low process emissions from lime kiln (3 %) could be phased out through CCS/CCU (Rahnama Mobarakeh and Kienberger, 2022) (improve). In terms of energy demand, electricity demand could increase significantly from 2 to 7 TWh if heat pumps are used on a large scale, replacing 6 TWh of natural gas (Alton et al., 2022).

Cost estimates for decarbonizing the pulp and paper industry are scarce. Abatement costs from full biomass firing are estimated to be around $EUR_{2023}$ 54/t$CO_2$eq (Bashmakov et al., 2022). Economy-wide estimates of investment requirements for decarbonizing low-temperature heat range from $EUR_{2023}$ 320–570 million (with the cheapest option being heat pumps) and the conversion of CHP plants is estimated to require $EUR_{2023}$ 140–230 million (Diendorfer et al., 2021).

### Chapter Box 4.1. Integrated scenarios for industry decarbonization in Austria

The study by Alton et al. (2022) presents two mitigation pathways for the industry and manufacturing sector in Austria up to 2050, with the goal of achieving full decarbonization. The results for the four energy-intensive sectors steel, cement, chemicals, and pulp and paper are summarized in Table 4.1. The first scenario, called 'Pathway of Industry' (POI), was developed based on an intensive stakeholder dialogue and represents their expected developments until 2030, with extrapolations until 2050. The second scenario, called 'Zero Emission' (ZEM), is based on a back-casting approach and reaches carbon neutrality by 2050, assuming breakthrough technologies. In the **steel** sector, both scenarios assume a shift to direct reduction (at constant steel output), using mainly (natural-, bio- and synthetic) gas in the POI scenario and mainly hydrogen in the ZEM scenario. In the **chemicals** sector, a shift from fossil resources to hydrogen, biofuels, biomass, and electricity is assumed. Due to the assumed methanol-to-olefins process, the production of methanol increases strongly, which also implies a higher energy demand for synthesizing feedstocks. The **cement** industry (included in non-metallic minerals) is assumed to deploy CCS technologies (amine scrubbing in POI and oxyfuel in ZEM), which increases electricity demand. In the **pulp and paper** sector, emissions are reduced by increasing the share of biofuels and using hydrogen in POI, whereas in ZEM electrification through heat pumps leads to zero emissions and lower energy demand. Overall, emissions from industry and manufacturing are reduced by 98 % (to 0.6 Mt in POI) and 106 % (to -1.6 Mt in ZEM). Compared to 2020, energy demand increases by 47 % in POI and 50 % in ZEM, with the largest increases in the chemicals sector (+227 % in POI and +294 % in ZEM).

**Table 4.1** Current (2020) and future (2050) energy demand, emissions for the four sectors steel, chemicals, non-metallic minerals, and pulp and paper, as well as for rest of manufacturing in Austria for two scenarios (POI and ZEM) (Source: Alton et al., 2022; Nagovnak et al., 2024). Note that numbers do not match Figure 4.7 due to differences in system boundaries.

| | **2020** | | | | | | **2050 POI** | | | | | | | **2050 ZEM** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Energy demand [TWh] | | | | | [Mt $CO_2$eq] | Energy demand [TWh] | | | | | [Mt $CO_2$eq] | | Energy demand [TWh] | | | | | [Mt $CO_2$eq] | |
| | Electricity | Hydrogen | Hydrogen transformation losses | Other fuels and feedstocks | **Total** | **Emissions** | Electricity | Hydrogen | Hydrogen transformation losses | Other fuels and feedstocks | **Total** | Excl. hydrogen | **Incl. hydrogen** | Electricity | Hydrogen | Hydrogen transformation losses | Other fuels and feedstocks | **Total** | Excl. hydrogen | **Incl. hydrogen** |
| Steel | 2.6 | - | - | 34.2 | **36.8** | **12.8** | 4.8 | 7.1 | 3.0 | 15.6 | **30.5** | 0.7 | **0.8** | 4.8 | 19.6 | 8.4 | 4.3 | **37.1** | 0.8 | **1.2** |
| Chemicals | 4.4 | - | - | 11.5 | **15.9** | **3.9** | 9.3 | 19.2 | 8.2 | 15.3 | **51.9** | -2.4 | **-2.0** | 8.3 | 23.2 | 10.0 | 21.1 | **62.6** | -4.8 | **-4.3** |
| Non-metallic minerals | 1.9 | - | - | 7.8 | **9.7** | **5.2** | 7.2 | 2.3 | 1.0 | 6.0 | **16.5** | 1.0 | **1.0** | 4.9 | 1.3 | 0.6 | 5.3 | **12.1** | 0.8 | **0.9** |
| Pulp and paper | 2.3 | - | - | 19.5 | **21.7** | **2.2** | 2.3 | 4.1 | 1.8 | 16.0 | **24.3** | 0.0 | **0.1** | 7.1 | 0.0 | 0.0 | 12.2 | **19.3** | 0.1 | **0.1** |
| Rest of manufacturing | 12.7 | - | - | 17.4 | **30.1** | **5.4** | 24.9 | 6.4 | 2.7 | 10.2 | **44.3** | 0.6 | **0.7** | 23.4 | 3.4 | 1.4 | 12.2 | **40.4** | 0.4 | **0.5** |
| **All manufacturing industries** | 23.8 | 0.0 | 0.0 | 90.4 | **114.2** | **29.5** | 48.6 | 39.1 | 16.7 | 63.1 | **167.5** | -0.2 | **0.6** | 48.5 | 47.5 | 20.4 | 55.2 | **171.5** | -2.6 | **-1.6** |
| 2050 POI/2020 | +104 % | | | -30 % | +47 % | -98 % | | | | | | | | | | | | | | |
| 2050 ZEM/2020 | +104 % | | | -39 % | +50 % | -106 % | | | | | | | | | | | | | | |

### Other manufacturing sectors

The GHG emissions from the remaining manufacturing subsectors (2 $MtCO_2eq$) account for 8 % of emissions from industry and manufacturing (Diendorfer et al., 2021) (see Figure 4.6). The emissions can be attributed to a large and heterogeneous number of manufacturing firms, mostly operating in the construction industry, followed by mechanical engineering, food and beverages, and woodworking industries. The same sectors are also the main emitters of GHG emissions, although other relevant processes include mining, the processing of non-ferrous metals, vehicle construction, and textiles. Due to the lower energy intensity of these sectors, only nine manufacturing plants are covered by the EU-ETS.

Although relatively less energy intensive overall, a significant share of the energy demand in the 'other manufacturing' sector is due to energy-intensive processes, requiring targeted mitigation measures. In the construction sector, by far the largest technical decarbonization potential rests in the electrification of engines or the switch to carbon-neutral gas for the operation of machinery and off-road vehicles (improve). In other sectors, significant reductions in GHG emissions could be achieved by installing heat pumps (shift) to meet the energy demand for process heat (<200°C), which is particularly high in the food and mining industries, and for room heating, for which natural gas remains a common energy source in machine engineering and the woodworking industries (Diendorfer et al., 2021).

### Economy-wide effects

Production costs and prices of carbon-neutral materials and goods are expected to be higher, yet the direct impact on consumers is estimated to be small. Price increases for typical final demand goods (such as plastic bottles, cars or houses) are estimated at 1–5 %, despite large price increases for materials (cement: 35–115 %, steel: 10–50 %, and primary chemicals: 15–115 %) (Bataille et al., 2018; Material Economics, 2019; Bashmakov et al., 2022). The effects on consumption possibilities (welfare) could be stronger if changes in income or employment are included. Bachner et al. (2020a), analyzing the transition of the European steel sector, show income (GDP) effects for Austria between +0.5 % and -1.5 %, depending on the assumption of production factor availability (idle or not). In particular, capital owners could benefit from distributional effects due to higher capital intensities (Bachner et al., 2020b). Regarding the timing of decarbonization, early action may be less costly in terms of foregone GDP per avoided ton of $CO_2$ (Bachner et al., 2020b; Steininger et al., 2021). For labor-market implications, see Section 4.7.

## 4.4.3. Climate related risks and adaptation of industry and manufacturing

Industry and manufacturing are affected by physical risks related to climate (change). Energy-intensive firms are often located along rivers for access to water and waterways, making them vulnerable to water scarcity and fluvial flood risk (Bashmakov et al., 2022). For Austria, Bachner et al. (2023) estimate the current direct flood risk via sectoral capital stock damages for the whole economy, represented by 72 sectors. Out of a total of 18 manufacturing sectors, 12 are among the top 30 sectoral losers, with the highest direct risks in the 'fabricated metal products', 'chemicals and chemical products', 'basic metals' and 'food products'. As the flood risk in Austria is expected to increase (see Cross-Chapter Box 1), a sectoral analysis of the future flood risk in Austria is necessary. Heat-induced labor productivity losses are also an important risk, both globally (Dasgupta et al., 2021) and for Austria (Urban and Steininger, 2015). Next to direct risks, indirect risks via supply chains are also a concern for industry (Bednar-Friedl et al., 2022b). Extreme weather events abroad (e.g., floods), but also gradual climate change (e.g., rising temperatures and resulting losses in labor productivity) can trigger negative economic effects domestically (Knittel et al., 2020, 2024).

In terms of adaptation, European industry has been found to have a low level of adaptation, with SMEs often lacking sufficient knowledge (Bednar-Friedl et al., 2022a). Little is known about adaptation in Austria's industry sector. Key adaptation options for industry are knowledge creation, research and development (R&D), and risk management, with governments and international communities seen as key actors for adaptation (Bednar-Friedl et al., 2022b). Some industries could benefit from adaptation, as demand for materials such as concrete or steel could increase, for example for flood protection or sea walls (Bashmakov et al., 2022). Relocation could also change exposure to natural hazards.

## 4.4.4. Necessary transformation of industry and manufacturing

Direct and indirect electricity demand is expected to grow strongly (Lechtenböhmer et al., 2016; Geyer et al., 2021; Nagovnak et al., 2024). Direct demand is estimated to increase by 110–130 % at constant production levels (Geyer et al., 2021; Alton et al., 2022). Thus, in addition to avoid measures, material efficiency (i.e., reducing material demand), and energy efficiency improvements, the transition to a fully renewable electricity supply is key to a system-wide decarbonization (Material Economics, 2019; Rissman et al., 2020; Geyer et al., 2021; Edelenbosch et al., 2024). Under insufficient domestic supply (see Table 4.A.3 for the range of estimates), imports could be a complementary strategy. However, uncertainties regarding the stability of the electricity grid and the flexibility of the energy system have been identified as key concerns (Bachner et al., 2020b). Due to these uncertainties, industries could relocate to regions with high renewable energy availability at low prices (Samadi et al., 2023; Verpoort et al., 2024) and high potential for CCS (Bashmakov et al., 2022), thus requiring a societal debate on this 'renewables pull' effect (Verpoort et al., 2024).

Estimated investment requirements for decarbonizing steel, plastics, ammonia, and cement in the EU are 0.2 % of gross fixed capital formation, but for individual firms, investment in (often costlier) low-carbon technologies might be too risky due to high uncertainties (see Section 4.4.2 for sectoral investment requirements). A particular feature is the high share of 'process emissions' (emissions from non-combustion processes in production), which require fundamentally new tailor-made processes and equipment (Odelenbosch et al., 2022). These are mostly available at relatively high levels of technological readiness (Alton et al., 2022), but some key technologies and their integration into existing process chains require further R&D (Gailani et al., 2024). Crucially, investment incentives are often weak due to the characteristics of these industries, the risk of asset obsolescence, and uncertainties about future technological and commercial viability (Wesseling et al., 2017; Bataille et al., 2018; Material Economics, 2019; Zhang et al., 2022). However, there are opportunities for first-movers to gain competitive advantages if the appropriate market framework is established (Karkatsoulis et al., 2016; Bachner et al., 2020b; Zhang et al., 2022). To achieve a decarbonized industry, a mix of measures is needed, in particular investment support schemes, contracts-for-difference, market-based instruments ($CO_2$ pricing, border carbon adjustment) and a strengthening of circular economy principles (Edelenbosch et al., 2024) (see also Chapter 6).

In industrial SMEs, where the energy intensity of core production processes is low, support processes (e.g., lighting, ventilation, heating) can account for a significant share of energy demand and have been found to be the most promising intervention points for achieving reductions in energy use (Johansson et al., 2019). The main firm-level barriers in industrial SMEs relate to lack of information and the insufficient financial viability of investments and alternative procurement models such as energy contracting (Fresner et al., 2017; Johansson et al., 2019; Hrovatin et al., 2021). A cost-effective policy mix to reduce energy demand in industrial SMEs provides tailored support through a combination of subsidized energy audits and subsidies for investments in technologies (Johansson et al., 2019). For more energy-intensive medium-sized enterprises, supporting the implementation of energy management systems, facilitating learning networks, and regulatory policies can increase the adoption rate of energy efficiency measures (Thollander et al., 2015; Paramonova and Thollander, 2016; Jalo et al., 2021; Johansson et al., 2022).

## 4.5. Energy supply systems

### 4.5.1. Characteristics of the current energy system/status quo

Although fossil fuel use declined from 75 to 66 % of total primary energy consumption when comparing the period 2003–2007 to 2019–2023, the Austrian energy system is still largely based on fossil fuels (Statistik Austria, 2024a) (see Figure 4.7a). Coal use shows the strongest decline (-35 %), followed by fossil oil use (-18 %). Gas consumption decreases slightly over the whole period (-6 %). The decline in fossil fuel use is made possible by a stabilization of gross energy use (improve measures), and a switch from fossil fuels to biomass (53 % increase), ambient heat (216 % increase), wind and solar PV (707 % increase), and hydropower (10 % increase) (shift measures) (see Figure 4.7a). As a consequence of the high use of fossil fuels, about 58 % of primary energy was imported on average in the period 2019–2023 (see Figure 4.7b). This affects Austria's energy trade balance and comes with several other challenges related to, inter alia energy security, affordability, and flexibility (see Section 4.2). At the pace of the energy transition until 2021, it is impossible to achieve a carbon-neutral Austria by 2040 (Auel and Schmidt, 2023).

The sector 'production' slightly increased its final energy consumption (+4 %), 'households', 'services' and 'other' decreased final energy consumption by 1 %, and 'transport' slightly decreased by 2 % when comparing 2003–2007 with 2019–2023 (see Figure 4.7c and d).

In 2019–2023, natural gas was mainly used in 'production' (58 %), followed by 'households', 'services' and 'other' (39 %). Natural gas use in the 'transport' sector was low (at around 3 %). Compared to the period 2003–2007, 'industry' and 'production' increased their share by 8 % at the cost of 'households', 'services' and 'others'.

Fossil oil is mainly used in transport (82 %), and this share even increased from 72 % in the period 2003–2007. 'Households', 'services', and 'other' have reduced their use of fossil oil for heating (the share decreased from 21 to 14 %). Overall, fossil oil consumption in the 'transport' sector decreased slightly from 96 TWh (2003–2007) to 89 TWh (2019–2023), taking into account the very weak years in terms of transportation consumption due to COVID-19 restrictions (Hartwig et al., 2022; Staehle et al., 2022).

Coal is mainly used in the 'production' sector (97 %), mainly for steel production. Compared to the period 2003–2007, this share increased by 17 %, as 'households', 'services', and 'other' have significantly reduced their coal consumption, mainly due to the fading out of coal as a heating fuel (shift measure). Coal use in the 'transport' sector has virtually disappeared.

The use of renewables has increased in absolute terms in all sectors, but the share of the 'transport' sector in all renewables increased from about 5 % in the period 2003–2007 to 10 % in the period 2019–2023, and it decreased in the 'production' sector from 34 to 30 %, while the sector 'other' remained constant.

As a consequence of the slow pace of the energy transition, fossil fuel combustion is still by far the largest emitter

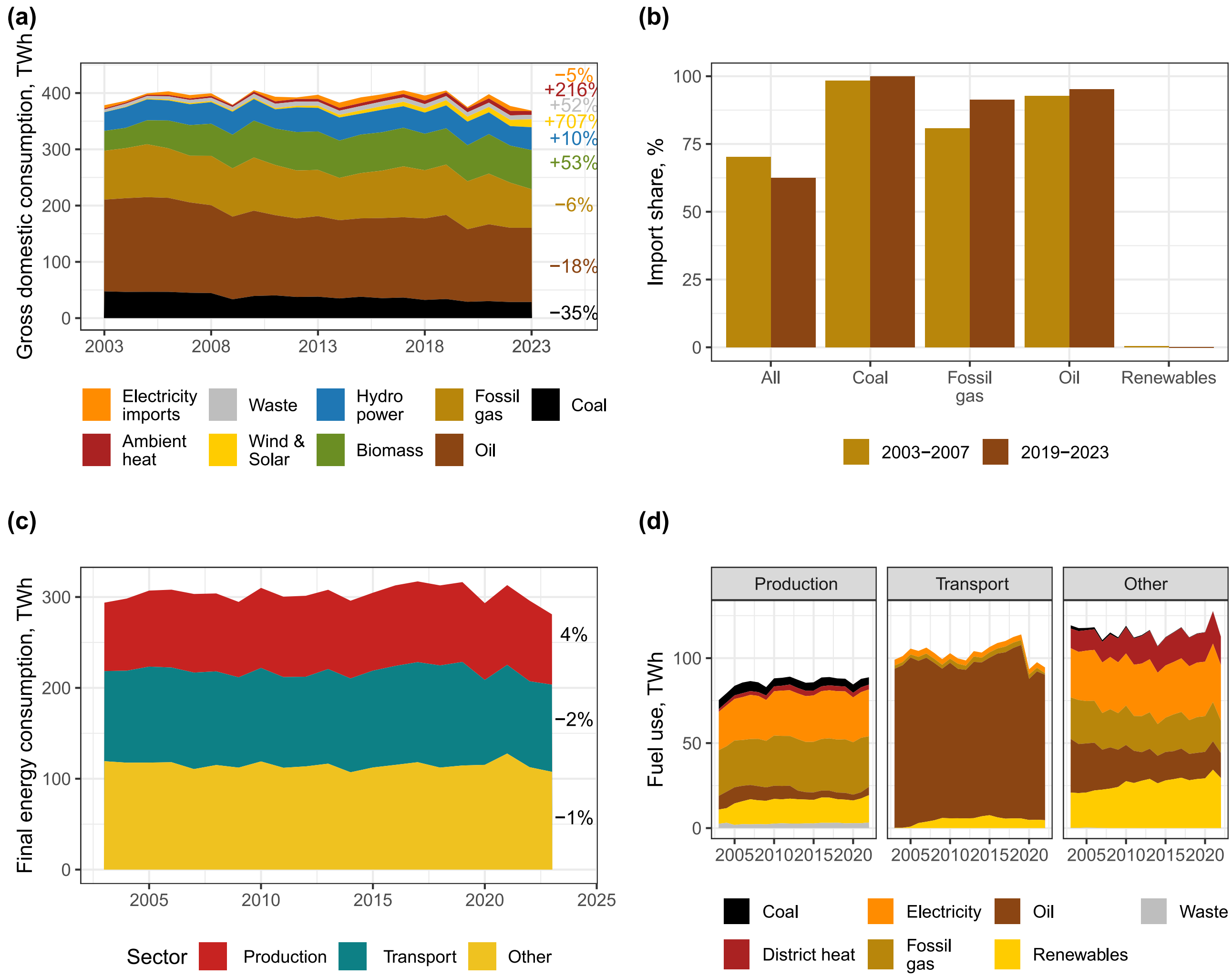



Figure 4.7 (a) Gross domestic energy consumption by fuel in Austria for 2003–2023 based on Austrian energy balance. (b) Import shares by fuel. (c) Structure of final energy demand by sector. (d) Final energy use by fuel and sector. The numbers on the right side of (a) and (c) show the growth rate in percent from the period 2003–2007 to 2019–2023, e.g., coal use has declined by 35 % in the period. The category 'other' includes households, services and agriculture. (Source: Energiebilanzen, Statistik Austria, 2024a).

of greenhouse gases in Austria (66 % in 2018–2022, compared to 71 % in 2003–2007) (Umweltbundesamt, 2025).

Austria's energy infrastructure is characterized by geographical and technological peculiarities. In the electricity sector, hydropower accounts for a large share of electricity generation in most of the federal provinces, with the exception of Burgenland and Vienna; wind power plants are located mainly in Burgenland and Lower Austria, and to a lesser extent in Styria. The Austrian electricity grid has a length of about 250,000 km. As far as the gas infrastructure is concerned, there are currently 47,000 km of gas network in Austria. In both cases, the vast majority is at the distribution network level. The Austrian gas storage facilities are located in Upper Austria and Salzburg (about 75 %) and in the east of Lower Austria (about 25 % of the total Austrian storage volume). Due to its location in Central Europe, Austria is an important energy transit country and the related infrastructure is also relevant for neighboring countries (BMK, 2024a).

### 4.5.2. Characteristics of the future energy system

A future carbon-neutral energy system can rely on a combination of domestic energy supply technologies and imported energy carriers, i.e., wind power, solar PV, biomass, geothermal energy, hydropower and imported hydrogen, other synthetic fuels and fossil fuels with carbon capture and storage (shift measures, strong co-benefits between these mitigation options and SDG 7) (see Table 4.A.3). However, there is little agreement on the best mix of these technologies, as many different technological pathways allow achieving climate neutrality in the Austrian energy system, and the underlying scenario processes make significantly different assumptions about the potentials of different technologies (see Figure 4.8). However, there is a consensus that renewable energies, especially wind power and solar PV, need to be strongly expanded, and that the electrification of land transport and heat supply is crucial. Both measures are a common driver of decarbonization in all available scenarios up to 2030, but the scenarios differ more after 2030. Electrification causes a substantial decrease of gross domestic energy consumption of 50–100 TWh by 2040 (BMK, 2024a; Schmidt et al., 2025). Under the assumption of unlimited potentials and from an energy system perspective, wind power fits seasonal demand and hydropower supply patterns better than solar PV. Systems with a higher share of wind power therefore have a higher level of reliability at the same cost or the same level of reliability at a lower cost (Scholz et al., 2017; Maeder et al.,

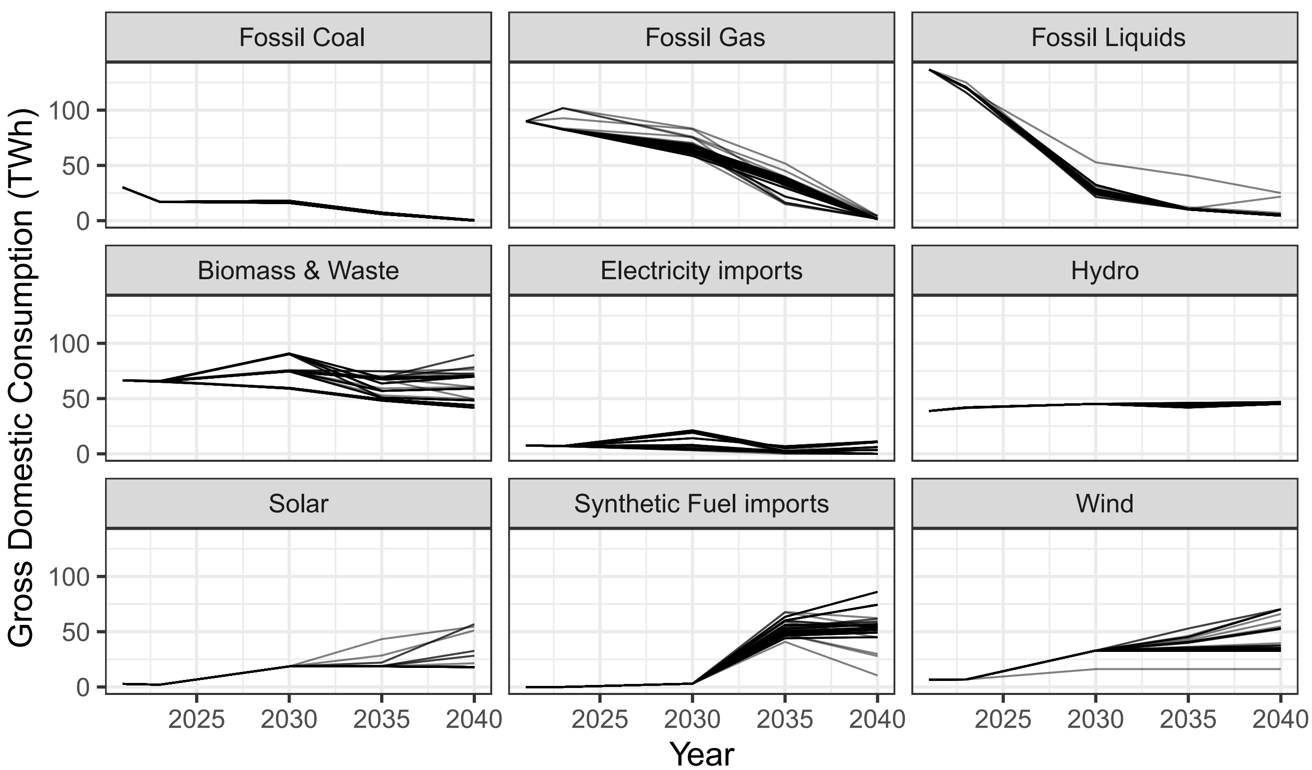



**Figure 4.8** Gross domestic energy use by energy carrier in Austrian net-zero scenarios. The reference data shown in this figure is available at aar2.ccca.ac.at/explorer.

2021; Wehrle et al., 2021; Schmidt et al., 2025). Furthermore, if synthetic fuels are available as imports, domestic electricity generation can be reduced, as the production of these fuels, especially for use in hard-to-abate industries, is electricity intensive (Schmidt et al., 2025). Similarly, biomass is a versatile fuel that can replace the use of synthetic fuels, but sustainable potentials are limited in Austria (Schmidt et al., 2025). Notably, in climate neutrality scenarios, biomass will be used in different sectors than today: Its use will be reduced in domestic heating as it is replaced by heat pumps and thermal insulation, while biomass will be instead upgraded to biogenic methane for use in high-temperature processes in industry (the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer).

**The electrification of energy services** supports the achievement of mitigation goals, as it allows for highly efficient delivery of energy services and the direct use of variable renewable electricity generation (Luderer et al., 2022; Sejkora et al., 2022; Schmidt et al., 2025) (the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer). Therefore, final consumption of electricity increases in all scenarios. Electrification means that sectors that previously operated in isolation will become much more integrated (Brown et al., 2018), such as the power sector, mobility, and heating and cooling, as formerly fossil-fueled processes in these sectors are electrified, for instance using heat pumps and electric cars (Schmidt et al., 2025). Further energy efficiency measures such as high insulation rates and building standards for new construction, as well as measures to reduce the level of energy services on the demand side, such as a reduction in heated area or driven distances, will help limit the necessary infrastructure expansion on the supply side (avoid measures) (the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer) (see Sections 4.2, 3.3, 3.4). In the transportation sector, demand-side measures are generally very important, especially if a very rapid electrification of cars and trucks, far beyond current penetration rates, is not achieved (Schmidt et al., 2025) (see Section 3.4). However, changes in demand for land transport services in a fully electrified land transportation sector will only have a limited impact on total gross domestic energy consumption due to the high efficiency of electric drives (Schmidt et al., 2025). In contrast, a major reduction in energy demand by industry is the most important driver of reductions in gross domestic energy use in decarbonization scenarios (Schmidt et al., 2025).

Scenarios of a climate neutral Austrian energy system indicate that **hydrogen, synthetic gases and fuels** will be used primarily in industry, air and ship transportation, and partly to balance the power grid (see Figure 4.9; the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer), as other uses are too costly (Ueckerdt et al., 2021). Hydrogen and synthetic methane play an important role in industry, where their use can only be avoided by expanding carbon capture and storage in combination with fossil fuels. As intensive carbon capture and storage pathways have not been extensively assessed in integrated energy system scenarios in Austria, the use of hydrogen, synthetic gases and fuels in industry is high in the available scenarios (Schmidt et al., 2025) (the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer). However, there are significant differences between the scenarios: First, if Austria does not produce raw iron, but uses either scrap steel or imports direct reduced iron pellets (shift and avoid measure), the demand for hydrogen in the industry sector decreases significantly (Sections 4.2 and 4.4). Second, if the availability of these fuels is limited or if they are expensive, the scenarios instead show increased electrification of industry, higher utilization of hydrogen than synthetic methane, and increased use of biomass upgraded to biomethane. Furthermore, synfuels are relevant for replacing fossil fuels in air and ship transport (see Section 3.4). In district heating and power generation, the use of hydrogen or synthetic methane depends on the scenario assumptions and the variability between scenarios is high. In land transport, synthetic fuels are used extensively only in scenarios where uptake of electrification is exogenously limited. For households and services, synthetic gas is exclusively used because of the lock-in of gas-based infrastructure for heating, i.e., the long lifespan of today's heating infrastructure requires the use of some synthetic gas as a substitute for fossil gas. Hydrogen, synthetic fuels, and gas are either imported or produced domestically, depending on relative cost assumptions and assumptions about the expansion of domestic renewables. In all scenarios, how-

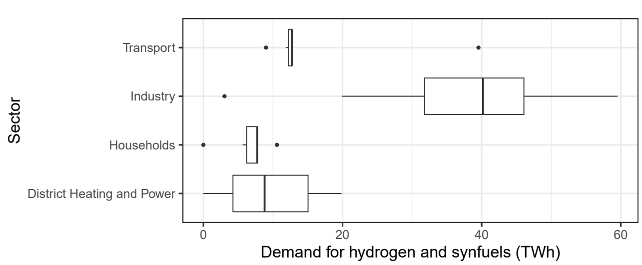



**Figure 4.9** Use of hydrogen, synthetic gas and synthetic fuels in different applications in the energy system (74 scenarios of a climate neutral Austrian energy system; the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer).

ever, dependence on imports of energy carriers is reduced compared to today because the use of hydrogen, synthetic gases and fuels is less than today's fossil fuel consumption. At the same time, material dependencies may arise in the renewable energy sector (see Cross-Chapter Box 5). A further reduction in demand also leads to a further reduction in import dependency (Schmidt et al., 2025).

In terms of **infrastructure**, the expansion of the electricity grid is seen of high importance for the integration of increasing shares of renewable electricity in the energy system. Costs for this are estimated at $EUR_{2023}$ 8.75 billion by 2034 (BMK, 2024a). In the gas sector, a parallel infrastructure for renewable methane and hydrogen is planned and associated with costs of $EUR_{2023}$ 1.9 billion until 2050 (BMK, 2024a).

## Energy supply security and resilience of systems and infrastructure

A central question is how the Austrian decarbonized energy system has to be designed while maintaining security of supply and resilience, considering all aspects of mitigation and adaptation. Current energy systems have relatively large buffers as fossil fuels are easily storable. Renewables-based energy systems show a reduction in these buffers and an increased demand for flexibility (Kondziella and Bruckner, 2016; Suna et al., 2022). In electrified systems with large shares of variable renewables, the size of buffers and associated costs may increase due to higher variability of supply. At the same time, the acceptable risk of electricity system failure may decrease, as electrification will interconnect many different sectors.

Flexibility options in the carbon-neutral electricity system can be provided by (a) sector coupling (for more detailed information on energy storage in buildings and mobility, see Chapter Boxes 3.2 and 3.3), (b) short- and long-term storage, (c) carbon-neutral firm capacity, (d) demand-side management (e.g., industrial or residential load shifting) (Märkle-Huß et al., 2018; Christensen et al., 2020; Mascherbauer et al., 2022; Schwaiger et al., 2023), and (e) exports/imports (Resch et al., 2020; Haas et al., 2022; Suna

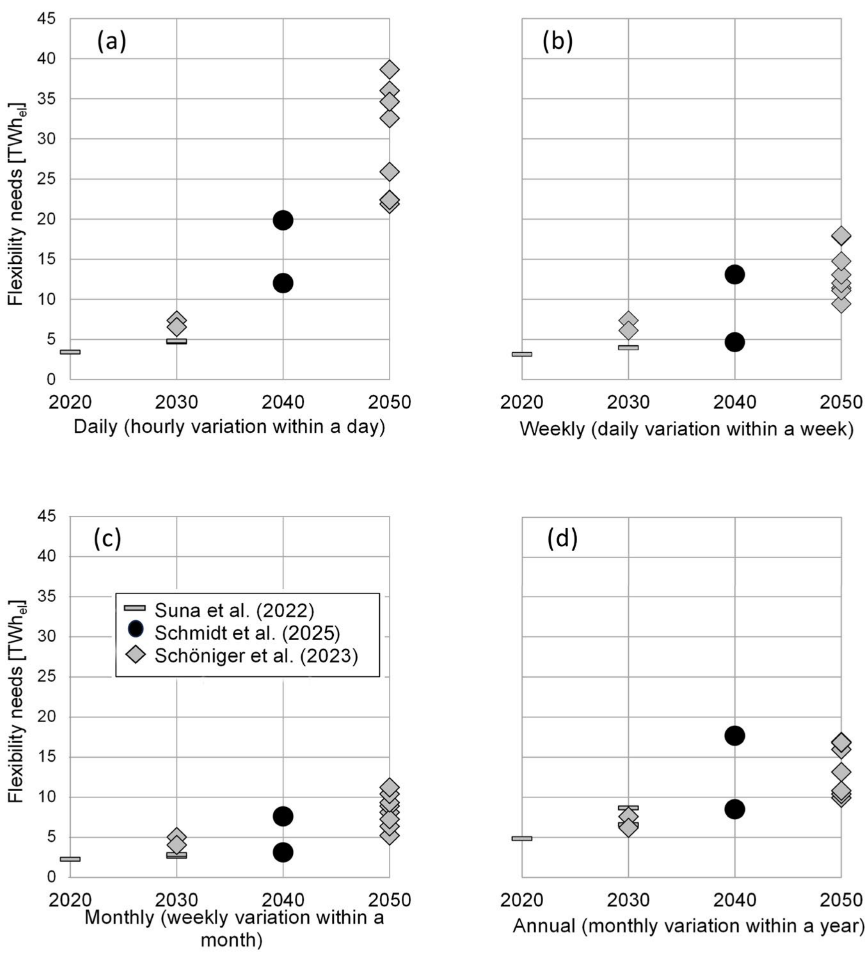



**Figure 4.10** Flexibility/storage needs in the power sector in different scenarios with increasing shares of variable renewable energy. The values are based on 14 scenarios and different years and depicted for daily (a), weekly (b), monthly (c), and annual (d) flexibility needs. The status quo (2020) is based on Suna et al. (2022), 2030 is based on Suna et al. (2022) and Schöniger et al. (2023), 2040 is based on Schmidt et al. (2025), 2050 is based on Schöniger et al. (2023). Source: Own illustration.

et al., 2022; Lienhard et al., 2023; López Prol et al., 2023). There are different timescales for flexibility needs and options (see Figure 4.10), which will have different dynamics in the future. Scenarios with a higher solar PV generation share show higher daily (hourly fluctuations within a day) and annual (monthly fluctuations within a year) flexibility demand than scenarios with a higher wind generation share due to the strong intra-day and seasonal characteristic of solar PV generation. Scenarios with a higher wind share show more fluctuations of the renewable electricity generation on a weekly and monthly timescale (Suna et al., 2022; Schöniger et al., 2023; Schmidt et al., 2025).

Harnessing the synergies of seasonal compatibilities of different energy demand and supply components can increase system stability (Jerez et al., 2013; Ramsebner et al., 2021; López Prol et al., 2024). Reducing energy demand in the building sector (see Section 3.3), for instance, reduces the need for seasonal storage, as there is a natural seasonal mismatch between heating demand (peak in winter) and renewable energy supply (surplus in summer) in Austria, which can be reduced in this way. Climate change impacts on demand and supply patterns might improve the seasonal correlation of renewable energy supply and the stability of energy demand due to reduced heating demand.

The transition to a more decentralized electricity system implies changes in system vulnerability that need to be further understood. Reducing energy demand is a no-regret measure to reduce the necessity of energy infrastructure and related risks (Kranzl et al., 2015) (see Section 4.2). Electricity systems with higher shares of renewable energies show lower sensitivity to fuel price shocks in Austria (Totschnig et al., 2017) and lower fuel import dependency (see scenario descriptions in Section 4.5.2).

In sectors where they can be used efficiently, fuels such as hydrogen, renewable gases, and other e-fuels might play a role and have to be domestically generated or imported as well as stored in the future energy system (see Sections 3.4, 4.2, 4.4). The efficient use of available renewable energy sources requires the use of e-fuels in hard-to-electrify sectors (Sections 4.6 and 3.4) and the use of synergies provided by electrolysis, for example the provision of electricity system flexibility (Reiter and Lindorfer, 2015; Greiml et al., 2021) and waste heat (Böhm et al., 2021).

## Climate change impacts on energy systems

The energy supply system will become increasingly linked to the climate system due to higher electrification and large shares of weather-dependent renewable energy (Cronin et al., 2018; Emodi et al., 2019; Yalew et al., 2020; Simoes et al., 2021; De Felice et al., 2023; Kapica et al., 2024). Climate change impacts the energy system in the fields of (i) energy supply, (ii) energy demand, and (iii) energy infrastructure due to natural hazards (Kranzl et al., 2015). Long investment cycles of energy infrastructure assets require timely adaptation of planning, building and operation to avoid lock-in effects (Seto et al., 2016; Fisch-Romito et al., 2021).

Climate change is expected to increase hazards that impact different parts of the energy system on both the supply and demand side: While heat waves and droughts particularly impact thermal electricity generation (cooling requirements) (Kranzl et al., 2010) and hydropower, transmission and other renewable generation technologies are more risk-sensitive to cold waves, wildfires, flooding, heavy snow, ice storms, and windstorms (Yalew et al., 2020). If energy infrastructure is not designed to be resilient, supply risks can increase, as higher weather dependence and more infrastructure damage from extreme events can lead to a stressed system (Mikellidou et al., 2018; Perera et al., 2020; Doss-Gollin et al., 2023). Climate change impacts on energy demand, supply, and infrastructure through extreme events (e.g., wind, droughts, cold waves, heat waves, floodings, wildfires, storms, and compound effects thereof) (Brás et al., 2023) or changes in long-term trends can lead to cascading effects and energy supply disruptions (Rübbelke and Vögele, 2011; Hossain et al., 2021). Energy systems, especially the increasingly important electricity system, are highly interconnected geographically, which can lead to large-scale spatial disruptions in the event of failure. Possible adaptation measures include reducing energy demand (Section 4.2) and cooling water demand, increasing the degree of interconnection of the energy system, increasing back-up capacity (flexible generation or storage), spatial and technological diversification of energy sources and flexibility options (Yalew et al., 2020) (see above), and integrating impacts of climate change on energy demand and supply into energy strategies and business decisions. An example of mitigation co-benefits is the improvement of energy efficiency in buildings, which makes them less vulnerable to climate change impacts (Zachariadis and Hadjinicolaou, 2014) (see Section 3.3). Energy system design in terms of generation mix, interconnection grade, and availability of flexibility options has a greater impact than weather variability between different years or climate scenarios (Totschnig et al., 2017; Bloomfield et al., 2021).

Table 4.A.2 gives an overview of climate change impacts on electricity demand and supply components in Austria, as

identified in the current literature. The supply side is affected by temperature effects on thermal power plant efficiency and cooling requirements, and by changes in meteorological variables such as precipitation/evaporation, radiation, and wind speed on renewable electricity generation patterns (Kranzl et al., 2015). There is no clear trend regarding the impacts on the supply side (wind, solar PV, and hydropower generation) in Austria. Depending on the climate scenarios considered, either increasing or decreasing annual mean electricity generation is projected and has to be differentiated regionally (see Section 7.4.2 Energy). The impacts on hydropower are expected to be stronger than on wind and solar generation.

Additionally to Table 4.A.2, Figure 4.11 shows modeled relative changes of annual renewable electricity generation and annual heating and cooling demand for different global warming levels (GWL) compared to the reference period 1981–2010 based on Formayer et al. (2023) and Schöniger et al. (2023, 2024).

There is *low agreement* on the effects of climate change on the sign of change of overall hydropower generation in Austria (Stanton et al., 2016; Wagner et al., 2017), with some studies showing increasing (e.g., Simoes et al., 2021; Formayer et al., 2023) and others showing decreasing generation (e.g. Kranzl et al., 2010, 2015; Eitzinger et al., 2014; Schleypen et al., 2019). However, there is *high agreement* that hydropower will show earlier runoff in spring, higher generation during winter, and lower generation during summer due to a change in the snowmelt period (Kranzl et al., 2010; Finger et al., 2012; Kling et al., 2012; Fuchs et al., 2013; Totschnig et al., 2017; Wagner et al., 2017; Blöschl et al., 2018; Formayer et al., 2023; Wechsler et al., 2023) (see Figure 4.12). This smoothed seasonality of hydropower is expected to decrease the need for seasonal storage (Kranzl et al., 2010; Blöschl et al., 2011). However, negative energy system impacts may arise from extreme events (droughts or flooding). For hydropower, an increase in interannual variability is observed, which poses a risk to the highly hydropower-based Austrian electricity system. However, the climate change impact on interannual hydropower variability is expected to be lower than the naturally high interannual variability of hydropower in Austria (until 2050) (Blöschl et al., 2018). (Pumped) storage hydropower plants are expected to be less affected by climate impacts due to their balancing capacity, which allows for some adaptation (Kranzl et al., 2010) (see Section 7.4.2). However, impacts of glacier melt dynamics are expected to limit the adaptive capacity of hydropower production with glacier catchments (Finger et al., 2012) and to affect the whole energy system in Austria (see Section 7.4.2).

On the demand side, climate change mainly affects the energy demand for heating and cooling (see Table 4.A.2).

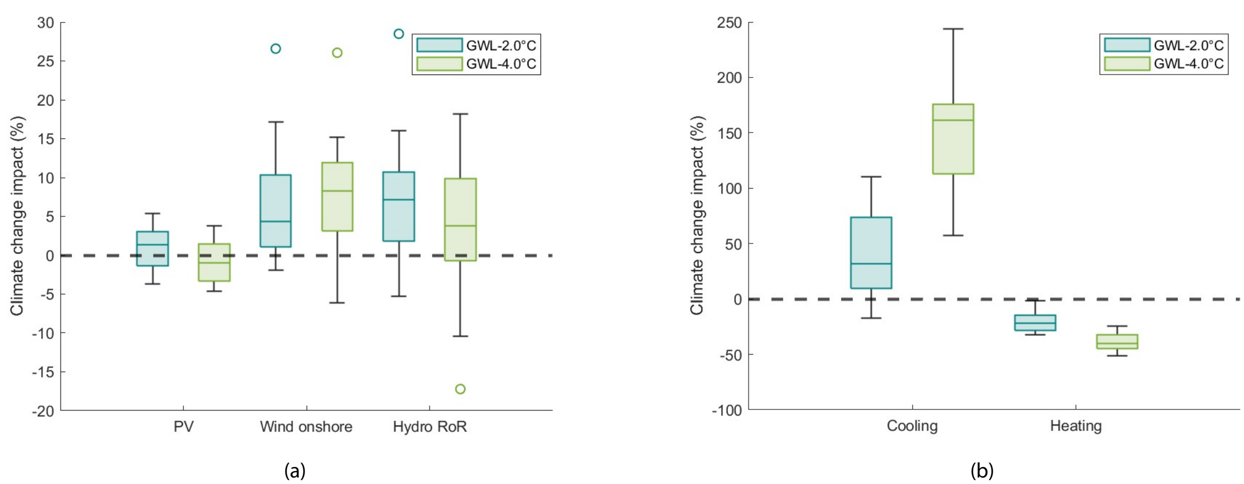



**Figure 4.11** Climate change impacts on the Austrian energy system for different global warming levels (GWL) compared to the mean of the reference period 1981–2010. (a) Relative changes of the annual electricity generation of PV, wind onshore, and hydro run-of-river and (b) on annual cooling and heating demand are shown. For each GWL, the box shows the 20 weather years in which that level is reached in the underlying climate scenario (2026–2045 for GWL 2.0°C and 2073–2092 for GWL 4.0°C). Findings: For wind and hydro, a slightly increasing annual generation is shown, for PV no trend is visible. There is a clear relative increase in cooling and decrease in heating demand. Despite the strong relative increase of cooling demand, there is an overall negative net effect on heating and cooling energy demand in Austria due to higher absolute heating than cooling demand. (Own illustration, data points are based on the RCP8.5 scenario of Formayer et al. (2023) and Schöniger et al. (2024)).

With increasing global warming levels, an increasing trend in cooling demand and a decreasing trend in heating demand are projected for Austria (see also Sections 3.2.3, 3.3.1). This sign of change is robust across studies and models (Bachner et al., 2013; Berger et al., 2014b; Kranzl et al., 2014a; Steininger et al., 2015; Damm et al., 2017; Bird et al., 2019; Ramsebner et al., 2021). This implies a more even seasonal profile of electric load by decreasing demand during the cold seasons and increasing the load during warm seasons. As heating demand is still expected to be significantly higher than cooling demand in absolute terms, the net effect of climate change on energy demand in Austria is found to be negative even under the strongest GWL considered (Bachner et al., 2013; Totschnig et al., 2017; Formayer et al., 2023). Kranzl et al. (2015) found an 18–20 % reduction in electricity demand for heating and cooling by 2050. Climate change impacts and adaptation on the demand side (e.g., peaking need for electric cooling during heat waves) can have significant effects on supply-side requirements (Totschnig et al., 2017; Rode et al., 2021; Viguié et al., 2021). Literature for Austria shows that critical situations for the electricity system are still mainly expected during winter, but heat waves are shown to pose an increasing risk to the Austrian and Central European electricity system (Schöniger et al., 2023; Gruber, 2024). If future energy system design and policies consider these climate impacts to build a resilient

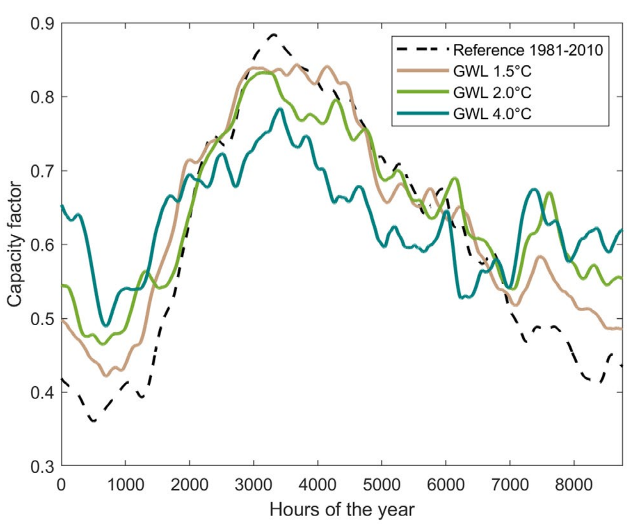



**Figure 4.12** Climate change impact on seasonal patterns of run-of-river hydropower generation in Austria for global warming levels (GWL) 1.5°C, 2.0°C, and 4.0°C compared to the reference period 1981–2010. (Own illustration; based on Formayer et al. (2023): SDM_ICHEC-EC-EARTH_rcp45/85_r1i1p1_KNMI-RACMO22E climate projections for GWL and ERA5-Land for reference period; GWL 1.5°C and 2.0°C contain data from the RCP4.5 and RCP8.5 scenario, GWL 4.0°C only from RCP8.5 scenario; 7-days rolling mean capacity factors are displayed).

energy system (van der Wiel et al., 2019), energy supply disruptions and their cascading effects can be avoided.

There is a research gap for quantitative climate change impacts on critical energy infrastructure in Austria. For other countries, peak capacity losses for thermal power plants in the range of 1.1–4.6 % at the end of the century have been calculated (Sathaye et al., 2013). The issue of increased capacity losses in transmission lines and substations due to higher temperature levels is found to account for up to an additional 8 % and 3.6 % of peak capacity (Sathaye et al., 2013), with a particular high risk in no-wind conditions at high temperatures. Grid-connected energy infrastructure can be impacted by hazards such as flows, floods, landslides, permafrost thawing, rockslides and other extreme meteorological events such as heavy precipitation, high temperatures, or strong winds (Schaeffer et al., 2012). Possible adaptation measures include incorporating future cooling demands into power infrastructure design parameters, or rerouting transmission in situations of local impacts where possible.

In terms of macroeconomic effects, the shift of the electricity load towards the summer is expected to result in gains in the overall energy system on the one hand, and costs due to increased cooling demand and electricity generation costs (e.g., increased peak load production, reduced hydropower during dry periods) on the other hand. Climate change impacts in the electricity sector are found to increase annual costs in the sector by about $EUR_{2023}$ 302.22–840.96 million in 2050 and, due to spillover effects, reduce GDP by $EUR_{2023}$ 216.81 million in the 2030s and by $EUR_{2023}$ 613.64 million in the 2050s (Kranzl et al., 2014b, 2015). For heating and cooling, a positive annual net effect of $EUR_{2023}$ 39.42 million (2016–2045) and $EUR_{2023}$ 65.7 million (2036–2065), respectively, was calculated (Kranzl et al., 2014b). Based on the same dynamics, Steininger et al. (2020) report average annual costs of $EUR_{2023}$ 347.42 million (2030) (2050: $EUR_{2023}$ 926.44–1,304.33 million – low border RCP4.5, high border RCP8.5). All costs are calculated without considering infrastructure failures or blackout risks due to extreme events and natural hazards. In general, there is a literature gap on costs linked to energy infrastructure damages and large-scale energy supply disruptions in Austria. In the electricity system, costs of such large-scale energy supply disruptions are estimated to be orders of magnitude higher than those associated with general electricity generation and can reach the future costs of an entire year's electricity consumption (Kranzl et al., 2014b). Reichl et al. (2013) estimate the costs of a power outage to the Austrian economy on a weekday morning in summer to be about $EUR_{2023}$ 504.35–576.4 million (6 h duration) and $EUR_{2023}$ 1,080.75–1,585.1 million (24 h duration), with the energy-intensive manufacturing sector bearing the largest share of these disruption costs.

### 4.5.3. The necessary transformation: Achieving a decarbonized energy system

Even under stringent demand-side reductions, the supply side of the energy system and the related grids will have to be strongly transformed to reach climate neutrality: Infrastructure will have to be partly expanded and partly built back (Schmidt et al., 2025) (the scenario data used in this analysis is available at aar2.ccca.ac.at/explorer). The technologies to harvest the low-hanging fruits of decarbonization, i.e., electrification of heating and mobility, and renewable electricity generation via solar PV and wind power, are readily available on global markets, but the expansion speed in Austria will have to increase considerably (Schmidt et al., 2025), although the maximum historical expansion of solar PV in 2023 is in line with climate neutrality goals (Statistik Austria, 2024a). However, to decarbonize industry, technologies and commodities are required, which are currently not available at scale, and where rapid upscaling will be challenging, such as for hydrogen production (Odenweller et al., 2022; IEA, 2023). For Austria, additional annual investment costs of a fully carbon-neutral economy are estimated to be in the range of $EUR_{2023}$ 6.2–10.8 billion, of which $EUR_{2023}$ 2.3–5 billion are for energy production, $EUR_{2023}$ 2.7–4 billion for transport, and $EUR_{2023}$ 0.7–0.9 billion for buildings (see Table 8.1). Relative costs depend, however, largely on uncertain assumptions about future fossil fuel prices, renewable energy (IEA, 2023) and capital costs (Bachner et al., 2019b).

The land resources required for the pathways to a carbon-neutral Austria do not technically limit the transition. This is particularly the case in scenarios where biomass use is not increased substantially above current levels: There is sufficient technical potential for wind power and solar PV (see Table 4.A.3) compared to biomass from agriculture or forestry, where complex trade-offs between energetic and other uses of natural resources exist (see Section 2.3.2). In particular, wind power has low direct land-use requirements (Turkovska et al., 2024), while solar PV land-use efficiency can be increased by using agri-photovoltaic schemes (Mikovits et al., 2024). However, biodiversity can be affected by energy system infrastructure: Birds, bats, and non-volant mammals are impacted by wind power, but adverse impacts can be mitigated to some extent, e.g., by the choice of turbine locations or by turning off turbines in periods with high risks for bat collisions (McKenna et al., 2025). Depending on prior land-use and management of PV parks, solar PV installations can be beneficial or detrimental to plant and pollinator diversity (Blaydes et al., 2021; Nordberg et al., 2021). While there are in principle sufficient raw materials available to enable a global energy transition by 2050 (Wang et al., 2023), their mobilization is nevertheless challenging and can entail important trade-offs, such as conflicts with traditional or indigenous populations (Owen et al., 2023) or negative environmental impacts (Berthet et al., 2024). A circular economy can reduce the needs for mining substantially (see Cross-Chapter Box 5), and ecologically responsible mining and sourcing can reduce environmental impacts (Sonter et al., 2023). Overall, the net requirements for mining will decrease as a result of the energy transition, as the reduction in fossil fuel mining overcompensates for the additional mining of raw materials used in low-carbon technologies (Nijnens et al., 2023). The risks, potentials, and uncertainties of carbon capture and storage technologies are discussed in more detail in Section 4.6.

In contrast, limited policy support is a crucial barrier in Austria: Implemented targets and corresponding policy support are still too low to achieve a fully carbon neutral Austria by 2040 (Umweltbundesamt, 2023b). Furthermore, even the federal targets for renewable energy expansion may not be met due to a mismatch with corresponding targets by federal states, e.g., for wind power (Baumann et al., 2021; BMK, 2023c). Even if policy support was sufficient on all governance levels, projects may fail due to a lack of acceptance by the local population (Scherhaufer et al., 2017; Sposato and Hampl, 2018; Seidl et al., 2019). The latter barrier may be partly overcome through compensation payments or participatory planning methods (Kapeller and Biegelbauer, 2020; McKenna et al., 2025). Additionally, power grid infrastructure is also subject to public opposition (Friedl and Reichl, 2016), but will have to be significantly expanded in carbon-neutral scenarios for the Austrian energy system (BMK, 2023c). Regulatory innovations such as energy communities can support the establishment of decentralized and decarbonized energy systems in a participatory manner (Haas et al., 2022). However, renewable energy subsidy schemes can increase income inequality if policies are not designed to distribute the potential welfare gains and losses from renewable energy uptake in Austria evenly (interaction with SDG10). The speed of the transition is also limited by the necessary expertise of the workforce, which can suffer from detrimental boom and bust cycles and needs corresponding policy solutions (Briggs et al., 2022). Of all the required supply-side technologies, solar PV is the most on track, both in terms of the realized expansion as well as in terms of the match between federal and federal province level goals (BMK, 2023c). However, as the generation profile of solar PV is unfavorable in Austrian conditions, overbuilding solar PV may imply the use of more integration technologies (Wehrle et al., 2021; Schmidt et al., 2025).

Table 4.A.3 and Table 4.A.4 show the potential of different renewable electricity potentials and cost in Austria.

## 4.6. Decarbonization of hard-to-abate industries by carbon capture, geological storage, and utilization

Carbon Capture, Utilization and Storage (CCUS) refers to a chain of technologies to prevent $CO_2$ (carbon) emissions by capturing carbon dioxide ($CO_2$) from suitable point sources, such as industrial facilities, and then permanently storing the captured $CO_2$ in the geological subsurface or using it as a feedstock for products (IPCC, 2005; Bui et al., 2018; Lehner, 2021; Ott, 2023). In combination with bioenergy (BECCS) or direct air capture (DACCS) technologies, CCS also offers the potential for negative $CO_2$ emissions and thus the direct and permanent removal of $CO_2$ from the atmosphere (Bui et al., 2018; IPCC, 2023b); this is referred to as Carbon Dioxide Removal (CDR). A schematic overview is provided in Figure 4.13. CDR methods that do not involve CCUS technologies are not covered in this chapter. The reader is referred to the Cross-Chapter Box 6.

Analysis of sectoral climate policies shows that currently planned measures are not sufficient to reduce emissions to the extent necessary to achieve the climate goals of the Paris Agreement (Nascimento et al., 2022). In this context, CCUS is seen as an essential component for achieving climate goals (Bui et al., 2018; IPCC, 2023b). According to recent assessments for the EU, this would result in an average demand for carbon capture by CCS of 230–430 Mt/yr in 2030 and 930–1,200 Mt/yr in 2050, while the scale of CCU deployment could cover a wide range of 47–800 Mt/yr in 2050 (Butnar et al., 2020). Consequently, the European Commission has identified the deployment of CCU and CCS technologies during this decade as critical (COM/2020/562 final). CCUS can play a crucial role in decarbonizing the Austrian economy, especially with regard to hard-to-abate industrial

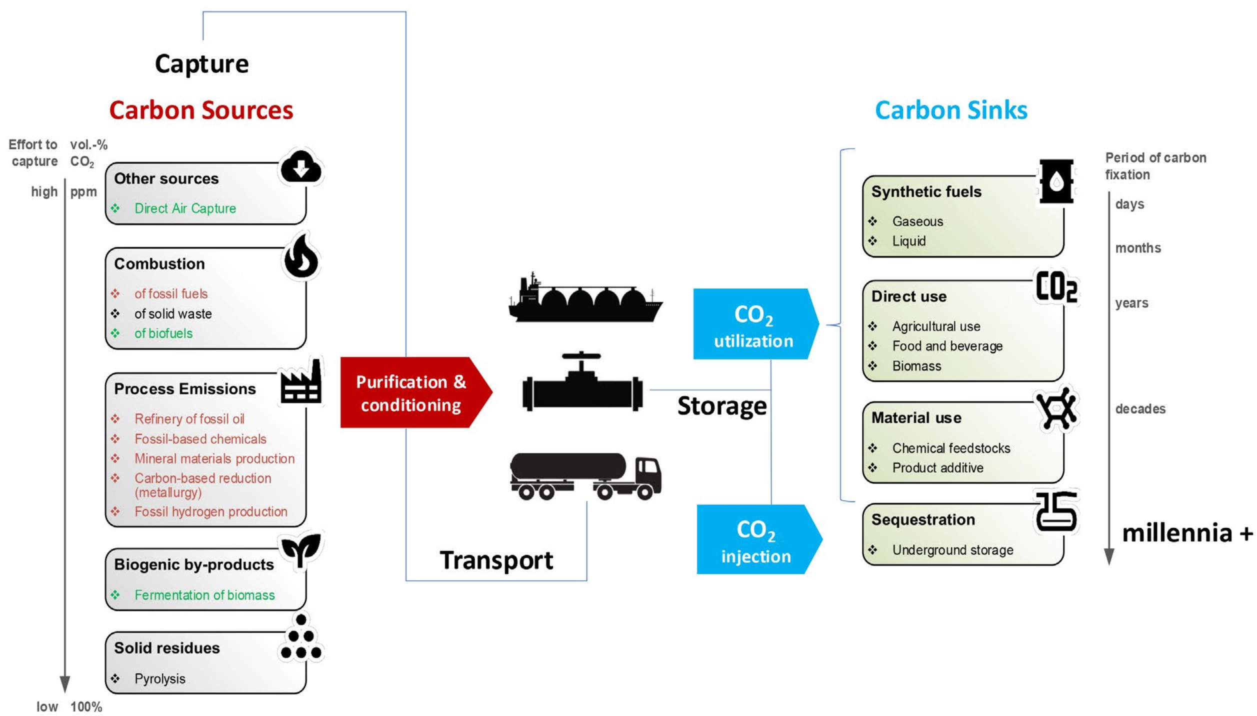



**Figure 4.13** Potential carbon sources, sinks, and a qualitative indication of capture effort and fixation periods. Modified from CaCTUS project proposal (ACRP, Klima + Energie Fonds, 2021) (Global CCS Institute, 2021; CaCTUS, 2024).

emissions. In particular, CCUS can support $CO_2$-intensive industries in Austria to meet $CO_2$ reduction targets while maintaining their competitiveness, which requires a clear definition of which emissions are generally avoidable and which should be classified as hard-to-abate (BMF, 2024; Hochmeister et al., 2024a; Ott and Kulich, 2024). In addition, Austria's biomass potential likely plays a role in offsetting and achieving negative emissions.

## Cross-Chapter Box 6. Carbon dioxide removal

*Harald Vacik; Alina Brad; Simone Gingrich; Tajda Obrecht; Holger Ott; Alexander Passer; Jana Petermann; Nicolas Roux; Harald Rieder; Dominik Steinberger-Maierhofer*

**Main message:** Carbon Dioxide Removal (CDR) describes negative emission technologies that offset unavoidable current and historical emissions to the atmosphere. The assessment of the potential of each CDR option relies in part on the same energy and area resources, therefore the options should be considered as interdependent. The successful implementation of CDR options also depends on several external factors, such as technological developments, the regulatory framework, public perception, existing land use and energy demand under changing climate conditions.

**Definitions and principles:** CDR techniques encompass all anthropogenic activities that remove carbon dioxide ($CO_2$) from the atmosphere and durably store it in geological, terrestrial and marine reservoirs or in products. CDR has two objectives: (i) to offset unavoidable anthropogenic $CO_2$ emissions to the atmosphere, and (ii) to create negative $CO_2$ emissions, i.e., offsetting historical anthropogenic emissions. Numerous existing and emerging CDR technologies are known, focusing on natural and technological means. They include existing and potential anthropogenic enhancement of biological or geochemical $CO_2$ sinks such as afforestation, reforestation, land restoration, and technical means such as bioenergy or direct air capture in combination with carbon capture and storage (BECCS and DACCS), biochar production (PyCCS) and chemical weathering in terrestrial or aquatic systems, but exclude natural $CO_2$ uptake not directly caused by human activities. For a positive CDR effect, the total quantity of atmospheric $CO_2$ physically removed and permanently stored must be higher than the total quantity of $CO_2$ emitted during the process.

**Potentials of CDR options for Austria:** The potential of the CDR options can only be assessed on a case-by-case basis. The many interdependencies require an estimate of the CDR potentials individually as presented in CCBox 6 Figure 1, and the implementation in Austria would therefore require a careful consideration of the best combination of options and the mutual impairment of their potential. The CDR options, their potential scale of application, their costs and effectiveness, as well as their interference with other land uses and $CO_2$ storage options are described in detail in Chapters 1, 2, 3 and 4. Considered aspects include technical readiness, land and other resource needs, geographical and geological constraints, primary energy demand, time scale of sequestration, environmental, social, and health impacts and potential risks, trade-offs and co-benefits. The technical and plausible CDR potential is presented in CCBox 6 Figure 1 for the current potential (considering the current capacities and constraints until 2030) and the future potential (up to 2050). Additionally, a qualitative assessment has been made for the required area and energy demand, the public acceptance and any constraints regarding the legal framework for implementing the CDR option.

The potential for the long-term carbon dioxide removal of different land uses has been assessed for soil management, agroforestry and renaturation, as well as different forest management options (afforestation, adaptive or extensive forest management). Two CDR options consider a land use change, where technical measures, reducing food waste or special diets allow to gain some area for afforestation measures. Among the forest-related CDR options, different management strategies (e.g., change of tree species composition, shorter rotation) are considered. Depending on the CDR option (Table 2.3, Sections 2.3.1 and 2.3.3), the total mitigation effects are within a range of -1.2 $MtCO_2$/ha and year and +8.0 $MtCO_2$/ha and year compared to the reference of the year 2020.

| CDR Options | Technical / plausible potential | Assumptions on plausibility (need for area, energy, investments and costs, public acceptance, legal famework) | | | | | Co-benefits / trade-offs |
|---|---|---|---|---|---|---|---|
| | $CO_2$/yr until 2030/2050 + Max ($CO_2$) | Area | Energy | Costs | Accept-ance | Legal adaptations | |
| **BECCS / DACCS** capture $CO_2$ for storage and utilization | CCS: 3 to 25 Mt $CO_2$/yr *• Total onshore storage capacity of several hundred Mt $CO_2$ in Austria *• CCU: 1 to 5 Mt $CO_2$/yr *• | + | +++ | +++ | no | required | High demand for energy from biomass might raise conflicts with other uses of timber and pulp wood *(figures and references see Section 4.6)* |
| **Soil management** use plants timber for biochar in soils | 0.9 to 3.7 t $CO_2$/ha/yr Based on global estimates 2030: 1 to 3.3 Gt $CO_2$/yr 2050: 1.1 to 4.9 Gt $CO_2$/yr | 0 | + | ++ | limited | not required | High competition on the market for timber and pulp wood as well as biomass for energy production *(figures and references see Section 2.3)* |
| **Afforestation (LUC)** of agricultural land through a protein transition (lancet diet) and halving food waste | Compared to 2020: 3.3 to 8.0 Mt $CO_2$/yr Compared to Reference Scenario: 3.0 to 12.9 Mt $CO_2$/yr | + | + | + | limited | not required | Loss of argicultural land and loss of biodiversity, lower income of livestock farmers, changes in landscape *(figures and references see Section 2.3)* |
| **Agroforestry (LUC)** increasing sinks through short rotation coppices, hedges and by technical mitigation measures on agricultural land | Compared to reference scenario: 0.1 to 0.4 Mt $CO_2$/yr | ++ | ++ | ++ | limited | not required | Loss of argicultural land, partly increased biodiversity, changes in landscape *(figures and references see Section 2.3)* |
| **Renaturation** of wetlands under agricultural use | 1 to 100 kt $CO_2$/ yr (GWP100) avg. -45 t $CO_2$/ha/yr up to >-60 t $CO_2$/ha/yr | + | 0 | ++ | high | not required | Changes in biodiversity and landscape (drainage of peatlands/rewetting on extensively managed peatsites) reduction in feedstock and market crops *(figures and references see Section 2.3)* |
| **Adaptive forest management** change of tree species composition | Compared to 2020: Sink is decreased by -0.1 to -1.2 Mt $CO_2$/yr ᵛ Compared to reference scenario: 4.1 to 4.9 Mt $CO_2$/yr ᵛ | 0 | 0 | + | limited | not required | Improved biodiversity, reduced vulnerability to climate change impacts, less availability of demanded coniferous timber assortments *(figures and references see Section 2.3)* |
| **Extensive forest management** reducing the overall use and harvest of wood | Compared to 2020: 1.4 to 4.4 Mt $CO_2$/yr ᵛ Compared to reference scenario: 9.3 to 11.1 Mt $CO_2$/yr ᵛ | 0 | 0 | + | limited | not required | Improved biodiversity, less availability of timber, less farmers' income and decreased rural employment *(figures and references see Section 2.3)* |

* only if limited by geological
• reductions through industrial CCUS not considered
ᵛ average values (2010-2150)

0 no additional requirements for area, energy or investments
+ small additional requirements for area, energy or investments
++ medium additional requirements for area, energy or investments
+++ high additional requirements for area, energy or investments

**CCBox 6 Figure 1** Assessment of the potential of Carbon Dioxide Removal (CDR) options in Austria.

BECCS and DACCS refer to geological storage of $CO_2$ captured from the atmosphere and are thus derivatives of CCS (see Section 4.6). While classical CCS projects capture $CO_2$ from point sources, atmospheric $CO_2$ is less concentrated and captured by biomass (BE) or by direct air capture (DA). It should be noted that the required renewable biomass is only available on a decentralized basis, and long transport distances must be expected for centralized combustion and subsequent sequestration. Technically, $CO_2$ can only be removed from the atmosphere with a comparably high energy input, which is why DA has not yet reached the necessary technological maturity. BECCS, including geological storage, is in principle available as a technology for achieving negative emissions, but faces a time challenge in terms of political, legal and technical implementation (Section 4.6). The provision of biomass is also likely to be a limiting element in the BECCS chain (Section 2.3.2).

Several factors influence the potential of biochar application to agricultural soils, such as pyrolysis production, soil conditions, climate, field management, biomass availability, making it difficult to estimate its CDR potential. Therefore, the reported global potential ranges from 0.65 to 35 $GtCO_2eq$/yr depend on the applied models and their assumptions (Tisserant and Cherubini, 2019). The IPCC (2023a) provides ranges of 0.1–4.9 $GtCO_2$/yr (WG1) and 0.1–6.6 $GtCO_2$/yr (WG3) in AR6 globally, Smith (2016) provides an estimate of 0.9–3.7 $tCO_2$/ha/yr, which is used in CCBox 6 Figure 1.

In 2024, the European Council and the European Parliament reached a political agreement to establish an EU-level voluntary certification framework for permanent carbon removals, carbon farming and carbon storage in products to facilitate the emission reduction activities in the EU (Regulation (EU) 2024/3012). The timing of carbon uptake and storage is important, as there is a need to remove large quantities of carbon from the atmosphere within the next few decades. A large potential for a permanent carbon storage is seen in the construction sector with the use of organic construction materials during the use phase of the built environment; a carbon uptake at the beginning of the life-cycle is seen as less mature and efficient and there are challenges related to certification schemes in buildings and the recycling of timber products (Kuittinen et al., 2023). In any case, CDR techniques will have cost implications: In the construction industry, price increases of 20–30 % for steel and 20–80 % for cement can be expected (Material Economics, 2019).

Research on public perceptions of CDR options is limited, but reveals low levels of public awareness and knowledge (Smith et al., 2023). Generally, conventional CDR methods such as afforestation are favored over novel approaches such as DACCS, which often encounter uncertainty (Bellamy et al., 2016; Dumbrell et al., 2016; Jobin and Siegrist, 2020; Brutschin et al., 2024). With respect to land-based CDR methods, concerns about land use, biodiversity, and environmental impacts are more frequently raised. BECCS also raises concerns about land competition, food prices, biodiversity, and the sustainability of biomass. Research on public perception of CCS shows safety concerns about leakage and seismic risks of underground $CO_2$ storage (Cox et al., 2020). In addition, public scepticism appears to be higher in wealthier countries, as studies have shown lower confidence in the potential of science and technology to address climate change in these countries. This would call for more country-specific approaches to the deployment of potentially useful technologies (Brutschin et al., 2024). There is also a need for a clear, transparent and robust definition of what counts as hard-to-abate and a clear delineation of residual emissions in the net zero year. These should indicate how much and by whom emissions should be reduced by the various CDR options by 2040, as well as the corresponding storage, utilization, and removal capacities needed (Brad et al., 2024).

**Main challenges with CDR in Austria:** CDR options could be used in all sectors to offset unavoidable anthropogenic $CO_2$ emissions into the atmosphere, as well as to offset historical anthropogenic emissions to ensure climate change mitigation. Although they can serve to compensate for residual emissions that are hard-to-abate, CDR options are not a substitute for emission reductions to reach climate targets (*medium confidence*) (see Section 4.6). Correspondingly, an important political challenge is to send robust political signals that CDR cannot compensate for any delay in phasing out fossil fuels, especially given the limited and uncertain CDR potentials (Brad et al., 2024).

CDR options in Austria include land-based biological (i.e., afforestation, reforestation, ecosystem restoration, and soil management) and technical processes to capture and permanently store $CO_2$, such as BECCS and DACCS. They differ in terms of their technical and plausible potentials, synergies and trade-offs, and technical readiness levels (*medium confidence*) (see Sections 2.3 and 4.6).

CDR options face several limitations; the availability of biomass for CDR may conflict with other land uses for energy production, construction purposes, pulp/paper industry, or conservation efforts; and long transport distances for the provision of renewable energy from biomass are to be expected. Geological storage capacities may also compete with other subsurface technologies, such as natural gas storage and future hydrogen storage operations (e.g., for steel production), and energetic uses, such as geothermal energy production and storage (Hochmeister et al., 2024a, 2024b; Ott and Kulich, 2024; BMK, 2024a; Kulich and Ott, 2025). Carbon capture and storage is currently prohibited on Austrian territory, but is currently under reconsideration by the Austrian CMS (see Section 4.6).

In the construction sector, there are several challenges related to the certification schemes in buildings and the recycling of timber products. Trade-offs exist also in storing carbon in buildings in comparison to other options (Maierhofer et al., 2024) and only a combination of various models and sectors together with the supply and demand as well as life cycle assessments of the whole supply chain of each CDR method can show that the total quantity of atmospheric $CO_2$ removed and permanently stored is greater than the total quantity of $CO_2$ emitted to the atmosphere (*medium confidence*) (see Sections 4.6 and 2.3).

The implementation of CDR requires future research to address the monitoring of CDR, such as imports of timber, reuse of material, and the definition of temporal aspects, such as the duration of $CO_2$ removal. It requires a robust common definition of permanent carbon storage, as the EU Commission's definition, for example, is incompatible with the terminology used in the UNFCCC and IPCC frameworks.

### 4.6.1. Current status of CCUS technologies

**$CO_2$ capture and transport:** CCS requires $CO_2$ in a pure state and in large quantities from so-called point sources or $CO_2$-intensive industries such as cement or steel production (Paltsev et al., 2021). Several technologies are available to capture $CO_2$ at the industrial site. These are largely mature (technology readiness level TRL 9) and are based, for example, on chemical absorption (e.g., amine scrubbing) or adsorption (Dziejarski et al., 2023). Existing industrial plants can be retrofitted for $CO_2$ capture, or special processes tailored to specific industrial processes can be used (Fröhlich et al., 2019). $CO_2$ capture is energy intensive, increasing energy demand in production processes, and water intensive, potentially putting pressure on water supply systems. Carbon capture largely determines the cost of CCUS operations (Kearns et al., 2021).

Because CCS places high demands on geological formations, the captured $CO_2$ must be transported over long distances to suitable storage sites, usually by pipeline or ship. The same applies to the use of $CO_2$, which can be centralized at production sites. Transport distances from the capture site to the storage site range from a few kilometers to several hundred kilometers onshore or offshore (Ausfelder et al., 2020). Shorter transport distances are generally more economical and energy efficient but limit the potential for CCUS deployments due to the accessibility of suitable storage sites. $CO_2$ transport by pipeline is in commercial use (NPC, 2019; Kearns et al., 2021) and is therefore at TRL 9. $CO_2$ transport by waterways has not yet been used for CCUS and is therefore at a lower TRL 4–7 (Ausfelder et al., 2020; Al Baroudi et al., 2021; Kearns et al., 2021). The combined cost of $CO_2$ transport and storage is generally assumed to be a uniform $EUR_{2023}$ 9.91 per $tCO_2$ (Smith et al., 2021), which is reasonable in some regions, but not in Europe. Europe has the highest transport and storage costs in the baseline scenario of around $EUR_{2023}$ 34.7 per $tCO_2$, as offshore storage is preferred. However, even in Europe, onshore storage is expected to be more economic, in the range of $EUR_{2023}$ 15.87 per $tCO_2$.

**Geological storage:** Suitable geological formations are found at depths greater than 800 m, where $CO_2$ is in a dense state that allows efficient use of pore space for storage (Angus et al., 1987; Benson et al., 2005). In this state, however, the $CO_2$ still has a lower density than the reservoir water and therefore experiences buoyancy; to prevent the injected $CO_2$ from migrating into higher layers containing drinking water or even into the atmosphere, a trap structure in combination with an impermeable caprock, e.g., an overlying claystone formation, is required (IPCC, 2005). Corresponding geological formations are known from oil and gas fields, which are suitable reservoirs for geological $CO_2$ storage, as are deep saline aquifers. In a suitable storage facility, $CO_2$ is permanently bound by physical and chemical processes (Xu et al., 2003; De Silva et al., 2015; Krevor et al., 2015; Brandstätter et al., 2025), providing high storage security (Benson et al., 2005). Despite technical maturity, geological reservoirs are individually different and require site-specific development. Numerical reservoir modeling and uncertainty analysis are required to ensure safe storage. Monitoring options must be in place to detect $CO_2$ leakage during the injection phase and beyond (IPCC, 2005; Directive 2009/31/EC). Upon closure of a storage site, legal obligations for monitoring and corrective, preventive and remediation measures should be transferred to the competent authority (Directive 2009/31/EC). Geological $CO_2$ storage in hydrocarbon reservoirs and saline aquifers is commercially applied and therefore mature (Benson et al., 2005; Bui et al., 2018). However, storage options in unconventional geological reservoirs such as coal seams and volcanic (ultramafic) rocks are less developed (Benson et al., 2005; Kearns et al., 2021). There are currently about 30 ongoing CCS projects, 11 of which are capturing more than 1 Mt/yr of $CO_2$ for long-term storage (Global CCS Institute, 2021, 2023). Although these rates are still far from the actual problem of anthropogenic $CO_2$ emissions, CCS technology is successfully applied and available as a critical technology.

**Carbon utilization:** Various industries and their products depend on carbon as a feedstock. Carbon supply has been primarily based on petroleum, coal (coke), and natural gas (European Commission: Directorate-General for Energy, 2020). Thus, alternative carbon sources are required for a sustainable and renewable circular economy. One option is CCU, which is based on either renewable sources or holding $CO_2$ in closed loops (Hepburn et al., 2019). In CCU processes, $CO_2$ is used as a C1-building block to synthesize carbon-containing products. However, most of these products rerelease $CO_2$ during their utilization (e.g., e-fuels) or at the end of their lifetime (e.g., plastics). Therefore, CCU contributes to an atmospheric $CO_2$ reduction only when the $CO_2$ has been taken from the air, $CO_2$ is held in a closed loop, or products are generated that bind $CO_2$ for at least several hundred years (Hepburn et al., 2019).

CCU products of great relevance are sustainable aviation fuels that can either be produced from biomass feedstock in different process routes or synthesized from $CO_2$ with green hydrogen (Richter et al., 2018) (for biomass potentials see Section 2.3.2 on sufficiency oriented bioeconomy). Mineral carbonation, i.e., the production of carbonates from $CO_2$ and metal oxides, is a CCU option with a durable fixation of $CO_2$ (Olajire, 2013). Appropriate metal oxides can be found in primary rocks (e.g., serpentine) or also in secondary feedstocks (e.g., slags and ashes) (Wang et al., 2018). The carbonates can be utilized in the pulp and paper industry or as fillers in construction materials. Another promising CCU option is to retain the $CO_2$ in a closed loop (Rosenfeld et al., 2020). One potential application of such looping processes is in the steel industry until it transitions to carbon-neutral production.

### 4.6.2. CCUS potential in and for Austria

In 2023, Austria's total GHG emissions amounted to 68.6 $MtCO_2eq$ (Umweltbundesamt, 2023a). The energy and industry sectors are responsible for more than 43 % of total emissions ($CO_2eq$), with decentralized $CO_2$ sources such as agriculture and transportation accounting for 39 % (Umweltbundesamt, 2023a). In Austria, the steel and cement industries emit about 14.1 $MtCO_2$/yr into the atmosphere. An overview of the largest industrial $CO_2$ sources and potential geological sinks in Austria is shown in Figure 4.14.

**Geological storage capacity:** An Austria-wide assessment of the CCUS potential is currently under development (CaCTUS, 2024). Significant potential storage regions are located in the sedimentary basins of the Upper Austrian Molasse Zone and the Vienna Basin as well as in the Styrian Basin (Hochmeister et al., 2024a, 2024b; Ott and Kulich, 2024; Kulich and Ott, 2025).

**Domestic hydrocarbon fields:** Hydrocarbon reservoirs are largely developed and well known, and therefore represent the fastest route to geological storage. The theoretical storage capacity of depleted hydrocarbon fields is estimated by Scharf and Clemens (2006) to be at 465 $MtCO_2$. A recent Austria-wide study (CaCTUS, 2024; Hochmeister et al., 2024a, 2024b; Ott and Kulich, 2024; Kulich and Ott, 2025) takes a more conservative approach and shows that the largest hydrocarbon reservoirs represent a total effective storage potential of 250 $MtCO_2$, taking into account fields with a storage capacity of more than 2 Mt. Excluding the highly perforated oil horizons, the largest gas and gas condensate fields still offer a total effective storage potential of >100 $MtCO_2$. Assuming operating times of 10 to 30 years (European Commission, 2024), the storage capacities result in possible storage rates of 3–5 $MtCO_2$/yr. Alternative uses of this underground space, such as hydrogen storage or geothermal energy recovery, are also taken into account.

**Domestic aquifers:** Saline aquifers have been hardly studied, with the exception of the Aderklaa conglomerate in the Vienna Basin; a theoretical storage capacity of 1,000 $MtCO_2$ has been calculated by Heinemann and Scharf (2004). Saline

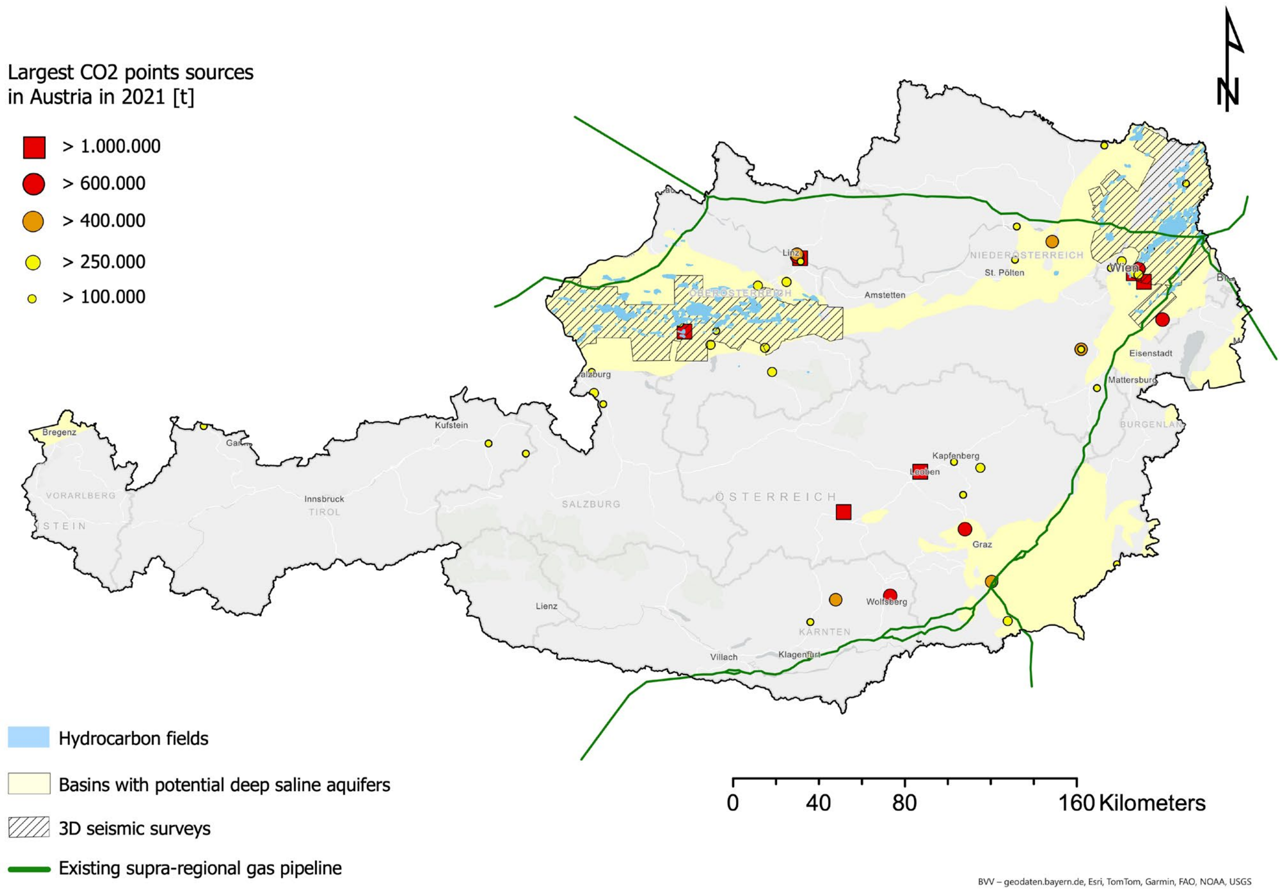



Figure 4.14 Potential hard-to-abate carbon sources >0.1 $MtCO_2$ emissions in 2021 according to E-PRTR or ETS, and potential geological sinks. Montanuniversität Leoben (Hochmeister et al., 2024b, 2024a; Ott and Kulich, 2024; Kulich and Ott, 2025).

aquifers urgently need to be explored. In general, however, aquifers can be expected to have many times the storage capacity of hydrocarbon reservoirs.

**Storage capacity inside Austria:** Depending on the exact definition of 'hard-to-abate $CO_2$ emissions' (BMF, 2024), which range from 7 to 14 Mt/yr, and with the estimated storage capacity including all uncertainties, it can be stated that the storage capacity in Austria is sufficient for several decades.

**Storage outside Austria**: Securing and developing storage capacity outside Austria depends on factors that are difficult to estimate in terms of time and realism. These factors include the development of a suitable transport network, international agreements and the availability of storage capacity (see, e.g., Baltac et al., 2023). It can be assumed that there is sufficient storage capacity in the North Sea, estimated to be in the order of several 100 billion tons in total (Karvounis and Blunt, 2021), but it will take time to develop and will only be available to a limited extent in the medium term. For example, the expansion of the Norwegian flagship project Northern Lights (Northern Lights, 2024) is estimated at only 5 Mt/yr by 2030. Austria is competing with other European countries. In any case, it can be assumed that large-scale storage outside Austria will be a later option (2040/2050). $CO_2$ storage in Austria therefore seems necessary, does not conflict with other European storage activities and would likely reduce Austrian emissions much faster.

**CCU potential in Austria:** No data are currently available specifically for Austria. In any case, CCU associated with fossil GHG emissions does not contribute to the removal of carbon from the atmosphere. CCU products produced from fossil $CO_2$ will eventually release GHG into the atmosphere at the end of their life cycle. However, carbon is needed for selected fuels and as a feedstock in the chemical industry. In the long term, CCU is an indispensable part of a future economic system. The availability and further development of CCU technologies and the necessary amounts of renewable energy for their operation must be ensured for the circularity of the carbon economy in a defossilized economic system (Purr and Garvens, 2021). Consequently, the potential of CCU in general, and for Austria in particular, is limited to $CO_2$ captured directly from the atmosphere or biomass as a carbon source. In addition, closed carbon cycles and carbonates as long-term carbon fixation options contribute to the $CO_2$ utilization potential. Against this background, a first estimate of the CCU potential in Austria is between 1 and 5 $MtCO_2$/yr, which has to be confirmed in the ongoing study (CaCTUS, 2024).

### 4.6.3. Necessary transformations and R&D

The development of CCUS requires a national and European $CO_2$ transport network from $CO_2$ sources to $CO_2$ sinks, exploration and development of the geological subsurface as well as solutions for the storage and utilization of $CO_2$. With the capacities explored and estimated to date in Austria, CCUS and geological storage in particular can make a significant contribution to national decarbonization. CCUS-specific R&D requires financial resources, an appropriate legal framework, public acceptance and a national CCUS roadmap for Austria (BMF, 2024; Hochmeister et al., 2024a; Ott and Kulich, 2024).

**Site-specific R&D on CCS:** Despite technological maturity, geological reservoirs require exploration and site-specific R&D for predictive modeling of $CO_2$ migration and reliable monitoring concepts for capacity and safety analysis. Therefore, geological $CO_2$ storage is not an off-the-shelf technology and should be considered early in the CCS implementation process.

**Phased implementation of CCS:** For geological storage, the timeframes to 2030 and 2040 are very short. This is because site development usually takes several years (Bui et al., 2018). Having storage capacity or export infrastructure in place by then will require rapid action and a strong commitment to implementation. The three domestic and international geological storage options discussed above are likely to have different development times and should therefore be phased over time. A phased approach allows for a timely entry into decarbonization through CCS and sustainable availability of storage volumes and rates in line with Austria's Carbon Management Strategy (CMS) and negative emissions ambitions. All options and their time constraints should be considered, e.g., Phase 1: Development of depleted hydrocarbon fields for a timely entry into decarbonization through CCS. Exploration of aquifers: Even in scenarios where aquifers are ultimately not developed due to the existence of alternatives, the precautionary principle requires the state be aware of possible future options and their storage capacity. Securing storage capacities outside Austria in accordance with the residual emissions to be expected in the future. Phase 2: Depending on the situation: Development of additional storage capacities in domestic aquifers or abroad.

**Public perception:** CCS projects do not usually fail for technical reasons, but because of a lack of social acceptance and the resulting political will (Witte, 2021). Early and targeted communication of the opportunities and risks of a technology offers the opportunity to bring negatively charged issues back to a factual level and should generally be given higher priority. In this way, the information level of society can be raised to a level at which meaningful opinion-forming can take place, which should then be seen as a prerequisite for creating acceptance (Cremer et al., 2008).

**CCU:** With regard to CCU, sufficient availability of renewable energy is a prerequisite for the climate-neutral operation of industrial processes. Cooperation with international CCU sites, which are expected to develop in areas with optimal conditions for renewable electricity generation, could be an opportunity for a circular carbon economy. In addition, direct air capture technologies and sustainable biomass feedstocks (e.g., cascaded biomass, microalgae) need to be further developed and optimized to achieve carbon neutrality (Purr and Garvens, 2021). The optimization of CCU processes in terms of energy efficiency, cost reduction through scaling and learning curves, and the development of novel catalytic, electrochemical, and photochemical CCU pathways pave the way for their beneficial implementation in a future defossilized economy (Klankermayer et al., 2016). Finally, a regulatory framework for CCU needs to be established, in particular for the crediting of CCU products in the EU Emissions Trading System (Böhringer and Lange, 2013; BMF, 2024).

## 4.7. Provision by work

### 4.7.1. Work and climate change

Work, including unpaid care and paid employment, dominates daily life in Austria, and the structural dependence of persons and welfare systems on paid work currently tends to impede climate-neutral provisioning as well as climate-friendly living (Pettinger, 2017; Kreinin and Aigner, 2022; Aigner et al., 2023b; Bärnthaler and Gough, 2023;

Gerold et al., 2023; Hoffmann et al., 2023; Mason and Büchs, 2023) (*high confidence*). 90 % of the Austrian population (>10 years) is involved in care work (on average 3.5 h/d per household), while only 49 % of the Austrian population are involved in paid work (on average 8.25 h/d) (Statistik Austria, 2024b). The current unequal distribution of paid and unpaid work for the care of people (children, elderly, those in need of care) is strongly influenced by gender-specific divisions of labor (Kuhl et al., 2011; Bauhardt, 2013; Dengler and Lang, 2019, 2022; Knobloch, 2019; Cohen and MacGregor, 2020). Work time preferences follow social norms, with 17.5–30 % of Austrian workers defined as overemployed, i.e., who want to reduce paid working hours (Gerold and Nocker, 2018). Although unpaid care (incl. caring for oneself, household, community, society as well as nature) and paid work are indispensable for the functioning of provisioning systems and the formal economy (Biesecker et al., 2000; Biesecker and Hofmeister, 2006; Cleveland et al., 2017; Smetschka et al., 2023c), work has received little attention in climate science. While many individuals depend on income from paid employment, work is also a source of material livelihood, social integration, the creation of meaning and the development of self-identity (Feigl and Wukovitsch, 2018). In its current form, employment causes consumption, is biophysically intense and has ambivalent health impacts (Gerold et al., 2023). The climate effects of employment can be assessed by considering the goods and services as outputs from work, the tasks and activities workers perform at the workplace, the impact of employment conditions on the sustainability of workers' and their households' lifestyles, and the efficiency of the production process in relation to socially desired provisioning (Bohnenberger, 2022a).

High-productive, energy-intensive work is well-paid and structurally linked to low-productive, energy-light, unpaid or low-paid, very essential work (*limited evidence, medium agreement*). Large parts of paid work do not meet the climate-mitigation requirements (Hoffmann and Spash, 2021; Hofbauer et al., 2023), for instance, when emissions are allocated to work according to income or production (Aigner et al., 2023b; Hoffmann et al., 2023). 60 % of production-based emissions are related to exported goods and services, and thus increase the consumption-based emissions of other countries (Aigner et al., 2023b). Production-based emissions per job and per value-added unit are unevenly distributed across sectors, geography, institutional form (state, private, non-for-profit), firm size, income, working-hours, and occupation (Gabelberger et al., 2020; François et al., 2023b; Heyen, 2023; Oberholzer, 2023). Employment in manufacturing, industry and transport (Hardt et al., 2020, 2021) is associated with high emissions. Employment in interpersonal care services causes lower emissions, but many of these activities are based on the upstream production of goods (Hardt et al., 2020; Aigner and Lichtenberger, 2021; Hardt et al., 2021; Hoffmann et al., 2023; Smetschka et al., 2023a). Due to their interpersonal nature, care and service sectors face barriers to fossil-fuel driven productivity, which leads to a devaluation of climate-friendly care that structurally links the two spheres (Baumol, 1967; Hardt et al., 2020; Aigner and Lichtenberger, 2021). Public provisioning, such as health and care, is a key part of the economy, and can lead to labor shortages and competition between the respective sectors. Social and economic marginalization and devaluation of unpaid care through the dominance of paid work takes place, which leads to time-competition between the two forms of work. Spending time on employment and market-based economic production reduces the time available for voluntary and alternative subsistence activities that satisfy needs with usually low-carbon emissions (Dengler and Strunk, 2018; Aulenbacher et al., 2021).

The work mode of living poses a structural barrier for climate-friendly mobility, food, housing as well as leisure practices, and fosters energy- and fossil-fuel-intensive practices (Hofbauer et al., 2023; Bohnenberger, 2022b; Gerold et al., 2023) (*medium confidence*). Both work acceleration (Rosa, 2005) and time pressure (Sullivan and Gershuny, 2018) affect climate-related decision making (Rinderspacher, 1985; Shove et al., 2009; Rosa et al., 2015; Schor, 2016; Großer et al., 2020; Chung, 2022). Employment and care are key motivations for the use of individual mobility in Austria and are therefore inherently related to emissions in the mobility sectors (see Smetschka et al., 2023b; Wiedenhofer et al., 2023). More than 50 % of travel distances of employees in Austria are work-related (44 % commuting and 9 % business related) (Tomschy et al., 2016). Although there have been changes in the work-induced consumption patterns, an overall reduction of work-induced emissions cannot be observed: In Germany, for example, increasing labor force participation increased household consumption footprints, offsetting technical efficiency improvements and declining paid work time per employee (Wiedenhofer et al., 2023). Similarly, mobility footprints (e.g., through teleworking) faced a (time) rebound effect as the number of trips declined but distance of commutes increased (Wiedenhofer et al., 2023). In addition to paid work, changes in unpaid care responsibilities also shift the modal split towards motor vehicles (Tomschy et al., 2016). A shift towards climate-friendly modes of living requires a reconfiguration of working time to enable caring responsibilities (Hanbury et al., 2023). Some studies show that free time is mainly used for care activities (Gerold et al., 2017), but workers perceive additional recreational time from working time reduction as a key benefit (Hidasi et al., 2023; Antal et al., 2024).

46 % of Austrians believe that their current job does not contribute to the green transition (*limited evidence, high agreement*), which can be associated with contemporary societal conflicts entailing multiple actors and levels (European Commission: Directorate-General for Employment, Social Affairs and Inclusion, 2022). Workers at 'green' workplaces are more likely to engage in pro-environmental behaviors, while workers at workplaces that lack requirements for environmental knowledge in daily tasks, or where workers do not see their own impact or have no control over their own tasks, are less motivated to engage in such behaviors (Ciocirlan, 2017, 2023). Societal conflicts entail conflicts related to transitioning to climate-friendly work-life patterns, but also a lack of transitioning to green jobs (Fritz and Eversberg, 2024). This leads to anti-environmental actions, such as the defense of climate-damaging industries, but also to pro-environmental phenomena such as climate quitting (Brand and Wissen, 2021). Public infrastructure, industrial lobbying and state investments form a powerful consortium that establish the institutions, infrastructure, and rules upon which individuals form their preferences for need-satisfiers such as mode of commuting or job preservation in the automobile sector. Historically, this has increased car dependency (Mattioli et al., 2020). Today, a tendency towards acknowledging the climate implications in public investment decisions can be observed in housing or mobility, but not in the domain of work. Work-related institutions currently disregard both the impacts of climate crisis on work and the mitigation requirements for shaping work through labor law, social security systems, public services and industrial relations (Müller et al., 2019; Kopf, 2021; Bohnenberger, 2023) (*limited evidence, high agreement*).

### 4.7.2. Work in a climate-friendly future perspective

A transition to a climate-friendly society will end the requirement for greenhouse gas emissions from paid employment or unpaid care (*limited evidence, high agreement*). This involves a complete shift away from climate-damaging products and services to climate-friendly outputs, incl. sectoral shifts and an end to employment-induced climate-harming consumption. More work will be undertaken in person-related and resource-light sectors and activities, while energy- and resource-intensive sectors will be smaller, reducing the dependency of workers on climate-harming jobs. An overall trend of anxiety and political instability currently inhibits an efficient market or publicly planned distribution of workplaces to more essential work. This can be superseded by limiting the role of paid work for livelihoods and subsistence. Thereby, the reduction of working hours in paid work, can enable a better adaptation to climate impacts, e.g., when shifting working hours to less hot time periods, reducing work intensity through additional breaks, shifting work away from overheated locations, providing cooling systems, including greening of workplaces (Schulte et al., 2016; Masuda et al., 2021; Bauer et al., 2022; Boltz et al., 2023; Bühn and Voss, 2023).

Greening and sharing of paid employment and unpaid care will ensure quality of life, good work and climate-friendly living, work-life balance and sufficient provisioning of care (*medium confidence*). A reduction in the volume of paid work, especially energy- and resource-intensive work, is necessary to avoid exceeding ecological limits (Seidl and Zahrnt, 2019; Hoffmann and Spash, 2021). The achievement of social goals is contingent upon the decoupling of income and social security from employment and paid work (Petschow et al., 2018; Kubon-Gilke, 2019). A more equal distribution of paid work and unpaid care reduces time pressure and thereby enables the sharing of goods and climate-friendly lifestyles (Smetschka et al., 2019, 2024b). Compensatory forms of consumption (Røpke, 1999; Shove et al., 2009) which are triggered by dissatisfying forms of work will cease to exist.

Given the current business-as-usual, work will be severely impacted by the unfolding of the climate-crisis (Parsons et al., 2021) (Chapters 1, 2, 3), requiring sectoral shifts to the provisioning of basic goods such as health, care, food, and housing (*limited evidence, medium agreement*). To ensure the climate-resilience of work-systems, transformative adaptation measures ensure workers' security against the backdrop of an increasing number of heat waves and other extreme weather events (*medium confidence*). This shift will coincide with demographic trends that will drastically increase the demand for care (Famira-Mühlberger and Firgo, 2019). Impacts of climate change include the destruction of production sites through natural hazard events such as fires, avalanches, and floods (see Chapters 1, 2, 3), as well as declining labor productivity due to heat stress (Parsons et al., 2021). Perspectives from employees confirm this for the Austrian health sector (Brugger et al., 2024a). For the past two decades, Parsons et al. (2022) estimate an annual labor loss of 20 hours per capita in Austria, a figure that is expected to rise substantially in the future (Parsons et al., 2022). Moreover, these impacts will disproportionately affect physically intensive workers and vulnerable groups (e.g., the elderly, people with disabilities), which in turn will lead to increasing care responsibilities, including new diseases (Chapters 1, 2, 3), and declining efficiency of current medication and general methods in the health sector (Bühn and Voss, 2023) (see Cross-Chapter Box 2).

### 4.7.3. Transformation towards climate-friendly work and green employment

To avoid climate-damaging production and to overcome labor supply constraints, climate-friendly regulation of labor markets can enable a shift from excess production to climate-friendly provisioning of essential services (Bärnthaler and Gough, 2023) (*medium confidence*). Production in energy- and emission-intensive sectors needs to be reduced, including hours worked in the respective sectors (Aigner et al., 2023b). Such a shift would also address future rising demand for provisioning of care (Famira-Mühlberger and Firgo, 2019). Climate-friendly public investments can (i) strengthen climate-friendly employment, (ii) satisfy societal needs, and (iii) and ensure a socially acceptable transformation (Krisch et al., 2020; Schultheiß et al., 2021). Climate-neutrality plans at the European and national level require comprehensive changes, especially in the production sector (Gabelberger et al., 2020; Steininger et al., 2021; Meinhart et al., 2022). In the transformation phase to a climate-friendly system, the volume of labor is likely to remain constant due to the necessary reconstruction of the infrastructure (Aiginger, 2016). Overall, climate mitigation policies are expected to increase employment until 2030 (Alexandri et al., 2024). Shifting to renewable energy creates additional demand for labor in the short and long run, and value added in the respective sectors until 2030 (Goers et al., 2020), leading to more equal and less polarized European labor markets (Alexandri et al., 2024). The shift towards renewable energy faces a shortage of low-skilled labor although the transition will mainly increase medium- and high-skilled employment. Shifting the tax burden from human labor to energy and resource consumption could smooth this transition (Köppl and Schratzenstaller, 2019).

Workplace codetermination and greened industrial relations can avoid climate-damaging production and support a shift to climate-friendly production processes and sustainable employment (Initiative Wege aus der Krise, 2019; Aigner et al., 2023b) (*medium confidence*). Employees and their representatives are aware of the need for transformation (e.g., Littig, 2017; Niedermoser, 2017; AK Wien, 2023, 2024; AK Wien and ÖGB, 2024), as are some companies (e.g., Global 2000 et al., 2017; BMK, 2022). Climate-friendly employment can be achieved through conversion of business models to more climate-friendly products and essential services (UNDP, 2015; Hoffmann and Spash, 2021; Hofbauer et al., 2023). Potential employment impacts have been explored, for example, for the phase-out of the internal combustion engine (Sala et al., 2020; Wissen et al., 2020). Unions and green collective bargaining can facilitate transitional assistance policies (SOC/747-EESC-2022-01-01, 2023; OECD, 2024). Guaranteeing material security and a fair distribution of transformation efforts is crucial (Specht-Prebanda, 2020; Wissen et al., 2020; ETUC, 2021; ÖGB, 2021). A just transition can be supported by stronger unionization in green sectors, strengthening unions as pro-environmental actors and improving working conditions in these sectors. A lack of compatibility of work activities and the business purpose with workers' values leads to moral stress and lower job satisfaction, which may explain the increasing climate quitting in climate-harming occupations (Net Positive Employee Barometer, 2023) and societal polarization about the green transition (Smetschka et al., 2024a). Climate-friendly provisioning systems (e.g., mobility, food) at the workplace may, however, positively contribute to climate protection at the workplace and beyond (*limited evidence, medium agreement*). This includes limiting business flights and limiting the serving of GHG-intensive foods such as meat or dairy products (*limited evidence, medium agreement*) and providing infrastructures for climate-friendly commuting, such as bicycle stations or incentives for low-carbon modes of transport for commuting (e.g., climate ticket, active mobility) (Heinfellner et al., 2024).

A redistribution of paid employment and unpaid care as well as relocating workplaces to people's living place through economic and labor market policies can enable climate-friendly work-life patterns (*medium confidence*). Shorter working hours are considered a suitable measure (Cieplinski et al., 2021; Vetter, 2023) to (i) facilitate a climate-friendly life outside of paid employment (Schor, 2005; Knight et al., 2013; Larsson et al., 2019), and to (ii) distribute the volume of employment more evenly (Antal, 2014; Gerold and Nocker, 2015; Seidl and Zahrnt, 2019; Figerl et al., 2021). The specific effects of reduced working hours on individual behavior are ambiguous (Hanbury et al., 2019, 2023; Hofbauer et al., 2023). A shift in societal values toward a more balanced work-life relationship can reshape expectations about the meaning of work (Aichholzer et al., 2019) and the desire for shorter working hours (Csoka, 2018; Arbeitszeiten im Fokus – Daten, Gestaltung, Bedarfe, 2021). Making paid and unpaid care more attractive by raising wages, reducing working hours, and increasing visibility, can create incentives to shift time to low-energy and low-emission care activities (Aigner and Lichtenberger, 2021) and reduce gendered inequalities in care work (Pirklbauer and Wukovitsch, 2019; Gottschlich and Katz, 2023). Climate-friendly time policy (Reisch and Bietz, 2014) and care-oriented time policy (Heitkötter et al., 2009) focus on time as a lever for political design and a more equitable distribution of work between the sexes. Time policy can support climate-friendly lifestyles (Hartard et al., 2006; Rau, 2015; Schor, 2016) through reduced time pressure, deceleration, and reduced mental load that foster climate-friendly decisions in everyday life (Hofmeister and Mölders, 2021), green volunteering (Winker, 2021), substituting resource-intensive practices with time-intensive ones in many lifeworlds (Buhl et al., 2017), positive health co-benefits (APCC, 2019; Dengler et al., 2024), structural conditions such as reduced commuting through spatial, urban and transport planning (see Section 3.3.2), and temporal support for care work.

A more equal distribution of wealth and income, job-guarantees and public provisioning of basic goods (housing, food, mobility) can increase economic security and thus enable green labor market transformations as individual material consequences of switching jobs are reduced (Dukelow and Murphy, 2022; Lee and Koch, 2023) (*medium confidence*). The current coupling of income, social security, recognition, and participation in employment constrains the scope for climate policy (Hoffmann and Paulsen, 2020; Bohnenberger and Schultheis, 2021; Gerold et al., 2023). Therefore, measures to increase economic security during transitional phases, including an ecologically driven planned economic decline, include an unconditional basic income, greater self-sufficiency (Littig and Spitzer, 2011; Paech, 2012), or the provision of comprehensive services of general interest (Coote and Percy, 2020; Bohnenberger and Schultheis, 2021; Büchs, 2021; Gough, 2022; Bohnenberger, 2023; Rehm et al., 2023). An examination of public spending through the lens of gender and climate justice presents an opportunity to achieve emission reductions in the care sector (Schalatek, 2012). Time banks, for instance, show a potential to connect care work and employment, thereby creating more socially and climate-friendly working time quotas (Schor, 2016; Bader et al., 2021).

Climate mainstreaming is required in all dimensions of labor and social policy, including labor law and unemployment insurance (*limited evidence, medium agreement*). Although employment is an important element of climate policy (Seidl and Zahrnt, 2019; Bohnenberger, 2022a; Kreinin and Aigner, 2022; Gerold et al., 2023), work has not been a focal point for climate-friendly interventions. There has been a focus on (re-)education and green skills particularly in engineering and managerial skills (Vona et al., 2015, 2018; Vona, 2018) and action plans are being developed mainly for the energy transition (for Austria, see BMK (2023a) and for the global level, IRENA and ILO (2021)). For details on (re-)education and green skills needs in Austria, see Dorr et al. (2023) and AMS (2024). Climate-related knowledge and skills also increase legitimacy (Pichler et al., 2021). Re-education in climate-harming occupations carries the risk of lock-ins in unsustainable jobs (Bohnenberger, 2022a). It is more promising to provide reskilling and upskilling support for jobs in care, education, and resource-light sectors, where labor shortages exist. In addition, in many instances, special education and, consequently, an adaptation of the curricula is needed (Dorr et al., 2023; AMS, 2024). Brugger et al. (2024b) might provide one best-case example for the health sector. A complete shift to climate-friendly work systems requires a comprehensive transformation of work, as emphasized by literature on Just Transition (ILO, 2015; TUDCN, 2019); Sustainable Work (UNDP, 2015; Barth et al., 2016; Littig et al., 2018) and Post-Work (Frayne, 2016; Hoffmann and Paulsen, 2020). Greening work requires a structural change of welfare systems towards a sustainable welfare state (Bohnenberger and Schultheis, 2021; Bohnenberger, 2023; Hirvilammi et al., 2023), which is currently being considered within Austria's social security outlook (BMSGPK, 2024). This implies integrating climate mainstreaming across all sectors and institutions of social security (Bohnenberger, 2021), including unemployment insurance and employment policy, where initial approaches have already been developed for the Austrian labor market service (Neier et al., 2022, 2024; Smetschka et al., 2024a). Work not only structures daily lives and production processes, but is also subject to a wide range of laws and political conflicts (Smetschka et al., 2024a). Achieving a transformation of work through targeted policies thus requires critical reflection and consideration of related actors and institutions, including social partners, unions, employer associations, social insurance and social movements (e.g., women's rights movements) (Smetschka et al., 2024a).

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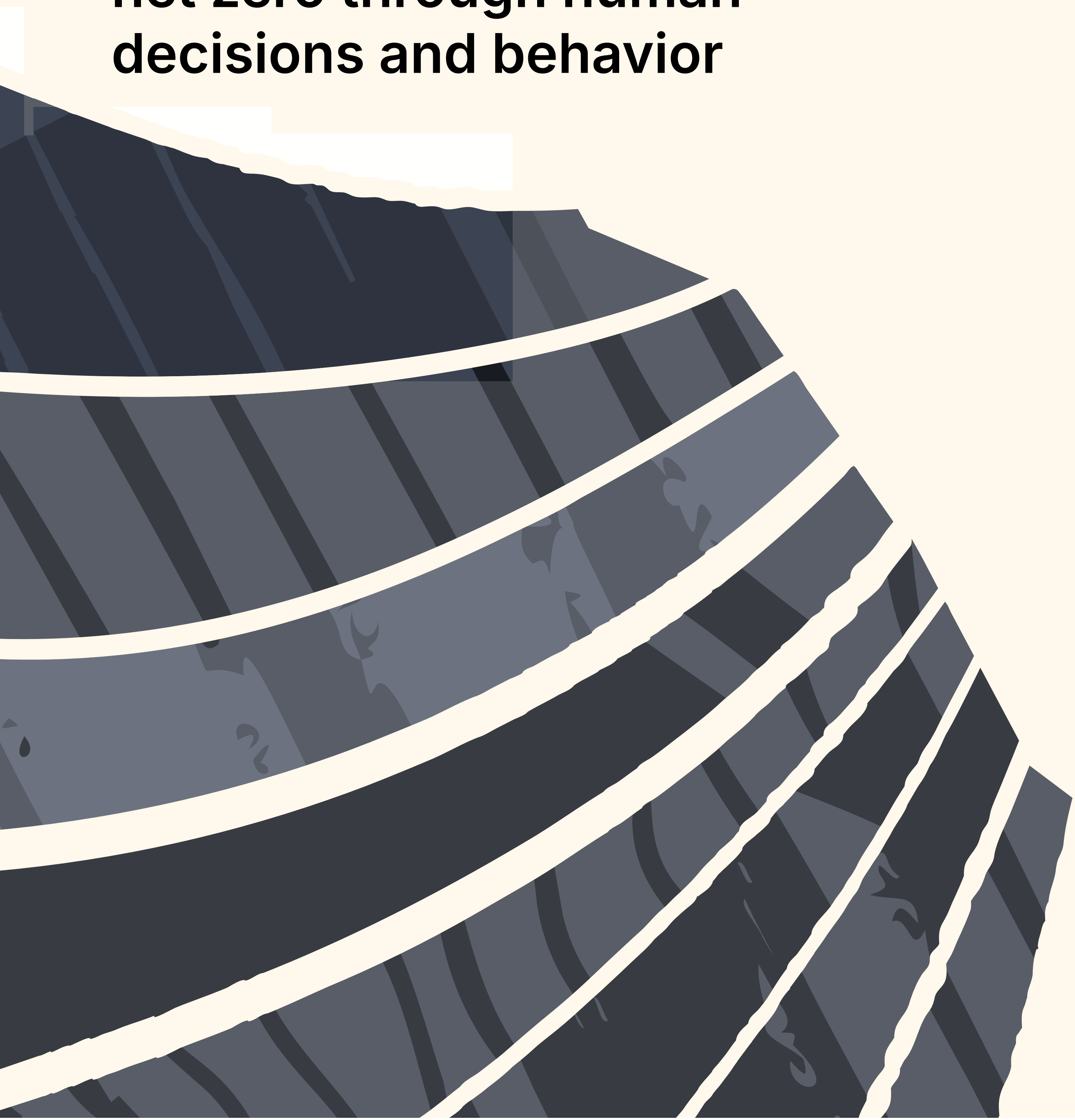
Chapter 5

# Navigating demand-side transformations to achieve net zero through human decisions and behavior



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## Chapter 5
## Navigating demand-side transformations to achieve net zero through human decisions and behavior

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## EXECUTIVE SUMMARY

**There has been strong societal climate concern and demand for climate action in Austria (*high confidence*) {5.6.3}. The social acceptability of policies strongly determines effective implementation (*high confidence*) {5.6.3}. Accompanying measures to alleviate fears of negative effects (e.g., 'Klimabonus' to alleviate fears of loss in purchasing power) as well as genuine societal engagement and co-creation approaches (e.g., civil consultation council) will yield fairer and more effective measures (*limited evidence, high agreement*). These measures together are likely to enhance the social acceptability of climate policies and remove barriers for changing lifestyles and consumption (*medium evidence, high agreement*) {5.1, 5.4, 5.6.3}.** Similarly, enabling factors for the circular economy include defining circular solutions as the default (positive lock-in), the use of enabling policy systems, such as strong information tools (e.g., labels), phasing out high-emission technology, and social pressure (*medium evidence, high agreement*) {5.5}. In addition, supporting renewable energy technologies, energy efficiency, carbon pricing and similar policy interventions designed to tackle climate change risks have uneven societal impacts. This raises the challenge of providing structural, long-term approaches that prevent any exacerbation of existing social inequalities and promote a fair and inclusive energy transition instead (*medium evidence, high agreement*) {5.3.4}.

**Demands arising from lifestyles and consumption are hard to change due to existing infrastructure (e.g., some locations lack railways or safe bike lanes) {5.3.3}, economic disincentives (e.g., subsidies for high-emissions products and services), and social norms (e.g., energy-intensive goods such as big cars or big living spaces socially rewarded as status goods) (*high confidence*) {5.3.1, 5.3.2}. Policy and infrastructure changes as well as cultural, behavioral and normative changes can increase the rate of emission reductions (*high confidence*) and can also facilitate adaptation to climate change impacts (*high confidence*).** Austrian consumption-based emissions are about 50 % higher than production-based emissions, with production-based emissions varying strongly across regions and consumption-based emissions across income (*high confidence*). Production-based emissions are lower in Austrian urban areas than in rural areas. However, whether urbanization leads to higher or lower consumption-based emissions depends on how cities are designed and the availability of climate-friendly consumption options {5.2.2}.

**Austrian households in the highest income decile cause substantially larger emissions than others (*medium evidence, high agreement*) {5.2.2}.** The top 20 % of Austrian households emit more than the bottom 50 %. Energy poverty vulnerability is particularly important and intertwined with a range of social factors, including unemployment, gender inequality, educational attainments, ethnicity, housing status, disabilities, and age. Notably, women are particularly vulnerable, largely due to factors such as the gender pay gap, their lower participation in the labor market, and the uneven distribution of caregiving responsibilities within families (*high confidence*) {5.3.4}.

**Firms, civil society organizations, and education organizations can foster behavioral change towards net-zero lifestyles by providing leadership and implementing change within their organizations (*medium evidence, high agreement*) {5.4}.** For example, collective action can constitute an important bottom-up component of both the energy transition (e.g., through the formation of energy or sharing communities) and adaptation efforts at the (local) community level. Collective action schemes have been demonstrated as being highly effective and stimulate wider and longer-term actions when certain identifiable pre-conditions are met for participation, organization and its embeddedness in broader policies. Crucial aspects include instilling a sense of community, empowerment, and trust that go beyond private gains and includes a broad range of participants; embedding collective action in complementary policies; and avoiding initiatives that are perceived as elitist and, therefore, create polarization and climate backlash in broader society {5.3.2}.

**Behavioral, lifestyle and consumption changes related to emissions not regulated under the EU ETS will likely entail stronger EU-wide reductions of emissions in the short term than changes related to emissions covered by the EU ETS (*high confidence*).** Thus, focusing on goals such as reducing the use of fossil fuels in home heating systems, making dietary changes, altering land use, etc. has a stronger short-term potential for emission reduction than tackling topics regulated by the ETS (e.g., switching to green energy providers, reducing flights within the EU) (*high confidence*) {5.1}. Once the EU ETS 2 becomes binding, equivalent comments can be made for emissions under that second carbon market within the EU.

**There are already numerous good examples of circular economy practices by citizens and businesses alike (*high confidence*) {5.5}.** These are framed by the adopted government strategy (BMK, 2022) based on international circularity concepts but are often not evaluated based on their effectiveness in reducing emissions (*medium evidence, high agreement*). Firms can be agents of change to support the net-zero transition: Austrian firms are already investing substantial funds to adapt to the negative effects of climate change and are making efforts to decouple their productivity from emissions {5.4.1}. Green-washing and other forms of information asymmetries undermine consumer efforts to shift consumption patterns in accordance with their pro-environmental preferences. Measures aimed at improving information for consumers and reducing exploitative practices by firms could enhance the share of climate-friendly products in the economy {5.4.1}. Circular Economy approaches promote change at the systems level, where consumers have a role to play, but where they can only achieve major results if regulations, material and ICT infrastructures support them (*high confidence*) {5.5}. Similarly, implementing circular economy solutions requires strong business solutions that drive this change (*limited evidence, high agreement*).

**The energy requirement to provide the so called 'decent living standards' (DLS) for all citizens in Austria for all critical dimensions implies an average energy demand per person per year of 32 GJ (*medium confidence*) {5.2}.** These standards include shelter of proper quality and temperature, sufficient mobility, the right quality and quantity of food, education, participation, and health services. This value falls on the upper end of the international range (9–36 GJ per person per year) and is equivalent to 15–30 % of the current total domestic energy consumption {5.2.1}. Austria has the leverage to reduce GHG emissions by adopting technology and reducing inequality (*high confidence*) {5.2.2, 5.3.4}, while maintaining service levels and reducing the emission footprint {5.2.2}. Policies, regulations, and technology standards targeted to lower rebound effects from technology adoption and promote digitalization to support the transition to the circular economy could enable stronger $CO_2$ mitigation objectives {5.5} (*high confidence*).

**Human responses to climate risks can amplify or reduce the expected impacts (*medium evidence, high agreement*) {Chapter Box 5.1}.** Disaster and crisis management plans, management plans for shortages of energy and natural resources, or extreme weather events can limit the expected impacts (*limited evidence, medium agreement*). Communication and compliance strategies of management plans must integrate behavior science principles to be effective (e.g., defaults for emergency notifications, support from role-models in society) (*high confidence*). These could build on the existing risk management structures (e.g., training courses as part of work safety on climate impact responses, local evacuation plans, early warning systems).

**Experts believe that the net-zero emissions system can be achieved in Austria by mid-century, because we have the necessary technology, resources, knowledge, and skills (*limited evidence, medium agreement*) {5.6.2}.** Regulations, technology standards, expansion of infrastructure supporting low-carbon lifestyles, incentives, and, in some cases, removing disincentives and including sanctions are needed to speed up the necessary changes and ensure a just and fair transformation process. Sharing knowledge about business and civil society forerunners, best-practice examples, and co-benefits for citizens can increase the public support for the process.

## 5.1. Chapter introduction

*Addressing the challenge*

Limiting global warming requires substantial transitions (Otto et al., 2020a) with rapid and deep emission reductions in all sectors to reach net-zero greenhouse gas (GHG) emissions by mid-century (IPCC, 2018; Doblas-Reyes et al., 2021). Austrian as well as global GHG emissions must decrease at rates of over 7 % per year. Responding to the challenges ahead of us requires a fundamental transformation in human behavior and lifestyles, infrastructure, energy supply, agriculture, and land use. To make low-carbon lifestyles attractive and preferred options for citizens, as well as to ensure the long-term effect of such changes, comprehensive structural changes are urgently needed in all areas of life (Aigner et al., 2023b). These cannot happen, however, without the support of society, individuals, communities, and different stakeholder groups. Therefore, different levels of analysis must be considered, ranging from those of individuals and social groupings to those of legal and governance frameworks, as well as the interactions between them. The assessment in this chapter places a focus on how to trigger social, demand-side change to create net-zero societies and addresses two main conceptual approaches.

We focus on the decision-making processes behind current choices and investigate the human dimension of the climate and energy system. As a complement to Chapters 1, 2, 3 and 4, which mainly address aggregate policy impacts and projections, we focus on the human decisions that generate such aggregate impacts. The need to satisfy people's demands for safe and comfortable shelter, mobility that allows them to work and participate, consumer goods and reliable lighting services, as well as access to essential public services, underlies the societal demand for materials and energy. These services, in turn, also satisfy higher human needs, such as for autonomy, mastery, and belonging. The levels and types of consumption determine the demand for resources, imply a provisioning system, and ultimately impact the climate and other environmental systems. As described in Cross-Chapter Box 3, technological and social innovations that lead to an improvement in the efficiency of service provision in response to Austrian demand can have multiplicative and cascading impacts. Chapter 4 describes the provisioning systems and solutions that have been developed to meet the demand for services and amenities, while Chapter 3 reviews the housing and mobility-related service, material, and energy demands. These, in turn, are driven by the human needs, lifestyles, and behaviors in society assessed in this chapter.

Second, climate change is generated by people; thus, the drive to reduce emissions and address adaptation to climate change impacts needs to come from people as well. People have different roles in societies, as citizens, but also as parts of households, larger communities, firms, governments, or NGOs (Creutzig et al., 2022b). Some individuals have very high agency as community leaders, opinion leaders in traditional or social media, or business and industry managers (Otto et al., 2020b; Hampton and Whitmarsh, 2023). All these entities are shaped by people and their individual or collective constructs (e.g., identities, values, norms). In this chapter, we cover the elements influencing decisions by households to decarbonize (Section 5.3) and the actors organized in different forms of firms (Section 5.4.1), organizations in higher education and research, NGOs, and activist groups (Section 5.4.2) or energy communities (Section 5.4.3). Governmental organizations have such idiosyncratic relevance that they are covered separately in Chapter 6. The order of these sub-chapters does not reflect a prioritized need to change regarding different actors or groupings. In Section 5.5, we put the different actors from 5.2, 5.3, and 5.4 together under an overarching conceptualization of the combined circular economy and sharing economy. We assess emission implications of inequality and wealth in society (Section 5.2.2), and finally we review socio-psychological factors associated with policy support, areas for social tipping and the social acceptability of decarbonization measures (Section 5.6).

Two approaches in particular shape our overall conceptual perspective, the integrative COM-B Model and tipping points. Some commentators contrast 'behavior change' and 'system change' and present a trade-off between these two perspectives on change. In this chapter, behavior change and system change present two complementary perspectives (United Nations Environment Programme, 2020). Research results highlight the interactions and feedback loops between individual choices and changes in the social structure, technology, and infrastructure. Taking an overarching perspective allows synergies to occur between top-down and bottom-up processes. We do not take an either-or perspective; instead, we posit that change happens at all levels of society from that of the individual to social to societal, using the framing of the COM-B model and social tipping points to describe these processes.

*Capabilities, opportunities and motivation for behavior change (COM-B model)*

The COM-B model describes proximal and distal factors that drive behavior (Michie et al., 2011). Proximal factors consist of (a) capabilities (C) that allow people to participate in an activity (e.g., knowledge or skills such as cycling), (b) opportunity (O) to engage in the behavior (i.e., external factors that enable the behavior such as access to a bike, safe cycle lanes), and (c) motivation (M) (i.e., automatic or reflective psychological processes that trigger behavior such as habits or values). The model also describes mechanisms of change in the form of interventions, such as education, modeling, incentivization and finally embeds this into systemic and structural change such as fiscal measures, regulation and environmental planning. We propose this model as background for the chapter because it is able to integrate analysis across different levels, from individual to societal while describing specific mechanisms of change.

*Social tipping points*

Another key framework is that of social tipping points, which describes how social norms, behaviors, and technologies can spread rapidly from a minority group to the majority of society (Tàbara et al., 2018; Farmer et al., 2019). A tipping point in both social and natural systems refers to a critical threshold in the system control parameter. Once this is exceeded by a small amount, the factors mentioned above can influence a crucial system feature of relevance. This leads to qualitative change in the system once a reference time has passed, allowing for the emergence of the effect (Lenton et al., 2008). Tipping points are related to the existence of multiple stable states. Systems can transition between these, implying that it is difficult to push the system back to the previous state once a new stable state has been achieved (Winkelmann et al., 2022). However, not all rapid changes lead to systemic change. In the literature, the term 'tipping elements' is used to refer to system components where rapid change is possible and that can push the evolution of the entire system to a new, qualitatively different state (Lenton et al., 2008). Social tipping can involve both desirable and undesirable dynamics (Stadelmann-Steffen et al., 2021). One important research question is how such rapid change dynamics can be used to navigate human societies toward the net-zero emissions system. Otto et al. (2020a) proposed that social tipping interventions could be solutions leading to rapid and deep systemic transformation. This process involves targeting sensitive intervention points (Farmer et al., 2019) and leverage points, which indicate places where intervention in a complex system is possible and where a minor shift in one thing can produce big changes in everything else (Meadows, 1999).

In an expert elicitation process, scientists and stakeholders were asked to scope interventions in Austria that have the potential to activate a systemic tipping process, thus reducing GHG emissions at the national level. The results of that exercise are presented in Section 5.6.

*Demand-side solutions and the EU Emissions Trading System (ETS)*

One point that deserves special attention in this introduction is the varied relevance of demand-side solutions to different sectors, depending on their coverage under the Emissions Trading System (ETS) in the EU. Reductions of emissions in sectors currently under the EU ETS[1] will not reduce the overall cap of the emission market. It will simply reduce the price of the emissions in the market, which will be then traded and used elsewhere in the economy, either within Austria or another EU country. Thus, to create more effective, short-term impacts on aggregate EU emissions, it is more effective to address elements that do not fall under the jurisdiction of the ETS system. These elements include direct oil consumption (e.g., heating in households, public buildings or firms, and road transportation with combustion engines) and impacts of dietary changes (e.g., increasing plant-based food or reducing the consumption of beef). For the elements that do not fall under the ETS system jurisdiction, any emission reductions are translated directly to emissions that are avoided. For the elements that do fall under the ETS system jurisdiction, only the reduction in the cap defined by the EU Commission (and, therefore, the associated number of polluting permits) entails a reduction in aggregate emissions. While the EU Commission might be more inclined to reduce the cap of the ETS for lower aggregate emissions under the trading system (and thus lower permit prices), as considered in the Market Stability Reserve, estimates suggest that 1 ton of additional abatement under the ETS could lead to a net long-term emissions reduction of as little as 0.4–0.8 tons (Perino, 2018), even if large uncertainties remain (Perino, 2019; Rosendahl, 2019).

[1] i.e., electricity and heat generation, industrial manufacturing and aviation sectors. See Chapter Box 6.1 for more details on the sectors currently covered under the ETS as well as sectors planned to be covered under the ETS2.

This has led to calls for policy mixes to achieve more ambitious progress for emissions under the ETS (Flachsland et al., 2020; van den Bergh et al., 2021). The changes made in Phase 4 of the EU ETS, introducing the Market Stability Reserve, and policies complementing emission abatements with those in the EU ETS, such as those supporting renewable energies, carbon taxes, energy efficiency measures and voluntary abatement efforts, are reducing the number of allowances issued in the long run and thus reducing total emissions (even if this is probably not on a 1:1 basis). More broadly, one could expect that having households and firms shifting to decarbonization will facilitate the political and social acceptability of more ambitious climate policies, which are discussed in further detail in Chapter 6.

*Carbon pricing and societal fairness*

At least in the short and medium term, further increases in energy prices are expected as a result of reductions in the total number of allowances planned by the EU ETS. These contribute to meeting the net-zero emission objective for 2050. These expected increases, as well as the crucial importance of fairness and people's perceptions of fairness, justify the introduction of the topic of social inequalities in energy supply in this chapter. Energy efficiency measures by households and firms are still highly relevant for climate policy. The social and political feasibility of an ambitious climate policy is challenged in a (likely) scenario involving higher energy prices (at least in a transition period), and more generally when higher prices for carbon-intensive products and services are expected (see also Chapter 4, esp. 4.5). How well households and businesses are prepared to increase their energy efficiency will determine how 'painful' higher energy prices will be for medium-term welfare and prosperity, as illustrated by the higher energy prices we experienced in 2022 due to the Ukrainian war. (In-) equalities are naturally a much broader relevant topic in the context of climate impacts, mitigation and adaptation measures, and are addressed in Section 5.2 on well-being. Some of the hesitancy to implement ambitious climate policies is related to the impacts that these could have on well-being and distributive issues, and particularly regarding impacts on disadvantaged households.

*What can be done, starting today?*

This chapter puts a special emphasis on a pragmatic view of how to foster social transformations to achieve net-zero emissions, *starting from* the current set of infrastructure (and technology), social norms, and laws. This means seriously considering the social and political acceptability of policies. Changes in social norms, infrastructures, services and regulations can 'unleash' people, as well as construct new preferences and values (Sunstein, 2019; Aigner et al., 2023b). Unleashing entails that what once was unsayable is said and what was once unthinkable is done. The emergence of new preferences and values takes us into a domain where more progress towards net zero could take place. And these preferences and values can be measured to evaluate our progress towards some of the transformative scenarios described in Chapter 8, which place Austrian society within the threshold of the new climate boundaries.

Finally, this chapter assesses the state of knowledge on how we can encourage people, firms, and other organizations to change their climate-relevant behavior, moving beyond the more conventional policy prescriptions of taxes and command-and-control. It thus describes an accompanying set of policies and broader measures that can be developed to reduce climate impacts and prepare people for less painful decarbonization processes, but still protect both people's right to free choice and well-being, maximizing social fairness and co-benefits.

## 5.2. Well-being and inequality related to climate mitigation and adaptation

Universalizing climate-friendly living requires reassessing the way local, regional and global systems operate for society, the economy and the natural environment. In line with the novel chapter of 'Demand, services and social aspects' in the IPCC AR6 (Creutzig et al., 2022b), we use the well-being and provisioning perspective to frame the human-side of climate mitigation and adaptation.

Well-being for all and reduced inequality within planetary boundaries is attainable through implementing a system-wide demand-side transformation that also achieves climate mitigation and adaptation (Oswald et al., 2020; Creutzig et al., 2022b) (*medium confidence*). The APCC Special Report on Climate-friendly Living connected the social sciences, norms, cultures and individual behavior with technology, infrastructure and structural set-up to assess the opportunities and drivers of climate-friendly living using four perspectives that show different aspects of the dimensions of change (Aigner et al., 2023a). (1) The *Market perspective* builds on the polluter pays principle and getting prices right to achieve decarbonization through market forces (*high con-*

*fidence*). Climate friendly choices become attractive when they become default and cheaper than the climate-harmful option. However, non-rational behavior and just climate transition are not well explained (Corvino, 2023) (*robust evidence, medium agreement*). (2) The *Innovation perspective* acknowledges the value of – mostly radical – innovation not only for technology, but for society, infrastructure, business models, among others. It also calculates with exnovation, i.e., elimination of harmful solutions (*high confidence*). For example, Mock (2024) explains the need for exnovation of car-based transportation to enable climate-friendly mobility system, e.g., in Austria (see Section 3.4). She explains the normative orientation underlining the SDGs, minimum thresholds (such as the decent living standards), as well as pledged targets and principles that mandate climate-friendly or socially beneficial solutions. (3) *The Provisioning perspective* assumes basic or fair needs to be provided with increased efficiency. Efficiency increase can originate from a multitude of sources, such as technical, organizational or behavioral improvements to provide the same or improved services as before to establish climate-friendly solutions (Grübler, 1998; Rao and Min, 2018a; Saunders et al., 2021) (*high confidence*). (4) The *Society-Nature perspective* uses knowledge on the intertwined co-existence of human and biophysical systems. Any change in one will directly affect the other.

In this section, well-being and climate-friendly living conditions are assessed mainly along the provisioning systems perspective (linking closely with the framework drawn in Chapter 4, Figure 4.1), to assess how to achieve a good and satisfied life that is within sufficiency levels without compromising well-being so that the provisioning leads to a reduction of the climate pressures.

### 5.2.1. Welfare, well-being and decent living

Policies are expected to benefit society and thus to take into account the effects on the well-being of all (Ilmola-Sheppard et al., 2020; Kikstra et al., 2021). The traditional approach to ever increasing economic growth, productivity and higher incomes is overturned by realizing that these do not directly lead to life satisfaction (Vogel et al., 2021). Using the provisioning systems perspective, the ultimate goal of ensuring well-being and increasing equality should be achieved with levelized services of high quality. Providing these material services is linked to drastically lower energy and resource demands, the transformation of service provision will have positive environmental, social and economic consequences.

#### Well-being and welfare perspectives and measures

Well-being definitions and metrics are diverse to capture multiple facets of the concept (see Lutz et al., 2021 for an overview), of which only a few are mentioned here. Hedonic and eudaimonic approaches of well-being (VanderWeele, 2017; VanderWeele et al., 2020) relate to different ways to achieve satisfaction. In the hedonic approach, well-being is linked to positive affect (hedonic happiness)[2] or life satisfaction (evaluative happiness) (e.g., Diener et al., 2018; Stone and Krueger, 2018; Krekel et al., 2020); whereas the latter describes whether an individual has the capability towards self-realization and full functionality. Hedonic concepts relate to what economists would describe as utility (Jones and Klenow, 2016) – and can thus be understood to be outcome-oriented, whereas eudaimonic concepts are often based on capabilities (Nussbaum and Sen, 1993) or needs-satisfier relationships, using dimensions or standards of life provisioning, as in the decent living standards (DLS) (Doyal and Gough, 1984; Max-Neef, 1991; Gough, 2015; Rao and Min, 2018a). There is an expectation to measure well-being to show changes and relationships, e.g., with climate change or climate mitigation. The indicators and indices range from measuring objective aspects, such as the physical and social satisfiers that enable a good life, to focusing on subjective aspects, including perceived functions, feelings and an evaluation of satisfaction (subjective well-being). Establishing the bidirectional relationship between well-being and climate impacts is highly necessary. Objective elements of well-being can be linked more directly to GHG emissions by assessing the amount of energy and resources to satisfy basic, acceptable or sufficient levels of needs and wants. Through them, it is possible to assess the mitigating outcome of improving service provision. The metrices are compared in Figure 5.1, indicating Austrian relative performance compared to the most comprehensive region available (e.g., World, OECD) for each measure.

- **OECD Better-life framework: 'How's Life?'** (OECD, 2020) covers both inputs of material conditions (e.g., income, employment, housing) and outcomes such as health, education, work-life balance, political governance, civic engagement, social engagement, personal safety as well as subjective well-being. According to these

[2] Note that hedonic and eudaimonic have a different meaning from how they are used in psychology.

measures Austria outperforms the average in jobs, health, environmental quality, social connections, safety and life satisfaction.

- **Statistik Austria (2021): 'Wie geht's Österreich 2000–2020'** (Wegscheider-Pichler et al., 2021) is similar to the OECD Better-life framework and covers material aspects, quality-of-life aspects (including measures of subjective well-being) and environmental aspects of well-being.
- **World Happiness Report** (Helliwell et al., 2023): For the time frame 2020–2022, Austria scores 7.097 on a 1–10 scale, ranks 11/137 (95 % c.i. for rank 8–15) (Helliwell et al., 2023, fig. 2.1), exhibits a happiness gap (top vs. bottom half of population) of 2.653 and thus ranks 18/137 (95 % c.i. 9–33) in ascending order of the gap (Helliwell et al., 2023, fig. 2.2).
- **Subjective Wellbeing Index** (Ivanović et al., 2022): Based on the Subjective Wellbeing Index (SWB), Austria is experiencing a high (and highest ranking) level of well-being amongst Central European countries (~6 % above the CEE average) and has experienced an increase across both rural and urban areas between 2008 and 2018.
- **Years of Good Life (YoGL)** (Lutz et al., 2021): The YoGL indicator combines life satisfaction and health, cognitive functioning, out of poverty aspects of well-being with age-gender-education specific life expectancy. By counting expected life years for which minimum levels of all well-being indicators are met, YoGL is a measure of remaining 'good' lifetime. Backcasting methods show that YoGL in Austria at age 20 has increased from around 34 (36) years for men (women) in 1950, to 51 (50) years in 2015 (Striessnig et al., 2021). This places Austria somewhat at the lower end of values experienced in other highly developed countries but high above the global average. Cast against the respective levels of total life expectancy, this implies that while 64 % (73 %) were spent in good life in 1950, these shares increased to 80 % (85 %) in 2015.

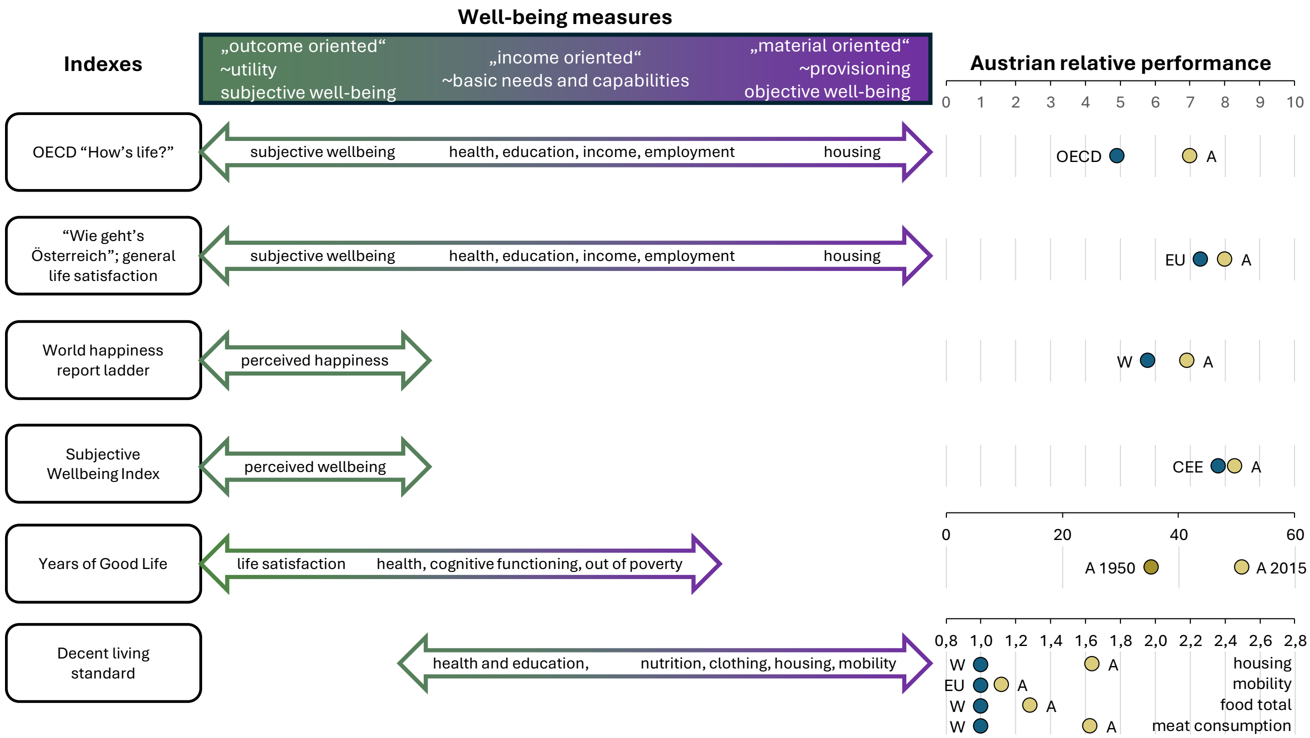


**Figure 5.1** Overview and comparison of well-being measures and indexes. The left panel depicts the content of the well-being indexes in terms of their coverage of subjective (left) to physical, i.e., objective (right) provisioning. On the right panel the values for Austria are contrasted to the largest comparable reference region for which data is available. Note that the decent living standards dimensions are presented in physical terms here, in terms of floorspace per capita for housing, motorized passenger-km per year for personal mobility, kilocalories (kcal) for full daily food intake and for meat consumption per person per day. A: Austria, OECD: Countries of the Organization of Economic Cooperation and Development, EU: European Union, W: World, CEE: Central Eastern European countries (Source: Own compilation using data from: Rao et al., 2019; Millward-Hopkins et al., 2020; OECD, 2020; Lutz et al., 2021; Wegscheider-Pichler et al., 2021; Ivanović et al., 2022; Helliwell et al., 2024).

- The **decent living standards (DLS)** framework is a basic universal basket of satisfiers to ensure a minimum, but not affluent quantity and quality of nutrition, safe shelter with minimum space and thermal comfort, sufficient and in-house water for drinking and basic ablutions, improved sanitation, lighting, clean cooking fuels, cold storage, access to the internet and broadcast media, and the use of motorized transport, including public transit, access to health care and education to support both physical and social well-being (Rao and Min, 2018a; Rao et al., 2019; Millward-Hopkins et al., 2020). While DLS dimensions are a set of finite satiable human needs that are universal, the number of resources and energy to provide these needs have geographical (e.g., colder climate), cultural (e.g., local dishes), norm (e.g., transport mode), and personal (e.g., being an introvert or extrovert) aspects (*high confidence*). The energy needed to ensure DLS for the whole population of Austria is much smaller than the current final energy demand, between 15–30 % per capita energy demand in 2023 (Millward-Hopkins et al., 2020; Kikstra et al., 2021). This indicates that providing everyone with basic well-being is possible with significantly lower environmental impact, while the beyond-DLS emissions provide more affluent or even superfluous lifestyles (see also Section 5.2.2).

Altogether, this evidence speaks to Austria scoring high on most well-being measures and dimensions on a global measure but with some variability in 'performance' as compared to other (European) countries with similar levels of development, and sizeable socio-economic inequality in some of the measures (*high confidence*).

### Impact of well-being improvement on climate change

Technical energy efficiency (in energy per GDP) has been increasing in all global regions since at least the year 2000, as has the per capita energy intensity in most of the regions (except for Latin America and the Middle East) (Saunders et al., 2021). In Austria, energy efficiency measures have saved 1.73 Mtoe energy in the residential housing sector and 0.74 Mtoe in transport over the last 20 years (2000–2021). In spite of other drivers (e.g., numbers and sizes of homes, more appliances, and more travel), modal splits have counteracted some of these savings, leading to an overall total increase in energy demand since 2000 and rather stabilized in recent years (Odyssee-MURE, 2024) (see Section 4.2.1). To provide a comprehensive framework for assessing the impacts of energy transitions on well-being, Köppl and Schleicher (2018), Schinko et al. (2021), and Sommer et al. (2021) developed a functionality approach relating energy services to the satisfaction of human needs (functionalities: Shelter, access to people, goods, services and places, and forms of other life support). At the same time, this approach was amenable to an economic general equilibrium analysis. Bachner et al. (2021) applied this approach in a study on the implications of a net-zero transition scenario by 2050 on the well-being of people in Austria. They found that well-being was enhanced in the scenario, although conventional economic indicators, such as the GDP, could potentially deteriorate.

Austrian citizens on average have access to well above the so-called 'basic levels' of the physical and societal dimensions of the decent level standards (Figure 5.2). As described in Section 4.2.2 material provisioning systems in Austria have the potential for sufficiency, efficiency and infrastructural transformation (see Section 5.3.3 for the latter) to provide well-being. According to a growing body of literature, human needs steadily decouple from energy or resource demands (Steinberger and Roberts, 2010). Beyond a certain energy level (a global average of 60 GJ per person or 1 $tCO_2eq$ in 2005), development indicators such as the Human Development Index and specific indicators, such as life expectancy, literacy, schooling do not increase much, i.e., reach a plateau (Preston, 2007; Steinberger and Roberts, 2010; Akizu-Gardoki et al., 2018, 2020). Although Austria has also started to decouple well-being from energy consumption mostly due to technology improvements, when considering embedded energy, the process is not steady and smaller than in most European countries (Akizu-Gardoki et al., 2018). Changes in lifestyle and sufficiency could close these gaps in Austria, which does not lead to constraints in well-being and benefits. In line with the reduction of the combined private and public floor space per person in an enhanced environmental (strong circular economy) scenario (Section 4.2.2), the WAM scenario ('With Additional Measures') of the 2020 National Building Renovation Plan of Austria (OIB, 2020) with further sufficiency measures (Alaux et al., 2024a), assumes a reduction of residential floor space from 46 $m^2$ in 2023 to 44 $m^2$ in 2050. Also in mobility, the Austrian 2030 Mobility Master Plan considers sufficiency as one of the three principles of Austria's future mobility system (BMK, 2021). The energy required to ensure DLS (see previous subchapter) in Austria means a minimum of 32 GJ final energy per person per year on average, which is at the upper end of the international range (9–36 GJ per person per year). DLS for all in

Austria requires no more than 15–30 % of the current total domestic energy consumption. In terms of material footprint of DLS, the international range is 3–14 tons material flow per person per year, while direct and indirect stocks are on average 32 and 11 tons per person, respectively (Vélez-Henao and Pauliuk, 2023). Austria has the leverage to reduce GHG emissions by adopting technology and reducing inequality (*high confidence*) (see Sections 5.2.2 and 5.3.4), while maintaining service levels and reducing the emission footprint (see Sections 5.2.2).

However, there are still vertical and horizontal inequalities that may suffer from a lack of adequate provision of many of the services. The latter refers to inequalities between individuals or households within a group (discussed, for example, in Douenne (2020) and Nabernegg (2021)). Statistik Austria has shown that in 2022, households with lower incomes were exposed to above-average energy costs in their homes (Statistik Austria, 2024a, 2024b), thus at risk of not even reaching DLS in the heating dimension. Vertical inequalities are inequalities between groups, such as people of different genders or ethnicities, who share a common identity, background, circumstance. Laa et al. (2022) find that organizing and financing public transportation in rural Austria remains a challenge. Eisfeld and Seebauer (2022)

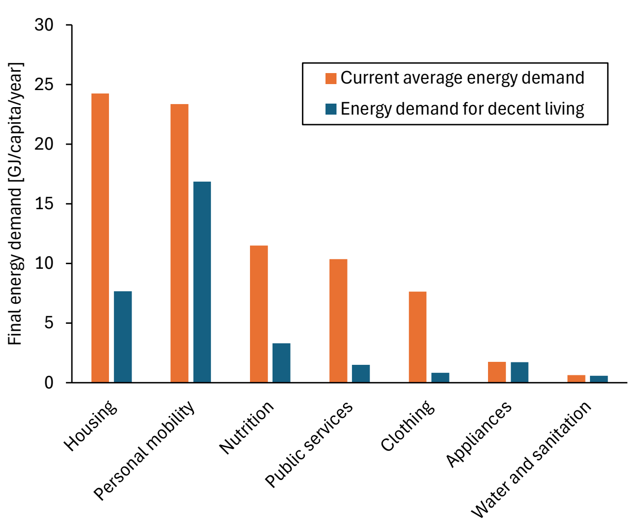


**Figure 5.2** Comparison of the final energy demands per capita per year to satisfy the decent living standards (DLS) along key dimensions. Blue columns show the energy demand required to provide the minimum services of DLS for all in Austria, as opposed to the average level of current services derived from statistics and surveys, assuming the same Austrian technological and structural intensities. Intensities include operational and life-cycle energy based on public data (Source: BMK, 2016; Kikstra et al., 2021; Statistik Austria, 2021b; European Environment Agency, 2023; Central Intelligence Agency, 2024; European Commission, 2024).

identified self-restricting populations to compensate their inability to pay for appropriate heating and cooling, noting large heterogeneity in the 'decent levels' across dimensions (e.g., regionally, urban/rural divide, income levels, and other social factors). However, when considering the level of provision of a 'good life' (i.e., beyond the basic and universal decent living standards), the energy and material needs are much higher.

The provision of health, education, and other public services at higher levels is associated with the higher achievement of well-being than the provision of other functions (Vogel et al., 2021).

### Impact of climate change on well-being

There is a broad consensus among scientists that climate change impacts (and climate policies) affect the well-being of individuals and communities (Fleurbaey, 2009; Stiglitz et al., 2018; Rao and Wilson, 2022; Dang et al., 2024) (see also Section 6.8) through extreme weather events, such as heat waves and floods, as well as through gradual changes, including those in European countries. Such impacts occur both due to material (income) losses and changes in health and, importantly, mental health. These are captured by direct measures of well-being such as life satisfaction. In the following, we assess evidence for the impacts of climate change on health, mental health, and well-being (see also Cross-Chapter Box 2); the economic impacts are assessed in Chapter 4. We emphasize the severe lack of evidence for Austria and, therefore, draw on international evidence placing focus on European countries.

**Health:** There is high level of agreement that climate change poses a severe threat to population health (e.g., Ebi et al., 2021; Romanello et al., 2021; Hensher, 2023), thereby greatly increasing the social costs of carbon (Bressler, 2021; Bressler et al., 2021) and the direct health care costs (Khan et al., 2016), with only limited scope for adaptation (Deschênes and Greenstone, 2011; Barreca et al., 2015, 2016; Bressler et al., 2021) (*medium evidence, high agreement*). Impacts occur through several channels and most notably temperature increases and extreme heat events (Gasparrini et al., 2017; Karlsson and Ziebarth, 2018; Bressler et al., 2021; Vicedo-Cabrera et al., 2021; Adélaïde et al., 2022; Masiero et al., 2022), pollution (but to a lesser extent in industrialized countries) (Fuller et al., 2022), flood risks, impacts on nutrition through higher food prices and food security (Lake et al., 2012), neonatal health (Cil and Kim, 2022; Palma et al., 2022), chronic diseases (Vandenberghe and Albrecht, 2018), new vector-borne diseases, and violence (Otrachshenko et al., 2021) (see also Cross-Chapter Box 2); and these impacts may compound over time due to reductions in individual and institutional capacity for adapting further (Borghi and Kuhn, 2024).

**Mental health:** Mental health impacts of climate change can appear in the form of post-traumatic disorder and anxiety in response to losses experienced during (repeated) extreme events and as a result of the more gradual accumulation of climate anxiety or the (negative) impact of change on other socioeconomic determinants of mental health (e.g., income, access to affordable goods and services, limited uncertainty). The latter shows a strong socioeconomic gradient (Fritze et al., 2008; Hrabok et al., 2020; Lawrance et al., 2022) (*high confidence*). Mental health impacts on adolescent and child populations, both in response to traumatic events (Ma et al., 2022) and general climate anxiety, have been demonstrated for high-income countries (Hickman et al., 2021; Martin et al., 2022). A supportive parenting style, family and social support, and especially peer group and school support have been found to be protective, but significant variance in the context and circumstances has been observed (*high confidence*). There is evidence that the effects are cumulative, but findings on whether these impacts occur in childhood are mixed (McBride et al., 2021; Vergunst and Berry, 2022). Further evidence shows that climate anxiety is widespread among scientists (Head and Harada, 2017).

While climate or eco-anxiety and eco-depression have been associated with lower mental well-being, these factors may also affect people's motivation to engage in pro-environmental behavior and activism, with conflicting results reported for eco-anxiety (Stanley et al., 2021; Ogunbode et al., 2022). In contrast, climate anger is positively correlated with both well-being and climate action (Stanley et al., 2021). The relationships are shaped by the context, with GDP having a positive effect on the relationship between climate anxiety – pro-environmental behavior and climate action – and personal experience, media, and social norms having more mixed effects (Ogunbode et al., 2022). The role of coping and coping styles is crucial here (Clayton, 2020). See also Cross-Chapter Box 2.

**Human capital accumulation:** Some evidence is available that heat exposure inhibits educational outcomes and, thus, cumulatively inhibits the accumulation of human capital as an important source of well-being in both low- and high-income countries (Graff Zivin et al., 2018, 2020; Park et al., 2020, 2021; Park, 2022). These effects can be mitigated by changing school infrastructure (air conditioning) and are disproportionately more evident in disadvantaged areas (*high confidence*).

**Subjective well-being – life satisfaction and happiness:** Evidence shows a positive impact of environmental amenities and a negative impact of temperature, pollution, and climate impact at aggregate (national) levels. However, impacts vary by local circumstances; for example, pollution impacts do not show a significant impact in London, while amenities do (Krekel et al., 2020, and studies reviewed therein).

### Trade-offs, synergies, and co-benefits related to the energy and mobility transition

**Impacts of a transition on well-being:** There is a broad consensus that climate change mitigation and the ensuing life-style changes (e.g., in food or mobility) have important co-benefits at the local level, increasing well-being as measured based on objective material constituents (Creutzig et al., 2022a) or improvements in health or mental health (e.g., Chang et al., 2017; Deng et al., 2018; Gao et al., 2018; Karlsson et al., 2020) (Cross-Chapter Box 2) (*high confidence*). Estimates of the value of co-benefits are high. In simulation studies, these can offset large parts of mitigation costs and/or justify the use of stringent climate policies (for lower air pollution in Europe, see Schucht et al. (2015); globally, see Scovronick et al. (2019); for dietary change globally, see Springmann et al. (2016)). Many of these co-benefits can be viewed through the lens of SDGs (see Section 8.3.1). Evidence is insufficient (and, thus, of *low confidence*), however, for the social dimensions of well-being, personal security, social cohesion, and political stability (Creutzig et al., 2022a). A parallel large body of evidence exists that pro-environmental behavior is associated with higher subjective measures of well-being (Zawadzki et al., 2020). The positive impact on well-being is thus broadly robust to the measure and can be of *high confidence*. Nonetheless, transition measures at a local level, such as the introduction of wind parks, can result in lower well-being and opposition (e.g., Pohl et al., 2018, 2021). This issue calls for enhanced planning, communication, and local stakeholder involvement (e.g., Friedl and Reichl, 2016). Finally, Mock et al. (2019) provided case study evidence for 11 environmental initiatives from five European countries, including Austria, demonstrating a positive impact of collective environmental action on psychological well-being.

**Energy-service perspective and role of public services:** Any far-reaching energy transition will imply major restructuring of infrastructures and, in many cases, a shift from private to public services. This implies that any evaluation of transformative measures should not be carried out by comparing individual measures/policies with a given nexus of service provisioning but should instead account for a change in the whole nexus. For this purpose, it is useful to think in terms of categories of energy or transport services rather than of specific means of energy consumption or modes of transport (Sovacool, 2011; Fell, 2017; Grubler et al., 2018) (see Section 4.2). The transition of the infrastructures underlying energy or mobility services must ensure coherent and comprehensive access to these services across space, time, and system boundaries, as well as inclusive access across all strata of the population. Such systemic interventions are expected to have positive impacts on well-being. Kletzan et al. (2006) describe these impacts for mobility and heating in Austria; Mathiesen et al. (2015) for smart energy grids; Steg and Gifford (2005) and Lucas et al. (2007) for transport policy scenarios in the UK; Steininger and Bachner (2014) for commuter car-sharing in Austria; Cloutier et al. (2017) for sustainable commute in US cities; and Buehler et al. (2019) for integrated urban-rural public transport systems in Austria, Germany, and Switzerland. This initial evidence would need to be corroborated (*limited evidence, high agreement*).

**Energy security improvement with energy demand reduction:** Energy security is a top priority for Austria because of the high dependence on imported energy. Disruptions due to wars, economic conflict, climate change, and price surges can threaten the long-term and the short-term provision of energy and related critical functions. As described in Chapter 4, Bento et al. (2024) showed that demand interventions, such as building renovation and electrification of mobility are more impactful than conventional supply-side approaches, such as fuel substitution or import diversification, in Germany, Spain and other countries studied.

There is considerable complementarity in the design of service provisioning systems and infrastructures for enhancing well-being. This allows for the potentially high leverage of joint and consistent adaptations to these systems, but also heightens path dependency and underlines organizational and budgetary challenges. This is because coordination across different government domains is required as well as single, major transformations besides incremental improvements, which are both challenging (see Section 1.4). A related topic is the need for systems to be designed coherently to meet the needs of all population strata in both urban and rural communities (Pearsall et al., 2021). High income populations ensure their well-being with unproportionally large energy and material footprint, as opposed to public, easily accessible infrastructure (evidence for the United Kingdom, Baltruszewicz et al., 2023).

A broad and large-scale energy system transformation offers an opportunity to redesign public services and welfare systems in other areas than energy, for example changes in the healthcare, education, urban development, water provision systems and many others that will be affected directly or indirectly (Weisz et al., 2020 for Austria; Hensher, 2023).

### 5.2.2. Socio-economic implications for emission footprints

Understanding the distribution of GHG emissions among different actors and entities is relevant (i) for deriving the respective emission responsibilities, potentials, and targets for emission reductions, as well as (ii) for designing policy interventions.

Austria's territorial per-capita emissions are slightly above the EU-27 average and substantially above the global average (Umweltbundesamt, 2022b). Unlike territorial (production-based) emissions, GHG footprints (consumption-based emissions) do not take into account emissions from the economic activities of a specific entity. Instead, they consider the emissions from the final demand of this entity (Steininger et al., 2016b) (see Section 4.1.1). Austria's GHG footprint is about 1.5 times larger than its territorial emissions, because the emissions embodied in imports exceed the Austrian emissions embodied in exports (Muñoz and Steininger, 2010; Giljum, 2018; Steininger et al., 2018; Nabernegg et al., 2023) (*high confidence*). Furthermore, national policies are available that address not only territorial emissions, but also consumption-based emissions (Steininger et al., 2018; Nabernegg et al., 2019) (*limited evidence, high agreement*). In terms of a global safe and just operating space for GHG emissions, Austria exceeded its fair share by a factor of 3.4 in 2015 (Fanning et al., 2022; University of Leeds, 2023). Furthermore, current emissions can be compared with a remaining Austrian GHG budget (see Section 8.2). If the Austrian emissions continue to be produced in the future as they were in 2022, the Austrian GHG budget that enables it to stay within a 1.5°C warming range without a temperature overshoot and to have a 66 % probability of reaching the target would be exhausted by mid-2025 (CCCA, 2022).

At the regional scale, territorial emissions vary considerably between Austrian federal provinces, ranging from 4.2–14.5 $tCO_2eq$ per capita in Vienna and Upper Austria, see Figure 5.3a (Umweltbundesamt, 2022a). This is mainly determined by the level of emission-intensive industrial production in the region. In contrast, GHG footprints are more evenly distributed across the provinces, as consumption patterns do not differ substantially between these regions (Muñoz et al., 2020). The most relevant differences identified by Muñoz et al. (2020) concern direct household emissions from transport and heating, which are linked to the degree of urbanization in each region (see also Chapter 3).

At the global level, the relationship between urbanization and GHG emissions depends on each country's development stage, with urban areas in low- to middle-income countries displaying higher per-capita emissions, while urban areas in high-income countries are often associated with lower per-capita emissions than rural or suburban areas (Lwasa et al., 2023). While urban areas may provide services such as housing and mobility with less energy (see Section 3.2), urbanization may increase income and consumption levels, which are associated with emissions (Jones and Kammen, 2014). Whether urbanization leads to higher or lower emissions, therefore, depends on how cities are designed and what climate-friendly consumption options are available to the citizens (Lwasa et al., 2023).

In Austria, evidence shows that cities have lower territorial per-capita emissions, for example, for Vienna and Graz compared to the Austrian or federal-province average (Pichler and Steininger, 2019; Stadt Graz, 2022; Umweltbundesamt, 2022a; Nabernegg et al., 2023). However, territorial emissions in Linz are an order of magnitude higher than the national average due to large, emission-intensive industries within the geographical city borders. Regarding GHG footprints, these patterns are less clear, as a study on Vienna indicates that this city has a lower GHG footprint than the Austrian average (Eisenmenger et al., 2022), while the footprints of Graz and Linz are estimated to be above the Austrian average (Pichler and Steininger, 2019; Stadt Graz, 2022; Nabernegg et al., 2023).

Emissions are also unequally distributed across individuals and households with different incomes. At the global level, income and emissions are strongly correlated (Bruckner et al., 2022; Chancel, 2022). Chancel (2022) estimated that "the bottom 50 % of the world population emitted 12 % of global GHG emission in 2019, whereas the top 10 % emitted 48 % of the total". Although a relatively small group of high-income individuals is responsible for a substantial share of emissions, researchers have largely focused on low-income groups when determining the impact of poverty reduction on emissions (Hubacek et al., 2017; Rao and Min, 2018b; Bruckner et al., 2022) or the impact of climate policies on low-income households (also see Section 5.3.4). Evidence for the GHG footprints of high-income individuals is largely lacking (Otto et al., 2019).

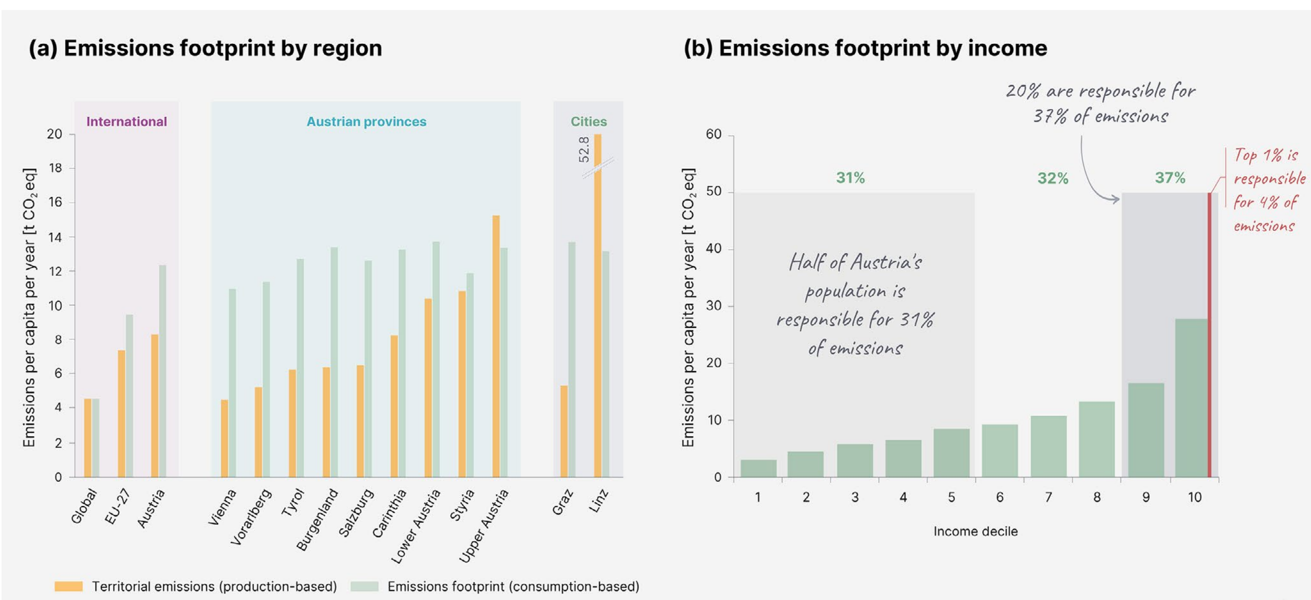


**Figure 5.3** Emissions per capita across regions and income groups. Panel (a): Territorial emissions and GHG footprints per capita in 2019 across global regions, Austrian provinces, and cities in 2019 (Steininger et al., 2018; Pichler and Steininger, 2019; Stadt Graz, 2022; Umweltbundesamt, 2022a; Nabernegg et al., 2023). Panel (b): Distribution of GHG footprints per capita across Austrian income deciles and the highest percentile (Theine et al., 2022; Nabernegg et al., 2023).

For Austria, studies on the distribution of emissions across households reveal a substantial but more equal distribution of GHG footprints than global GHG footprints (see Figure 5.3b) (Greenpeace, 2020; Muñoz et al., 2020; Nabernegg, 2021; Theine et al., 2022; Nabernegg et al., 2023) (*medium evidence, high agreement*). Theine et al. (2022) estimate that the GHG footprint of the highest income decile is 4.1 times larger than that of the lowest income decile. Household GHG footprints, therefore, closely follow increasing expenditure in income deciles, with mobility expenditure being a key driver. However, emission estimates for low- and high-income groups based on survey data are subject to higher levels of under-representation and under-reporting (Flachaire et al., 2022); therefore, the inequalities might be even larger.

In a similar study on German households, Schuster and Otto (2022) showed that the lifestyle GHG emissions in the lowest and highest emission groups can differ by a magnitude of ten. Income, education, age, gender, and regional differences resulted in distinct emission profiles (Schuster and Otto, 2022). The authors analyzed lifestyle $CO_2$ emissions in sectors including housing, transportation, and consumption. In the housing sector, the most important sources of emissions were identified as heating and electricity use. The per capita living space increased with income and most of the respondents lived on their own or in two-person households. Excessive living space per person is ineffective from an energetic perspective, but changing housing preferences through political means or incentives is difficult to achieve. There are, however, interesting examples of policies and measures that encourage the use of smaller living spaces, which could also be implemented in Austria. These include the moving bonus offered by the city of Frankfurt when moving out of a social housing flat (Wuppertal Institut für Klima, Umwelt, Energie, 2024), provided that the current flat is too large and the new flat is smaller, or eco-villages that often involve small private spaces but larger shared spaces (Wiest et al., 2022; Jany et al., 2023). Reductions in emissions in the housing sector are likely to occur as access to fossil fuel-free heating systems improves, as people switch to renewable energy sources in general, and as house insulation and energy-efficient home appliances improve (see Section 3.3).

In the transportation sector, it is noticeable that the mobility of the majority of the population is relatively low. The remainder, however, have extremely mobile lifestyles. The highest proportion of lifestyle GHG emissions from the wealthiest individuals globally is due to extreme mobility, including frequent flying with private jets and in business cabins (Otto et al., 2019). Additionally, travel and cars are still status symbols, and not only for the wealthiest members of society. The highest emissions in the transportation sector arise in the 30–49 age group (Schuster and Otto, 2022). This could be because this age group has a fixed income, its members often advance in their careers and private life (start a family, acquire larger living spaces, commute longer distances, etc.), but also because they are trying to establish themselves socially through the use of status symbols. Research points out that policies need to incorporate elements of social justice by targeting and curbing the emissions of the wealthy, since they can afford clean technologies, and their lifestyle choices have important downstream influences on the aspirations and lifestyles of people in other social classes (Otto et al., 2019). In addition, men have a higher footprint in the transport sector than women.

In the sector of consumption, which includes food and non-food products, the $CO_2$ emissions from nutrition are not group-specific. Dietary habits are not income-specific, and, in the German sample, the respondents across different regions and milieus had relatively similar eating habits (Schuster and Otto, 2022). Reducing meat consumption in different social groups could contribute the most to reducing $CO_2$ emissions. Other variables, including education and cultural background, did not influence emissions from food consumption in the German sample. Emissions due to non-food consumption were, however, again strongly correlated with income. The authors also pointed out a few gender differences in the emission patterns. To give an example, men tended to consume more meat and had therefore higher food consumption emissions, however, women had slightly higher emissions from clothing purchases than men (Schuster and Otto, 2022).

These multiple lines of evidence show that privileged members of society consume disproportionately more resources and energy to maintain their lifestyles than less privileged members. In addition, the least privileged members, who are usually less mobile and often live in marginal areas and under poorer conditions, are disproportionately more heavily affected by environmental pollution and climate extremes including for example heat waves (Brimicombe et al., 2024). The poorest social groups also often perform work that exposes them more to the impacts of climate change, including occupations in agriculture and construction. These inequalities must be taken into account. Defining a universal, irreducible, and essential set of material conditions for ensuring basic human well-being, along with indicators and quantitative thresholds that reflect local customs and preferences, can help to go beyond simply eradicating poverty and encourage the social participation of the least privileged members of society. Redistributive policy instruments, setting standards and bans on most polluting and harmful activities and technologies can help to achieve more equitable outcomes.

## 5.3. Mitigation and adaptation decisions of citizens and households: Lifestyles and consumption

### 5.3.1. Human behavior and social norms

Changing the GHG footprint of Austrian society is crucial for delivering the transformative change needed to meet national climate objectives. Up to 62 % of the Austrian GHG footprint are related to private household consumption with the main components of mobility (20 %), residential energy use and housing (17 %), and food (9 %) (Aigner et al., 2023c). While these emissions occur within the current provisioning system, behavioral and lifestyle choices are central determinants for their reduction. Citizens' impact is even greater if the influence on governments, business, and finance are considered (Newell et al., 2021). Despite the role of government institutions for infrastructure provision, researchers in the behavioral sciences take theoretical perspectives to look at the role of social determinants, bounded rationality conditions including nudging, as well as monetary incentives and to explore fast decarbonization processes (Newell et al., 2021). These elements affect or are affected by attitudes, values, and beliefs as well as broader cognitive, affective, and social processes (O'Brien and Klein, 2017; O'Brien and Yazdani Aliabadi, 2020).

Behavioral biases and social norms play a critical role in hindering or promoting climate mitigation actions (Nielsen et al., 2021). Behavioral biases such as the tendency to maintain the status quo bias and present bias can help explain the insufficient behavioral change observed. For instance, individuals may prefer to stick to fossil fuels for transportation, rather than explore alternative modes, due to the familiarity and convenience of their current behavior. Additionally, individuals may tend to prioritize immediate gains over long-term benefits, making them less willing to invest in sustainable lifestyle changes (i.e., present bias). Moreover, individual consumption patterns and the social comparison aspect of consumption are also relevant to the limited uptake of sustainable lifestyles (Cialdini and Jacobson, 2021). Research has shown that GHG emissions are positively related to income and wealth, indicating that those with a higher socioeconomic status tend to consume more and have a greater environmental impact (Ravallion et al., 2000; Theine et al., 2022). Evidence-based policy interventions can be designed to address the barriers that impede behavioral change and support more sustainable ways of living (e.g., in line with the COM-B model). By developing targeted interventions that are tailored to meet the needs of specific groups, such as households with different socioeconomic statuses, values or motives, policymakers can increase the chance that their efforts will lead to changes in behavior (Nielsen et al., 2020a, 2020b), and even more so, because European National Energy and Climate Plans (NECPs) lack political interventions that ensure sufficiency (Zell-Ziegler et al., 2021; Lage et al., 2023). Examples include nudging techniques and behavioral interventions that guide individuals towards more sustainable choices, taxes on environmentally harmful products that provide a financial incentive for individuals to choose more sustainable options, and subsidies that encourage the adoption of sustainable technologies and behaviors.

One technical note must be addressed in this sub-chapter: It mainly touches on the literature with an international rather than an Austrian context, as only few studies with a particular Austrian context on behavioral biases and heuristics exist. Exceptions include the Austrian APCC Report on Structures for Climate-Friendly Living, that emphasizes the need for institutional and infrastructural changes supporting individual behavioral and lifestyle changes (Aigner et al., 2023b) (see also COM-B model). However, it is realistic to assume that findings from international studies (mainly conducted in Western countries) are informative for understanding the Austrian context[3]. Nevertheless, these circumstances clearly outline the need for more research and more randomized control trials of specific policy interventions in the Austrian context.

#### Behavioral biases and decision heuristics influence sustainable behavior

Reducing global GHG emissions can be described as a global public goods problem (Barrett, 2007). While the scientif-

3 See, for instance, a study on loss aversion in 53 countries, showing loss aversion also among most Austrian participants (Wang et al., 2017).

ic evidence clearly indicates that it would be beneficial for everyone to cooperate on a global level across countries, individual polluters face free rider incentives, which tempt countries and individuals to take advantage of others' efforts while making no effort themselves. In this case, the free rider benefits from an expected world that has low GHG emissions, without making any effort (*high agreement*). As a consequence, climate mitigation actions are not undertaken at sufficiently high levels, and GHG emissions increase further (Hasson et al., 2010; Blanco et al., 2020). The 'tragedy of the commons' problem is also closely related to the problem described above, and the literature outlines the need of institutions to diversify (i.e., institutions that add to local and regional institutions by focusing on global challenges). Ostrom et al. (1999) offer evidence that indicates how to overcome some of these problems.

With respect to climate adaptation policies, however, the structure is slightly different, as this problem can be subsumed under a private good problem. In this case, the adapter (e.g., country, individual) primarily (and sometimes solely) benefits from the implemented adaptation strategy (Hasson et al., 2010; Blanco et al., 2020; McEvoy et al., 2022) (*high agreement*).

While the global GHG mitigation problem can only be solved by international cooperation and by governments and other stakeholders cooperating, the behavior of individuals and communities play an important role as well. They play a role as citizens, because they vote for certain parties (governments) that are more or less in favor of climate mitigation and adaptation policies. Importantly, a country's total carbon emissions are strongly determined by its carbon footprint (see Section 5.2.2), namely emissions that cannot be influenced directly by individual behavior. According to the Federal Ministry of Climate Action, Environment, Energy, Mobility, Innovation, and Technology, the gray footprint amounts to approximately 25 % of Austria's GHG emissions. In addition, a country's $CO_2$ footprint is also defined by its citizens' behavior, including consumption, mobility, and the choice of renewable energy purchase (Ivanova et al., 2020; Creutzig et al., 2022b) (*robust evidence*).

Thus, in addition to structural factors, various behavioral biases can hinder people's willingness to adapt their behavior by preventing individuals from taking appropriate action.

First, confirmation bias is the human tendency to seek information that confirms our prior beliefs or knowledge and to disregard information that opposes our prior beliefs or knowledge (Kappes et al., 2020). This bias is often fueled by a lack of accurate knowledge or exposure to biased information, which can be disseminated through certain media outlets or political parties (Lazer et al., 2018). Confirmation bias can play a significant role in hindering sustainable behavior change, as it causes individuals to selectively seek out information that confirms their pre-existing beliefs or values, while ignoring or discounting information that challenges these. For instance, a significant number of people are not interested in knowing the extent of their carbon footprint and even admittedly ignore such information before making environmentally relevant choices (Thunström et al., 2014; Reisch et al., 2021) (*medium evidence*).

Second, present bias refers to the tendency of individuals to value the present more highly than the future. This bias can lead people to overvalue the immediate costs of climate mitigation policies, such as a carbon tax or changes in individual diets or heating systems, while placing less weight on the uncertain future benefits, such as the reduced frequency of extreme weather events (Weber, 2010). A study in Germany shows that people with present bias consume more electricity than people without such bias (Werthschulte and Löschel, 2021) (*medium evidence*).

Third, loss aversion refers to the tendency of people to strongly prefer avoiding losses compared to acquiring gains of the same magnitude (Kahneman et al., 1991). Loss aversion and the related status quo bias can hinder efforts to increase sustainable behavior (Nicolson et al., 2017; Ghesla et al., 2020). This is an additional reason that people may be reluctant to change their habits: They perceive the potential losses of altering their behavior as greater than the future benefits of behavioral change. In addition, the future environmental benefits will only materialize if a large portion of the world's population and governments take an adequate number of actions soon. This could result in individuals maintaining their carbon-intensive behaviors rather than adopting more sustainable alternatives (*robust evidence*).

Fourth, ingroup and outgroup biases in the form of the perceptual bias (Zhao and Luo, 2021) and pluralistic ignorance (Sparkman et al., 2022) might play a critical role as well. In countries or societies with strong polarization in public opinions, ingroup and outgroup biases can be particularly damaging to sustainable behavior, as individuals may become more entrenched in their beliefs and less willing to consider opposing viewpoints. For instance, Sparkman et al. (2022) investigated individuals' perceptions of national concern about the climate crisis and support for climate mitigation policies in the US. They documented that the vast majority of Americans underestimate the national support for climate mitigation policies and for climate concern, and these misguided beliefs might undermine their own action and engagement (*robust evidence*).

Fifth, social norms are collectively agreed-upon rules about how to behave in specific situations (Bicchieri, 2005), and social norms have been shown to influence a number of climate change-related behaviors (for a summary, see Cialdini and Jacobson, 2021). Examples come from littering (Cialdini et al., 1990), energy conservation (Allcott, 2011; Andor et al., 2020), and water conservation (Ferraro et al., 2011; Schultz et al., 2016). A recent meta-study of 430 primary studies and 10 meta-studies by Bergquist et al. (2023), shows that social comparison/norms next to financial incentives were the most effective tools (*robust evidence*). Although norm-based information is known to be effective in promoting desirable behaviors, it can also have negative consequences, such as the boomerang effect, where individuals revert to undesirable behaviors, and the backfire effect, where individuals adopt the exact opposite behavior, as evidenced by Gangl et al.'s (2022c) study in Austria where a norm-based intervention resulted in increased (rather than decreased) littering in community-building waste disposal areas.

## Behavioral change and habit formation – suggestions and pathways

Environmental behavior and behavioral change can be influenced by a variety of measures. These range from classic public policies such as taxes to information provision, and newer policy approaches, including behavioral nudges and comprehensive behavior change programs similar to those used in public health (e.g., Allcott, 2011; Spotswood, 2016; Carlsson et al., 2021). The concept of 'nudging' is central in a behavioral approach to public policy and accounts for the fact that decision-making can be influenced by subtle modifications to the decision context (via 'exploiting' behavioral biases) without reducing options or changing economic incentives (Thaler and Sunstein, 2009; Schubert, 2017; Nisa et al., 2019). There is evidence and agreement that the provision of social norm-based information – providing information on what 'most people' do or approve of – can successfully initiate behavioral change in many settings, including energy and water consumption, recycling, and the provision of public goods, to name only a few (Rege and Telle, 2004; Allcott, 2011; Abrahamse and Steg, 2013; Delmas et al., 2013; Ferraro and Price, 2013) (see also above) (*robust evidence*). Nudges altering the choice architecture include defaults for green energy providers (Ebeling and Lotz, 2015) and related energy choices such as defaults for heating and cooling settings (Brown et al., 2013), as well as more prominent ordering and positioning of green food alternatives (Garnett et al., 2020; Gravert and Kurz, 2021). There is evidence that choice architecture interventions can promote climate change mitigation actions, but, for the most part, only make small to medium contributions to mitigation with median effect sizes of up to 10 % (Hummel and Maedche, 2019; Nisa et al., 2019; Van Der Linden and Goldberg, 2020; Meier et al., 2022; Mertens et al., 2022). Classical paternalistic methods such as taxes, bans, and subsidies show larger effects, but acceptance among citizens is variable (Dechezleprêtre et al., 2022) (*robust evidence*). Systematic cost-benefit evaluations of behavioral interventions are lacking in the scientific literature, but Benartzi et al. (2017) have provided evidence for the advantages of behavioral change nudging approaches compared to traditional policy approaches.

Moreover, impacts of nudges are heterogeneous, depending on the characteristics of the person involved, other situational factors, and the persistence of effects varies (Bao and Ho, 2015; Brandon et al., 2017; Mertens et al., 2022) (*medium evidence*). One implication of this literature is that interventions may need to be tailored to the populations or settings of interest. Thus, it is important to pre-test interventions in the specific context. Another consideration is that the effectiveness of nudges may be temporary, with their impact potentially diminishing over time. As many environmental behaviors have a habitual component, including energy and water use, meat consumption, and commuting, it is crucial to factor in the time stability of effects in intervention design (Verplanken and Whitmarsh, 2021). Research in related domains (health behavior) indicate that monetary incentives in the form of rewards can foster good and stop bad habits (Gneezy and Rustichini, 2000; Charness and Gneezy, 2009; Royer et al., 2015; Rohde and Verbeke, 2017; Carrera et al., 2018). Such incentives, however, bear a risk of undermining intrinsic motivation (Gneezy et al., 2011; Bowles and Polanía-Reyes, 2012) (*robust evidence*). Results from information-based interventions and nudges on habit formation are mixed and depend on the context in which they are applied (*medium evidence*). Gravert and Olsson Collentine (2021) find no effect of information on sustained public transport ridership, while Ayres et al. (2013) and Byrne et al. (2021) find that information provision can overall promote short- and long-term behavior changes in energy and water use, but with modest to small contributions to resource savings. In addition, nudging techniques have been criticized recently, also due to publication bias (DellaVigna and Linos, 2022;

Maier et al., 2022). Moreover, the answer to the question of whether nudges are unethical is far from clear, with arguments both in favor and against it (Sunstein, 2015), although proponents have pointed out that the existing choice architecture may also be problematic from an ethical perspective.

At the same time, there is strong evidence that monetary incentives can also change pro-environmental behaviors and contribute to the formation of sustainable habits (Maki et al., 2016), also for mobility which is generally more difficult to change (Gravert and Olsson Collentine, 2021) (*robust evidence*). However, incentives are also debated due to concerns that they might primarily work in the short term and potentially undermine intrinsic motivation as stated above (Frey and Oberholzer-Gee, 1997). Overall, evidence suggests that, while information provision and nudges can work to a certain degree (with zero effect as well) (as outlined in DellaVigna and Linos, 2022; Maier et al., 2022), their immediate impact is smaller than that of monetary incentives (*robust evidence*). Recent research, however, suggests that combining interventions (i.e., monetary incentives with information and nudges) can help make individual interventions more effective (Drews et al., 2020; Khanna et al., 2021).

## 5.3.2. Collective action

Individuals do not make decisions in isolated self-reference but are subject to the social structure, which is made up of (i) institutions (i.e., informal norms, customs and traditions, and formal constitutions and rules); (ii) organizations; and (iii) the technosphere (i.e., infrastructure and technology) in which they are embedded. This take is increasingly accepted across all social sciences (Williamson, 1998; Dietz et al., 2003; Axsen and Kurani, 2012; Charness and Sutter, 2012; Bamberg et al., 2018; Otto et al., 2020b). Agency, in this context understood to be the capacity to change energy and resource use patterns, lies on the spectrum between individual and collective (also see figure 1 in Otto et al., 2020b). By pooling their resources and efforts under collec-

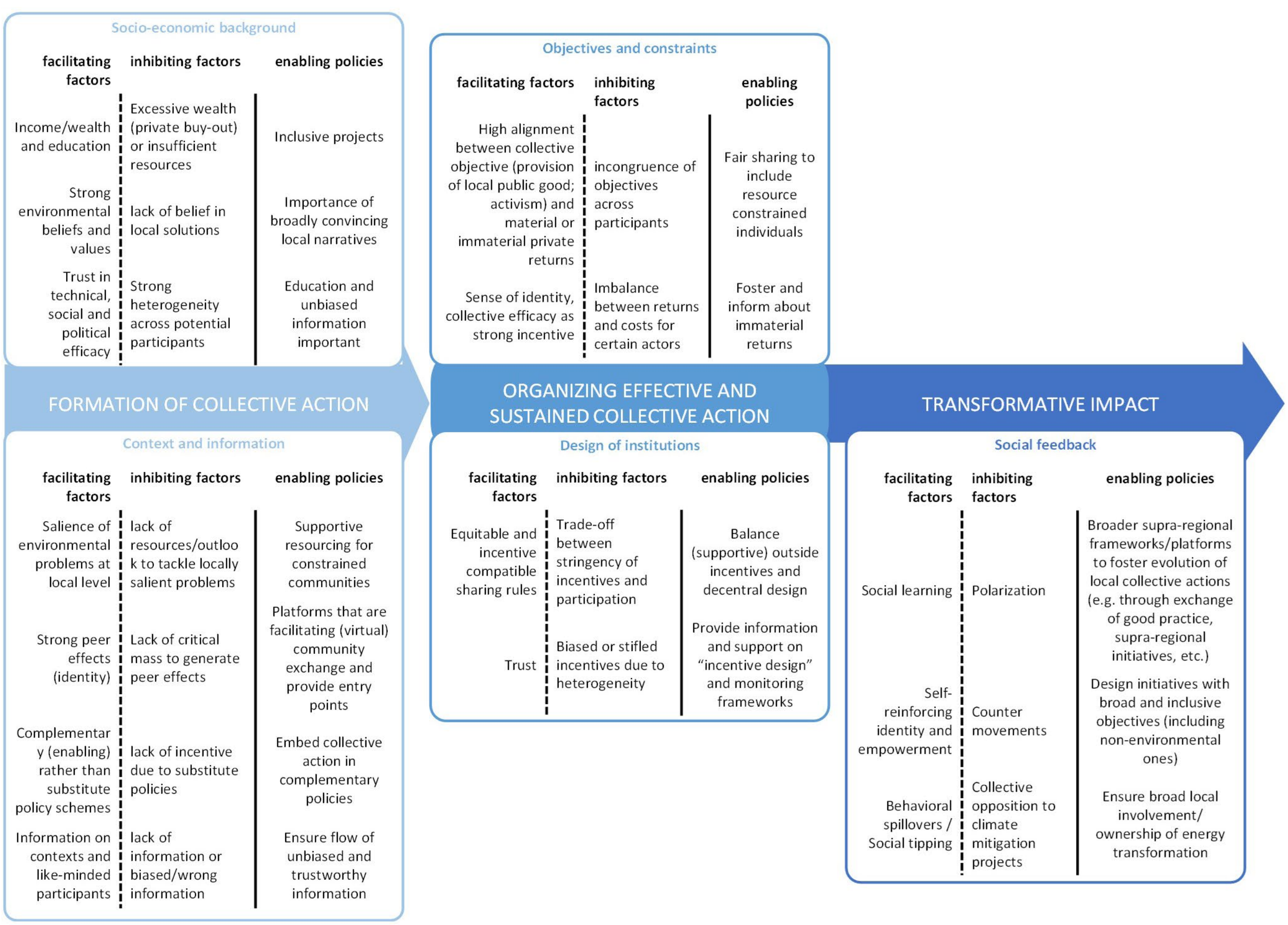


**Figure 5.4** Determinants of collective action along the formation-organization-impact line.

tive agency, individuals are able to attain outcomes that they would not be able to achieve individually. Collective agency often includes the build-up of longer-term organizational or physical infrastructure and can thus be understood to be of a strategic nature. It is typically aimed at (i) enhancing and managing the provision of local public goods, i.e., club goods or commons, such as food- or car-sharing initiatives, joint investments in renewable energy infrastructures (energy communities), or the provision of shared infrastructures for adaptation (communal flood defenses, support systems in case of heat waves); and/or (ii) generating political clout.

The scope for *establishing and sustaining successful collective action with transformational impact* depends on a number of factors, which we group along the formation-organization-impact line for the purpose of assessment (see Figure 5.4). Domains include the s*ocio-economic background* of (possibly) participating individuals as well as the *context and information* that determine the formation; *objectives and constraints* and the consequential *design of institutions* that enable sustained organizational effectiveness; and the role of *feedback* for transformative impact. For each of these domains, enabling and inhibiting factors are identified as well as the scope for enabling policies (Figure 5.4). We restrict evidence to high-income, mostly European contexts, including the few available Austrian studies. The more limited evidence on collective action undertaken against climate transitions (e.g., wind parks or grid structures) is assessed followingly on negative feedback. The specific assessment of energy communities as well as NGOs and civil society can be found in Sections 5.4.3 and 5.4.2, respectively.

### Socio-economic and socio-psychological background of participating individuals

The willingness to engage in community action – and for many of the studies quoted, the willingness to invest financial and time resources into community renewable energy infrastructures within a number of European countries – has been shown to increase with age, income/wealth, and education (Dóci and Vasileiadou, 2015; Yildiz et al., 2015; Bauwens and Eyre, 2017; Ebers Broughel and Hampl, 2018; Curtin et al., 2019) (*high confidence*). In addition, the willingness to engage is found to vary according to the residential context (higher engagement in rural communities in Germany, but no significant impact in Austria) (Kalkbrenner and Roosen, 2016; Ebers Broughel and Hampl, 2018) (*medium confidence*) and to increase with the intensity of energy usage (Bauwens and Eyre, 2017) (*medium evidence, low agreement*). Pro-environmental beliefs and trust in the technical effectiveness of renewable energy solutions (or collective efficacy more generally) also play a strong role (Bamberg et al., 2015; Dóci and Vasileiadou, 2015; Kalkbrenner and Roosen, 2016; Mignon and Bergek, 2016; Ebers Broughel and Hampl, 2018; Howe et al., 2019; Reichl et al., 2021) (*high confidence*). Finally, lack of financial resources, financial competency, and risk aversion tend to inhibit investments in communal energy (Ebers Broughel and Hampl, 2018; Curtin et al., 2019) but not necessarily the willingness to engage in the form of in-kind contributions (Kalkbrenner and Roosen, 2016) (*medium evidence, high agreement*). Related evidence on food sharing initiatives shows that members are also recruited from the educated middle classes, although income and wealth play a lesser role, because most contributions are based on time and effort, factors which otherwise rely less on financial resources. Trust and the belief in convincing solutions also matters (survey findings in Nikravech et al., 2020) (*high confidence*).

### Context and information

Context matters for the formation and successful implementation of collective action in terms of the scale and scope of the underlying environmental commons problem (e.g., in the context of adaptation) (Adger et al., 2005), of the broader socio-economic background into which private or collective actions are embedded (Steg, 2023), and of the policy context (Villamayor-Tomas et al., 2019).

**Salience:** Generally, individuals are more inclined to undertake collective action if climate change is perceived as real and salient (Bateman and O'Connor, 2016; Brink and Wamsler, 2019; Mildenberger et al., 2019; van Valkengoed et al., 2021; Steg, 2023; Wannewitz and Garschagen, 2023) (*high confidence*). Scholars debate, however, whether the experience of local extreme weather events is enhancing collective action to increase future protection or rather stifling it due to the perceived or real loss of resources and capacity and a sense of low self-efficacy (Adger et al., 2009; Adger, 2016; Wannewitz and Garschagen, 2023) (*robust evidence, low agreement*). A study from Germany based on a representative population sample, points out that the experience of seasonal temperature change is associated with stronger personal climate change concerns as well as the willingness to mitigate climate change, although with a weaker effect (Pfeifer and Otto, 2023).

**Socio-economic context:** With respect to the formation of collective action to promote sustainability, peer effects play a strong role. Specifically, the presence of local social capital, as embraced by community initiatives (aimed at sustainability but also at other objectives), combines environmental beliefs and beliefs in the efficacy of renewable energy schemes and other such initiatives. This combination boosts such schemes by also pulling along community members with weaker environmental beliefs (Dóci and Vasileiadou, 2015; Bauwens, 2019; Broska, 2021) (*high confidence*). In contrast, a lack of norm and belief conformity as well as trust, due to, for example, socio-economic heterogeneity and anonymity, may generate particular challenges in urban environments (Wannewitz and Garschagen, 2023). In settings in which close spatial proximity is not important, these issues can be overcome, however, by using internet-based platforms and communication (Nikravech et al., 2020).

**Policy context:** The embedded nature of collective action in clear-cut complementary regulatory and legal frameworks helps to foster the foundation and functionality of collective action (Villamayor-Tomas et al., 2019). This occurs in two ways. First, collective action is promoted through reductions in uncertainty and transaction costs (affecting coordination) call for organizational support and policies aimed at the sharing and diffusion of information. Second, it is promoted through changes in payoffs and their perception and an increase in normative consonance (affecting prisoner's dilemma and zero-sum situations), which call for support in terms of framing but also hard policies such as regulations and taxes. Case study evidence shows that typically more than one of these influencing channels need to be activated to encourage collective action, implying that policies need to be coherent across governance scales (central, local, individual) and degrees of agency (formal, collective, individual) (Villamayor-Tomas et al., 2019) (*high confidence*).

This hints at a strong role for communication, personal and social factors (Biresselioglu et al., 2020; Nikravech et al., 2020). Cases included Austria, where the reliability of information provided by neutral parties, the role of convincing narratives, the provision of knowledge on energy efficiency, a focus of policies on long-term rather than short-term costs, and higher knowledge/better information on the part of media representatives were specifically called for.

Supporting policies are leveraged by a psychological signal given through policy institutions and policymakers about more widely shared pro-environmental values and beliefs (Steg, 2023). In contrast, direct policy interventions made to meet similar targets may also discourage efforts by substituting private and community initiative and signaling that there is 'no need' (Reichl et al., 2021). Thus, stronger financial incentives in Italy as opposed to Austria to garner photovoltaic investments have been found to crowd in economic motivations but also to crowd out motivation for collective energy (Braito et al., 2017).

**Contextual information:** Good information with respect to the underlying socio-technological setting and political context and the associated payoffs has been shown to strongly enable collective action (Mignon and Bergek, 2016; Geiger et al., 2017; Ebers Broughel and Hampl, 2018; Curtin et al., 2019) (*high confidence*). Ebers Broughel and Hampl (2018) show that financially-relevant information on community renewable energy projects raised the willingness to invest in Austria and Switzerland, and false beliefs stifled it. For Austria specifically, there is evidence that, while individual attitudes and behavioral intentions are rather pro-climate, considerable knowledge gaps, misunderstandings, and barriers also exist (Thaller and Brudermann, 2020), a finding that is consistent with evidence from Germany (Fischer et al., 2019).

Information also matters regarding the values shared by (potential) participants. Climate concerns in others are often underestimated (Steg, 2023) (*high confidence*). Thus, the lack of information on shared environmental beliefs may lock collective (and private) action into a 'spiral of silence' (Donsbach et al., 2014; Geiger and Swim, 2016; Amel et al., 2017; Bouman et al., 2021). Geiger et al. (2021a) show that (a lack of) information about the political identity of other group members in association with (false) beliefs about their willingness to contribute to environmental objectives has a strong impact on personal behaviors in the lab. There is also a risk that inaccurate meta-beliefs may boost polarization and stifle pro-environmental behavior.

### Objectives and constraints

The stated objectives of collective action at the community level typically embrace (1) the provision and sustenance of local public goods that either help to serve climate mitigation or climate adaptation objectives at a community level (Bisaro and Hinkel, 2016; Wannewitz and Garschagen, 2023) or (2) the provision of information/education, lobbying and other forms of activism at a civil society level (e.g., Boucher et al., 2021; Fritsche and Masson, 2021). These can be understood to translate to varying degree into individual objectives, namely (a) material, in particular financial returns; (b) immaterial returns, such as a sense of identity that comes with a shared vision and set of values; and (c) a sense of self-empowerment, as well as a more general communal sense of belonging (Dóci and Vasileiadou, 2015; Bamberg et al., 2018; Schulte et al., 2020; Broska, 2021; Fritsche and Masson, 2021; Vesely et al., 2021) (*high confidence*). There is clear evidence that tackling climate action can in and of itself increase well-being (Zawadzki et al., 2020; Creutzig et al., 2022a).

While collective actions of type (2) are mostly associated with immaterial returns of type (b), these have been shown to be leveraged by emotions both positive (sense of individual empowerment, empathy) and negative (anger, sense of injustice) (e.g., Brown et al., 2019; Landmann and Rohmann, 2020; Furlong and Vignoles, 2021). Type (1) actions are associated with both types of returns (a) and (b), but the extent to which material or immaterial considerations dominate is inconclusive and context-dependent (Walker, 2011; Sagebiel et al., 2014; Bauwens, 2019; Schulte et al., 2020). According to evidence on renewable energy communities in Belgium, financial returns dominate in large communities, whereas shared values dominate in smaller communities with social interaction (Bauwens, 2019). Heterogeneity in the objectives across members within each initiative has also been shown to matter (Bauwens, 2016). Evidence from behavioral experiments shows that cooperation enhances adaptation to environmental uncertainty; high inequalities among the resource users, however, hinder cooperation (Heinz et al., 2022).

## Design of institutions for sustained collective action

The importance of institutions, and in particular sharing rules, punishment/reward structures, and the information flows that support them as facilitators of sustained collective action, have been documented by recent experimental economic and a variety of other social science studies.

**Role of sharing rules and punishment/reward structures:** Blanco et al. (2018, 2021) show that externally sponsored collective action tends to be more successful when personalized and/or effort-related payments are made compared to equal sharing. Focusing on risky settings, Blanco et al. (2020) show that public and private insurance against losses related to a collective resource are substitutes, implying that collective action (as a form of public self-insurance) is weaker in settings where individuals can rely on private protection (and vice versa). A laboratory experiment on car sharing in Austria demonstrates that both legal and community sanctions tend to raise contributions (Hartl and Hofmann, 2022).

**Endogenous choice of institutional rules:** Dannenberg and Gallier (2020) survey evidence on the extent to which and how social groups choose their own institutions to overcome commons problems and find that institutions are self-chosen to a larger extent by more cooperative groups. However, they may not always be implemented. Thus, there is no conclusive evidence on the superiority of self-governance. Dannenberg et al. (2014) provide experimental evidence on the formation of coalitions. While the endogenous choice of mechanisms that sanction deviation enhances participation, large participation also stifles commitment. Gallier et al. (2019) provide experimental evidence on parochialism vs. efficiency: While there is a revealed preference for parochialism, no impact was found on choosing relatively more efficient arrangements.

**Socio-economic heterogeneity:** A diverse socio-economic background of group members tends to render agreement on sharing and punishment/reward structures more difficult (Araral, 2009). In such cases, a strengthening of the immaterial rewards to collective actions is helpful to raise incentives when individual objectives are heterogeneous (Bauwens, 2016). Collective action can be sustained over the longer term only if it meets criteria of distributive and procedural fairness (Adger, 2016; Steg, 2023) and is associated with mutual trust among participants and in the responsible parties (Steg, 2023; Wannewitz and Garschagen, 2023) (*high confidence*).

**Information on compliance:** Functioning of collective action is affected by information on compliance, particularly when it comes to containing the incentive to get a free ride on others' efforts. Bühren and Dannenberg (2021) show how successful collective action hinges on information about the composition of the group with respect to free riders vs. cooperators. Hartl and Hofmann (2022) show that public information about compliance (by way of a 'badge') shapes the sanctioning mechanism in the context of their car-sharing experiment.

## Social feedback

**Positive:** One type of positive feedback process drives the emergence of the collective itself. Here, the attainment of social empowerment (or effective collective agency) itself can become an important objective (Bamberg et al., 2018), which has scope for creating effective feedback and increasing ambition. Thus, the establishment of citizen power plants in Austria has been found to enhance empowerment in a number of ways, although this process tends to be biased towards the status quo (of established schemes and structures) and better-resourced individuals and communities (Schreuer, 2016). Learning within the collective, the strengthening of norms and identity and the resulting desire for consistent behavior, as well as a spillover from group efficacy into self-efficacy, may trigger and reinforce further collective action involving new themes and participants (Garmendia and Stagl, 2010). This learning may also trigger changes in private environment-related behaviors (Jugert et al., 2016; Sloot et al., 2018; Broska, 2021; Jans, 2021). However, a recent meta-analysis finds no evidence of this on average, suggesting that positive spillovers are the most likely if the (presumed) spillover can be traced back to normative goals and was triggered by an autonomy-supportive intervention (Geiger et al., 2021b). A second type of positive feedback relates to the spillover of action to other individuals, a process that may lead to social tipping, as discussed in greater detail in Section 5.6.2.

**Negative (risk of polarization and collective counter-action):** Processes towards pro-social collective behaviors are often accompanied by and may even trigger anti-social behavior, where market integration, economic diversification, and strengthened group identities have been identified as key triggers of the simultaneous development of pro-and anti-social behavior (Basurto et al., 2016). There is ample evidence that beliefs and values correlate closely with (party) political world views (Hornsey et al., 2016; Ziegler, 2017), although findings by Reichl et al. (2021) suggest a more nuanced view, at least in Europe, according to whether conservative/socio-democratic views pertain to economic issues or social issues. In the latter study, conservatism implies less environmental concern (*robust evidence, medium agreement*).

Incentives to strengthen group identity (Akerlof and Kranton, 2000; Fritsche and Masson, 2021) may thus lead to polarization, especially if identities are established in a conspicuous or moralizing way (Kurz et al., 2020; Furlong and Vignoles, 2021). In particular, communication styles, deliberate political messaging, and influencing activity in interaction with biased media and in particular social media reporting have a strong reinforcing role here (Farrell, 2016; Chinn et al., 2020; Falkenberg et al., 2022). The role of educational differences is more highly contested and may depend on the specific generation (Kahan et al., 2012; Ross et al., 2019). Countering polarization tendencies requires broad and inclusive population-based initiatives, careful policy balancing and interventions (Fritsche and Masson, 2021; Tindall et al., 2022; van de Grift and Cuppen, 2022), and effective communication strategies (Chu and Yang, 2018) (also see Section 5.6.3).

Collective action may also be directed against renewable energy projects, and in particular the placement of wind or solar farms. While part of such opposition may be understood as 'not in my backyard' (NIMBY) behavior that may be mitigated by appropriate compensation, recent evidence, including from Austria (Scherhaufer et al., 2017), points at more complex motivations behind group formation, involving issues of local identity. Overcoming collective resistance, or even better avoiding it in the first place, then requires more holistic patterns of community involvement and ownership, both metaphorically and literally (Devine-Wright, 2011; Petrova, 2013; Botetzagias et al., 2015; Boyle et al., 2019; O'Neil, 2021) (*high confidence*).

### 5.3.3. Interaction with technology and infrastructure

Many of the changes discussed above are within the agency of individual citizens. However, there are also limits to individual agency, and legal, policy, and infrastructure changes must take place to enable individual behavioral and lifestyle changes (Wiest et al., 2022). Using technology will always have an impact on the energy and material demand, as well as on pollution (Coccia, 2022). On the other hand, technology can be a means of providing or consuming in an easier, faster, or otherwise more preferable way than without technology. As such, technology does not hinder the net-zero transition (IPCC, 2022), instead it supports the development and roll-out of renewable technologies, development of new business models, as well as expansion of infrastructure for renewables and low-carbon lifestyles.

Technology is 'a means to do things', consisting of technical artifacts ('hardware') and a disembodied element of knowledge ('software') (Grübler, 1998). Infrastructure covers physical objects and structures such as roads, railroads, power supplies, buildings, and factories. Both technology and infrastructure, i.e., the elements of the technosphere, influence social structures and the way society operates (Spaargaren, 1997), and contrasts the aggregate of all artificial objects with the natural world (Herrmann-Pillath, 2018). Just as social norms impose constraints on human behavior and decisions, on the one hand, they structure human interactions and provide opportunities, on the other hand. The co-evolution and interaction of the technosphere and the policy systems, accompanied with social norms create a carbon lock-in that is hard to break (Unruh, 2002). Thus, the technosphere can be viewed as humanly designed constructs that provide certain opportunities, but also limit certain choices of individuals operating at different geographical and time scales (Donges et al., 2017). The lifespan of large infrastructural objects extends sometimes to more than 50 years, which is comparable to the lifespan of one human generation (Otto et al., 2020b). Infrastructure such as roads or railways enable or disable certain individual and political choices.

Empirical data show that the adoption of energy efficient technologies and small-scale renewables can contribute to 30–70 % of the GHG emissions reduction potential in buildings (Creutzig et al., 2022b). Technological advances have led to significant improvements around the world and in Austria (Odyssee-MURE project, 2021; Saunders et al., 2021). The availability of materials and rare metals for the net-zero transition might hinder the transition speed, and the implementation of circular economy principles might lower the demand for new materials and metals.

Technology has multiple connections to sustainability and a clear human dimension. Certain technologies provide alternative, more sustainable solutions than others. This is achieved by improving their technical efficiencies or by lowering their carbon content directly or indirectly (through their lifecycle). This can *improve* the climate or environmental impact of an energy service, such as for mobility and living space (see Cross-Chapter Box 4). For example, the specific consumption of cars in Austria has improved by 0.753 % per year between 2000 and 2019, with an overall efficiency gain of the transport sector of 0.529 % per year measured by ODEX. The ODEX combines the energy efficiency trends of the different modes of transport (cars, trucks and light vehicles, bus, motorcycles, air, waterways, rail) (Odyssee-MURE project, 2021). This makes Austria slightly slower in improvement than the EU average (0.6 % per year improvement). On the other hand, due to the increase in vehicle size, modal shifts and extension of distances, technical efficiency improvements were completely offset. Technology can contribute to mitigating climate change by enabling the *avoidance* of a given service or of an associated energy or material consumption. For instance, digital technologies can be used to optimize room temperatures, leading to lower energy consumption as long as people's behavior doesn't counteract the technical gains. Or teleworking technologies can lead to as large as 80 % lower $CO_2$ emissions from commuting (Hook et al., 2020). Finally, a system of technologies can fully *shift* the solution space, such as rolling-out passive buildings, shifting industrial practices, or inducing a modal shift in personal mobility to non-motorized or shared mobility (e.g., walking, biking, car-sharing, bike-rental).

The interaction between the technosphere and human decisions is critical to the ultimate environmental implications of the technology and technology systems (e.g., buildings) in all cases where the technology is used, adopted or accepted (Huckebrink and Bertsch, 2021). The influence of lifestyle has been studied only to a limited extent and more Austrian results would be needed. In a study of the Community Energy Saving Program (CESP) in the UK, the average energy saving was 30 % compared to the pre-retrofit condition, but behavioral adjustments varied widely (Elsharkawy and Rutherford, 2015). In another UK study, electricity savings ranged from 0 to 50 %, depending on how the occupants used the new technologies (Araya Mejías et al., 2021). The improvement of energy services through technology and/or lifestyle and behavior, needs to be further evaluated specifically for Austria. Beyond the introduction of new and additional policies and/or technologies, exnovation (Scherhaufer et al., 2017) and negative learning should also be explored and better understood (see Section 5.2). Exnovation leads to discontinuation of ineffective solutions, allows for adaptation with new or changed behaviors and therefore improves techno-human impact on the environment.

Subsidy programs aimed at, for example, extending public transportation networks or car-sharing facilities, as well as building codes and standards, such as shared laundry and freezer space in apartment buildings, can support positive interactions between technology and human behavior. On the other hand, policies and financing mechanisms for specific technologies create market distortions and can lead to an energy efficiency gap (Saunders et al., 2021); therefore, these should be used with caution, for short time scales, and with a conscious decision to consider the non-intended impacts. Promoting smaller living or working spaces in new buildings could also help limit the sprawl of technology and infrastructure (Wiest et al., 2022). It is essential that new infrastructural projects are aligned with the net-zero objectives and that they support, or at least are not in conflict with, the net-zero emission system goals (Aigner et al., 2023b).

### 5.3.4. Social inequalities in energy supply and related policies

Austria is steadily shifting to a renewable energy system, but this transition results in significant inequalities. Social inequality in the context of the energy supply arises from the combination of inequalities in income, energy prices, and energy efficiency in the residential sector. Embedded in the issue of social inequality, it is of interest to define minimum standards in energy efficiency in the residential sector, secure energy supply, and affordable energy (services; electricity and heat) for particularly vulnerable parts of the population. In such a context, energy poverty can be seen as a manifestation of social inequalities that can lead to social exclusion, the origin of which is complex and multidimensional (*high confidence*).

This chapter addresses social inequality in the energy supply and places a special focus on the issue of energy poverty, providing descriptions of particularly vulnerable groups, the related legal frames and policies, and measures that can be used to combat this problematic issue at the national level.

## Energy poverty and vulnerability factors

Energy is a fundamental resource in modern societies, the lack of which can diminish wealth and living standards, forcing individuals and households into situations of marginalization, and even jeopardizing their physical health (Brunner and Mandl, 2014; Demski et al., 2019; Shyu, 2021) (*high confidence*). Struggles caused by the lack of access to energy services or disproportionate energy costs are known as *energy poverty* (Primc et al., 2021; Salman et al., 2022).

Despite efforts and advancements to alleviate energy poverty in Austria, a legal definition for this term is still lacking (Dobbins et al., 2019; Bouzarovski et al., 2021). In this context, the Austrian Ministry for Social Affairs (BMASGK) commissioned a comprehensive expert study to determine the magnitude of this phenomenon in Austria in 2018 and create the most suitable definition of energy poverty for the Austrian context. As a result, definitions of 'energy poverty' and 'at risk of energy poverty' were proposed for those households 'at risk of poverty or social exclusion' (AROPE) being unable to afford essential energy services (i.e., power, heating, and hot water supply) (Matzinger et al., 2018). In Austria, energy poverty is acknowledged to be a complex issue, which can only be measured by using a diversity of indicators. Initially, Austrian statistical records on energy poverty focused mainly on excessive energy expenditure (Statistik Austria, 2017, 2019). The 2021 publication added the affordability dimension to consider those households which showed low energy expenditures because they sacrificed a basic level of energy use to cover other elementary needs (Statistik Austria, 2021a). The latest reports even consider eight indicators to draw a more accurate picture (C/2020/9600; Statistik Austria, 2022).

Three of these indicators are the most highly recognized causes of energy poverty, namely poor energy efficiency, low income, and high energy bills (Boardman, 2013), although further dimensions have been suggested (e.g., labor market situation, welfare state type) (Middlemiss, 2022) (*high confidence*). Vulnerability to energy poverty is associated with many social characteristics like unemployment, gender inequality, ethnicity, tenancy, impairment, and age (i.e., the elderly are more at risk) (Snell et al., 2015; O'Sullivan et al., 2017; Churchill and Smyth, 2020; Sánchez et al., 2020; Ivanova and Middlemiss, 2021; Petrova and Simcock, 2021; Primc et al., 2021; Wang et al., 2021). The novel perspective of the foundational economy that emphasizes the actual burden born by households using the *residual income* approach sheds different light onto energy poverty and aims for more inclusive climate change mitigation policies (Calafati et al., 2021; Russell et al., 2022) (*limited evidence, medium agreement*).

Austria has one of the lowest energy poverty rates in Europe (EPAH, 2022) (*high confidence*). Prior to the energy price hike of 2022, 3.2 % of all Austrian households indicated that they were unable to keep houses adequately warm, whereas 3.3 % had high energy costs while living under risk of poverty (Statistik Austria, 2022, 2024a). Furthermore, energy-poor households are often in arrears with a debt (Butler and Sherriff, 2017). Households that are traditionally disproportionately affected by high energy expenses in Austria reflect people who have a minimum compulsory education (nearly threefold that of non-energy poor), live alone (twofold of non-energy poor), and are elderly (32 % higher). Household composition and size are indeed important determinants of energy poverty (Robinson, 2019; Seebauer, 2021; Sunikka-Blank and Galvin, 2021; Eisfeld and Seebauer, 2022). One-person households constitute a large majority (i.e., 71 % considering the high energy expenses approach and 56 % by limited affordability) (Statistik Austria, 2022, 2024a). Energy poverty also has a gender dimension (Robinson, 2019; Clancy et al., 2020; Sánchez et al., 2020; Sunikka-Blank and Galvin, 2021). Various factors contribute to the higher vulnerability of women, such as the gender pay gap, labor market participation, and the uneven distribution of family caregiver duties (Mort, 2019). Despite the COVID-19 outbreak, energy poverty remained stable until 2022[4]; however, due to rising energy prices, Statistik

[4] When this assessment report was last updated, EU-SILC data were only available up to the survey year 2022 (carried out in the first half of that year)

Austria (2022) started a special survey on a quarterly basis, which also included energy affordability. Data show a considerable increase in energy-poor households. While in Q4 2021, dwelling energy affordability affected 6.0 % of Austrian households, this value rose to 12.1 % in Q4 2022, which constituted an unprecedented record value for Austria. Recovery happened at a slow pace, but in Q4 2023, the portion of households unable to afford essential warmth decreases to 7.5 % due to lower energy prices (Statistik Austria, 2024c).

The linkage between energy efficiency and energy poverty has been clearly recognized (Boardman, 2013); however, dwelling energy efficiency (e.g., measured by means of *Energy Performance Certificates*) is not part of national statistics reports on energy poverty. Using the *Low-Income-Low-Energy-Efficiency* indicator could reveal a more precise picture and serve as a basis for more accurate policy interventions that counteract any rebound effect (Abbasi et al., 2022). Dwelling characteristics like type of building, year of construction, floor space, and ownership status have an impact on energy consumption. In 2022, the vast majority of energy poor households, not able to afford adequate warmth, lived in apartment buildings (73 %), had floor space up to 80 m² (66 %) and paid rent (75 %). Regarding energy expenses, 45 % of energy poor households dwelt within old buildings constructed before 1960 (Statistik Austria, 2022, 2024a).

Tenants often have few options to invest in energy efficiency measures, while landlords rarely invest in retrofitting despite of the economic viability of investments in such energy efficiency upgrade, a situation known as the energy efficiency gap (Galvin and Sunikka-Blank, 2018). Tenancy regulation in Austria tend to protect tenants; however, the split incentives dilemma in rental housing hinders advancements in energy efficiency in the building sector (Seebauer et al., 2019). Nonetheless, this issue has a lower effect on social rental housing since social housing cooperatives are not profit-seeking (Kranzl et al., 2020). Social housing in Austria serves a social mandate and provides housing with a limited-profit margin (IIBW, 2016; Klien and Streicher, 2021), where social housing providers have a great potential to implement coordinated interventions and prevent energy poverty (Croon et al., 2024). In Austria, the share of social housing as main residence is 7 % city-owned and 17 % cooperative owned (Statistik Austria, 2022, 2024a). Estimates of the Austrian Federation of Limited-Profit Housing Associations (GBV, 2021) suggest that energy poverty could affect around 2–3 % of all cooperative (social rental) housing tenants (i.e., between 13,000–20,000 households). Nonetheless, integrating both climate and social housing policies seems necessary to achieve decarbonization goals while reducing social inequalities (Seebauer et al., 2019). After all, income and GHG emissions have a strong correlation (see Section 5.2.2).

Apart from energy poverty, high energy prices have an impact on food and mobility poverty; however, these synergetic effects are rarely addressed (Essletzbichler et al., 2023; Penker et al., 2023) (*limited evidence, medium agreement*). Politically, food security is considered an accomplished goal in Austria (BKA, 2020) and thus an adequate monitoring of social inequalities related to food consumption, health, and climate impacts is missing (Penker et al., 2023). Transportation cost constitutes an over-average economic burden for households under risk of poverty compared with the rest of the population (Frey et al., 2023). Synergetic effects are to be considered in order to avoid the perpetuation of existing social inequalities and rather promote an active contribution to the transition goals by all parts of society (Essletzbichler et al., 2023).

### Regulatory framework, measures, and their impact

The EU's European Green Deal (COM/2019/640 final) prioritizes a fair and just transition, with regulatory frameworks ensuring affordable and inclusive energy services (see Section 6.8.1). This includes addressing energy poverty with an EU-wide definition (C/2023/408) and a new urban mobility framework (European Commission, 2021) to promote sustainable development and reduce social inequalities.

In Austria, the regulatory framework (BGBl. I Nr. 110/2010; BGBl. I Nr. 150/2021) requires energy suppliers and authorities to consider vulnerable households when implementing energy-saving measures, to raise awareness, and to reduce overall number of affected households (BGBl. Nr. 140/1979). There are restrictions on power disconnections for utility bill arrears (ElWOG, GWG), and energy consumers gained the right to pay by installments in May 2022 (para. 82 BGBl. I Nr. 110/2010). The Energy Efficiency Act (BGBl. I Nr. 72/2014) established the coordination Office on Energy Poverty (KEA) to facilitate stakeholder collaboration for effective energy poverty reduction. The dialogue is crucial amid the increasing energy poverty, highlighting the need for targeted, comprehensive measures (see Section 6.3).

Climate change mitigation measures aim to ease the transition to cleaner energy for households, focusing on: (i) building renovation, (ii) regional development planning, (iii) renewable energies, (iv) energy consumption, (v) mobility, and (vi) natural hazard protection. The Austrian government has introduced support programs in energy and mobility to counteract inflation (BMNT, 2019; IEA, 2020; Jensen and Carvalho Fachada, 2021). However, these measures have varying impacts on societal groups, with concerns raised about short-term relief over long-term benefits, especially for vulnerable groups (Seebauer, 2021; Fink et al., 2022b). While these climate change mitigation measures are discussed in Chapter 3, Chapter 4, and Chapter 6, we outline the most relevant ones in terms of their effects on vulnerable groups.

**Building renovation** measures encompass government schemes supporting various improvements such as loft, floor, and wall insulation, along with the installation of other energy efficiency features. Grants cover the initial costs of rooftop photovoltaic or solar thermal systems (also part of renewable energies, below), heating system replacements, draught insulation with heat recovery, and offer more benefits for middle-class households with sufficient savings for energy-efficient retrofits (Seebauer, 2021). However, those in rental dwellings often face the 'landlord-tenant dilemma', where long-term building renovation investments are disadvantageous for both parties (Petrov and Ryan, 2021; Fink et al., 2022b, 2022a) (*high confidence*).

**Regional development** planning measures support energy-efficient urban planning, building revegetation, and green roofs/facades, but these can be costly for vulnerable households (landlord-tenant dilemma). They enhance property value but risk green gentrification (see Section 3.2.1), pushing vulnerable groups to more affordable areas (Kadi and Matznetter, 2022). The full extent of this impact is a research gap (Seebauer et al., 2021) (*limited evidence, medium agreement*).

**Renewable energy measures** support citizen energy communities, energy counseling, and expanding electric vehicle charging infrastructure. These efforts are effective for reaching vulnerable groups, especially when incentives are tailored. Information campaigns are more effective when combined with actionable solutions, and peer counseling has shown promise in reaching vulnerable groups who may not seek public support otherwise (Seebauer et al., 2021) (*limited evidence, medium agreement*).

Measures related to **energy consumption** include carbon taxes and tax exemptions for maintenance, repair, and overhaul, as well as measures designed to simplify the availability of spare parts, equipment, and information (Seebauer et al., 2021; Österreichs E-Wirtschaft, 2023). Energy taxes have a regressive effect on the lowest income segments, which bear the higher burden in relative terms. Those with higher income can easily afford shifting to sustainable systems, and higher taxes on fossil fuels play no substantial role in practical terms (Becker et al., 2021; Mayer et al., 2021). On the other hand, people in the lowest income segments lack the ability to build up savings and thus cannot afford to shift to cleaner solutions (Petrov and Ryan, 2021; Seebauer et al., 2021). The relatively higher tax burden is even greater for those in the lowest income quintile disregarded by tax exemptions (Bernhofer, 2021). The 'Klimabonus' (i.e., Austrian climate dividend) has an important redistributing effect, but the accuracy of its social impact over time has not yet been determined and can be considered as research gap (Bolte et al., 2024) (see Section 6.5.1) (*limited evidence, medium agreement*).

**Mobility** support schemes are designed to enhance public transportation availability, promote climate-friendly modes, offer electric vehicle rebates, and facilitate sharing initiatives and commuting allowances. This includes expanding cycle networks and making cycling more appealing. While mobility is often overlooked in energy poverty discussions and definitions, it is gaining importance. Electricity and heat are key factors, but mobility is increasingly significant. Public investments in this area benefit low-income households the most, as about half of those in the lowest income bracket do not own a vehicle (Berger et al., 2020; Blanck et al., 2020; Blanck and Kreye, 2021; Seebauer et al., 2021) (*limited evidence, medium agreement*). Austria prioritizes improving public transport infrastructure and schedule frequency (Austrian Federal Chancellery, 2020). However, the European Commission (2023) indicates a rising trend of mobility poverty, affecting 40 % of Austrians living below the poverty line.

**Natural hazard protection** measures place a focus on civil protection, emergency planning, and hazardous site remediation, as do public awareness campaigns. Climate change introduces additional challenges, particularly impacting vulnerable groups. Heatwaves and increased temperature exposure have health risks for residents in densely populated areas with limited green spaces (Reischl et al., 2018; Seebauer et al., 2021) (Cross-Chapter Box 2).

### Initiatives of the private sector to tackle energy poverty in Austria

Energy supply companies in Austria have launched a variety of initiatives intended to alleviate and tackle energy poverty. Support under these initiatives is offered in different ways, such as by offering professional energy counseling, granting alternative payment facilities, and/or funding for renewal of domestic appliances. Eligible households apply for this support by contacting one of several social organizations, which serve as a link between households and energy suppliers (Gouveia, 2019). Since 2009, around 16,000 individuals from all over Austria have received support from the "Electricity Assistance Fund" initiated by Caritas, which is endowed by energy suppliers like VERBUND (2022) and Salzburg AG. Similar initiatives can be found at the regional level like the Energie AG Oberösterreich and Linz AG's Energy Solidarity Budget in Upper Austria (Energie AG, 2021). In February 2023, in response to the energy price crisis, Caritas Austria, Volkshilfe, and the Ministry of Climate Protection (BMK, 2023) launched a similar initiative offering aid to low-income household in order to favor decarbonization by reducing their energy consumption.

### Identification of priorities to combat energy poverty

Various political measures have been implemented to address energy poverty, but a unified national strategy is crucial for long-term solutions (Seebauer et al., 2019) (*medium evidence, high agreement*). Professional energy counseling has been a starting point, but this may not suffice if it is limited to advising on energy savings (Kyprianou et al., 2019). Immediate energy counseling is necessary, offering short-term relief for temporary hardships or acute financial crises. This could involve replacing inefficient appliances, introducing one-time subsidies, placing limits on disconnections, or allowing retrofitting in cases of urgent health risks (International Commission on the Futures of Education, 2021).

Medium-term measures include relief such as green electricity exemptions and appliance replacements for improved efficiency. Long-term strategies involve building refurbishments like upgrading windows and doors to enhance energy efficiency as well as supporting the establishment of citizen energy communities (E-Control, 2012; Kyprianou et al., 2019; Rechnungshof Österreich, 2020; European Commission, 2022). Implementing these measures not only creates or sustains jobs but also reduces illness, revitalizes neighborhoods, and promotes social inclusion (Heeman et al., 2022).

Historically, the degree of energy poverty in Austria has remained stable, despite political efforts (Statistik Austria, 2022) (*robust evidence, medium agreement*). Structural, long-term approaches are needed to prevent energy poverty. Thermal refurbishments of buildings, as demonstrated in projects like SINFONIA in Innsbruck, are essential (Peper and Failla, 2021). Raising awareness in energy-poor households can lead to behavioral changes and cost savings, while replacing old appliances and heating systems can result in significant energy savings (Słupik et al., 2021). It is also important to state that improving the thermal properties of buildings is the key to cutting energy consumption (Boltz and Pichler, 2014; Słupik et al., 2021). Efforts such as the 'Sauber Heizen für Alle' grant targeting low-income households demonstrate the potential of such efforts to reduce inequality and eradicate energy poverty (Umweltförderung, 2024). Improving housing conditions and upgrading appliances have been shown to effectively reduce energy consumption and costs, leading to $CO_2$ emissions reductions (Papantonis et al., 2022).

Overall, addressing energy poverty presents opportunities for synergy with climate change mitigation goals. Tackling poverty and energy poverty can have positive climate impacts, enhancing the quality of life while reducing $CO_2$ emissions through improved energy efficiency (Austrian Federal Chamber of Labour, 2021).

## 5.4. Organizations as agents of change

Beyond individuals and households, many organizations are making choices that define our aggregate impacts as a society. Organizations are powerful agents of change, because decisions on how to run these organizations define their direct $CO_2$ footprints, but also because they affect the barriers and enabling factors for individuals and households in society. Similarly, organizations can be references in climate transformations, illustrating more sustainable ways of operating to their members (including employees). This can also have an impact on organization stakeholders. For example, Creutzig et al. (2022b) highlight the relevance of middle actors – such as building managers, landlords, consultants, technology installers, or car dealers – for influencing the behavioral patterns of other people and the associated climate impacts. Moreover, social processes can multiply and enforce individually held beliefs and empower people in organizations.

This section first covers firms, then moves to higher education and research institutions, NGOs, and civil society organizations, and finishes with communities. The sub-section on firms focuses on the within-firm operational decisions that define $CO_2$ footprints as well as the economic incentives that encourage firms to be greener. See Chapter 4 to learn more about the broader implications of firms' decisions on system-wide structures. The sub-section on higher education and research organizations, NGOs, and civil society reviews the important roles of largely non-commercial entities. The sub-section on communities considers meaningful aggregates of people in close proximity such as neighborhoods and people coming together with similar aims such as interest groups. Such communities can emerge bottom-up against existing governance structures or they can be encouraged and deliberately fostered in a more top-down manner.

### 5.4.1. Firms as agents of change

There is a widespread assumption in the political debate, the media, and among business stakeholders that a trade-off between the financial and environmental performance of firms is inevitable. It is common to find opposition to recommendations and regulations that can strengthen environmental standards, as well as to discussions about greening the business sector. At the same time, empirical evidence suggests that the voluntary certification of good environmental practice, such as the Eco Management and Auditing Scheme (EMAS), ISO 14001 or the European Eco-label (EU Flower), is widespread and that many firms voluntarily adhere to high standards of performance that go beyond environmental relations. According to the KPMG Survey on Sustainability Reporting (KPMG, 2022), 96 % of the world's largest 250 firms by revenue, based on the Fortune 500 ranking, report on sustainability or environmental, social, and governance issues. Referring to climate, 64 % recognize climate change as a risk to their business, and 80 % report carbon targets. The majority of them (56 %) link their targets to the global 2°C target in the Paris Agreement, and the majority (59 %) intend to reach their targets only through emission reductions (34 % by combining emission reductions and carbon credits, and 7 % not specifying their method). The adoption of the Task Force on Climate-related Financial Disclosures (TCFD) has increased substantially in recent years. This standard was established in 2015 by the Financial Stability Board in response to the threat of climate change to the stability of the global financial system and, in 2022, was adopted by 61 % of the largest companies (KPMG, 2022). Considering the top 100 companies by revenue in 58 countries, territories, and jurisdictions, in Europe 82 % of these report on sustainability, which is an increase of 5 % over the previous year. In Austria, the percentage of the top 100 firms reporting according to standards of the Green Reporting Initiative (GRI) is 89 % (among the top 10 internationally). The share of adherence to local stock exchange guidelines is lower and does not stand out internationally. Similar comments apply to the use of Sustainability Accounting Standards Board, developed in 2011 to guide companies on investor-focused sustainability disclosure. Overall, it is natural to ask why firms engage in such voluntary practices in the first place, as this empirical observation seems inconsistent with the recurrently repeated narrative seen in the business forums that environmental action by firms negatively impacts their financial performance.

A large body of international literature shows that there is no general empirical support for the assumption that being green is harmful to firms (Blanco et al., 2009; Molina-Azorín et al., 2009; Albertini, 2013; Dixon-Fowler et al., 2013; Endrikat et al., 2014; Velte, 2022) (*robust evidence, medium agreement*). The wide range of data published for different sectors, types of firms, and countries does not support the view that environmental action generally comes with a trade-off regarding the financial bottom line. Indeed, the general picture that appears is that improved environmental performance has a small but positive impact on the financial performance of firms. Evidence suggests that increased operational efficiency and lower cost of debt are the mediating factors explaining the positive impact (see, e.g., Gao and Wan, 2023). Firms can do better in terms of economic and financial performance by being greener, provided that the measures implemented are proactive and based on re-designing processes (rather than end-of-pipe technologies), moderate in terms of abatement levels, and supported by investors and consumers (Blanco et al., 2009; Dixon-Fowler et al., 2013).

Sustainability concerns are prominent among Austrian job seekers and consumers alike. Statistics show that 65 % of Austrians are willing to pay more for climate-friendly food, and 78 % support labeling foods to show their environmental impact, indicating a strong market for green products in Austria (European Investment Bank, 2023). Accordingly, many Austrian companies have switched to advertising the environmental friendliness of their products and services rather than focusing on price or quality. While so-called 'green claims' are becoming increasingly popular, accusations of 'greenwashing' are also on the rise (CMS, 2023). An EY study revealed that only 46 % of Austria's top companies publish sustainability reports, and merely one-third of these firms have their environmental data externally audited. This rate is considerably lower than, for example, in Germany, where 73 % of companies undergo such audits (Ernst & Young Global Limited, 2022). Upon closer examination, explicit instances of greenwashing are evident in Austria. The Austrian Association for Consumer Information (VKI) actively targets this issue by performing 'greenwashing checks'. This initiative allows consumers to report misleading green claims. The VKI assesses these claims and, if deemed deceptive, publishes the findings on its website, potentially damaging the reputation of the involved company. Moreover, the VKI can take legal action against companies making unsubstantiated or vague environmental claims, reinforcing its commitment to enforcing truthful advertising in compliance with Austrian law. In Austria, several greenwashing cases have led to legal actions. For instance, after a VKI complaint, a brewery was found guilty of falsely advertising its beer as '$CO_2$-neutral brewed' and was ordered to re-label its products. Another case involved an association of dairy farmers that claimed their products supported climate protection but withdrew their ad after receiving criticism. Additionally, the recyclability of a ballpoint pen was contested due to the impracticality of recycling it in Austria (CMS, 2023). In another case, an Austrian court ruled that Austrian Airlines AG engaged in greenwashing by advertising '$CO_2$-neutral' flights between Vienna and Venice using 100 % sustainable aviation fuel (SAF), despite the fact that SAF constituted only about 0.1 % of global aviation fuel and the actual use in these flights was only up to 5 %. The court ordered the airline to correct the misleading advertisements by sharing accurate information on its social media platforms (Lahey, 2023).

Moreover, the use of sustainability labels and logos has risen in Austria. Such labels typically require a certification process, which must be transparent and objective. The VKI has criticized some Austrian labels for failing to genuinely substantiate their sustainability claims due to non-transparent and objective processes (CMS, 2023). A prime example of the importance of product labeling can be seen in the food industry in Austria. Although, transport accounts for only about 6 % of the total emissions from the global food system (Poore and Nemecek, 2018), Austrian consumers value regional products, which they view as being of higher quality and more eco-friendly. To support this, Austria introduced new laws in 2022 requiring origin labeling on processed foods and communal catering for meat, milk, and eggs, which were effective as of mid-2023. Additionally, since July 2022, Austrian farmers have had to disclose the origin of their products in the supply chain, impacting their food marketing strategies (CMS, 2023).

It is relevant to emphasize that there are also costs associated to 'no-action' strategies by firms. Total annual net damages from climate change for Austrian firms across multiple sectors – agriculture, forestry, energy, building management, tourism, water supply, waste management, sales, transport, and urban green spaces – have been estimated to range from EUR 2.5–5.2 billion by around 2030. These figures include damages associated with natural disasters and health impacts. Projections for 2050 suggest that these combined costs could escalate to between EUR 4.3–10.8 billion annually (Steininger et al., 2015, 2016a, 2020). Most critically: How do Austrian firms themselves perceive the impacts of these threats, and what are their responses? According to a large-scale survey by the European Investment Bank (EIB) from 2022 and 2023, 64 % of Austrian firms reported that they feel exposed to physical risks from climate change (EU: 57 %), and 43 % have set climate targets (EU: 41 %). Furthermore, Austrian firms are more proactive than the EU average in addressing climate risks, with a higher percentage of firms stating that they implement mitigation measures while simultaneously planning or investing in climate adaptation strategies. The implemented mitigation measures by the Austrian firms include enhancing new green technologies or products (47 % in Austria vs. 32 % in the EU), investing in energy efficiency (76 % vs. 57 %), generating renewable energy (61 % vs. 37 %), and focusing on waste minimization and recycling (77 % vs. 64 %), as well as sustainable transport options (54 % vs. 43 %). Overall, 94 % of Austrian firms in the survey stated to implement some form of mitigation, compared to 88 % in the EU. Additionally, 30 % of the Austrian firms stated to have developed adaptation strategies (EU: 14 %), 37 % to have set actual adaptation measures (EU: 20 %), and 11 % to use insurance to hedge risks (EU: 10 %). A significant 47 % of Austrian firms in the sample are engaged in any adaptation activities, surpassing the EU average of 33 %.

Austrian firms increasingly view climate transformation as an opportunity, whereby 38 % saw benefits in 2023, up from around 32 % in 2022, percentages that are higher than EU averages for both years (European Investment Bank, 2023). Evidence from the previous 2020–2021 EIB survey showed that roughly one-third of Austrian firms believe the transition will positively affect their demand (34 %, EU: 34 %) and reputation (33 %, EU: 38 %), with potential negative impacts on the supply chain noted by 27 % (EU: 25 %). Of the surveyed Austrian firms, 29 % employ dedicated climate staff, surpassing the EU average of 23 %. The primary barrier identified by the firms for further investment in climate action is the uncertainties surrounding taxation and regulatory frameworks (European Investment Bank, 2021). Additionally, Austrian companies recognize the importance of meeting sustainability goals in recruitment. This is important as 72 % of Austrians under the age of 30 consider a prospective employer's climate impact important when job hunting, with 21 % ranking it as a top priority (European Investment Bank, 2023). Austrian family firms have adopted a diverse array of environmental strategies. These include energy conservation measures, optimizing transportation routes to minimize traffic, sustainable resource utilization, using alternative packaging materials, and engaging in collaborative projects with the agricultural sector. The primary motivation behind these environmental practices appears to be compliance with eco-certification standards (Kuttner et al., 2021). Lastly, significant barriers to sustainability integration have been found to include resource constraints and organizational inertia, which prevent effective resource allocation that supports the achievement of sustainability goals (Kiesnere and Baumgartner, 2019).

As business owners, investors, and employees, individuals can have an impact on advancing towards greener societies. The debate on whose responsibility it is to take action on climate neutrality, with firms, governments, and citizens acting as mutually exclusive agents of change, is not well-founded and quickly becomes a circular argument. Firms argue that they do not sell more green products or turn greener in operations, because consumers are not ready to pay the additional price premia; consumers argue that they cannot afford additional price premia and that governments are responsible to guarantee a healthy environment; and governments argue that they are not pushing for stronger green guidelines and regulations for firms because they do not have the support from citizens to do so and would lose power in upcoming elections. All these actors are interrelated rather than mutually exclusive. Again, the empirical observation that 'green firms' have emerged and are thriving in the Austrian economy is a reality check against the most pessimistic accounts of alternative, lower emission impact, economic arrangements. However, an open question is the extent to which greener operations can become a strong feature of mainstream business, enabling them to affect a shift in the overall operation of the economy. This is particularly relevant for 'discount firms' which operate on very small profit margins and typically serve the less-favored sectors in society. However, there is reason to believe that the shift can spread to the majority of the business sector: The KPMG survey on sustainability reporting shows over the years that large global companies tend to lead the way in sustainability reporting, with the top 250 internationally ahead of the top 100 at the country level, and these ahead of others (KPMG, 2022). Thus, looking at the sustainability performance and evolution of the larger companies can be a useful gauge for identifying broader trends that are eventually adopted more widely.

Although evidence from companies and organizations across the EU suggests that behavioral interventions such as nudging can effectively promote green behavior (e.g., among employees) (see, e.g., Brown et al., 2013; Handgraaf et al., 2013; Mehrwert Berlin, 2022), relatively few examples are known of Austrian firms employing such techniques to achieve sustainability goals. A notable exception is a field experiment conducted during the summer of 2021 by the Institute for Higher Studies (IHS) in partnership with the ARA, an Austrian packaging collection and recycling company. This study tested different designs of waste collection bins against a control group with no bins in 90 locations in Leoben, Steyr, and Krems. The findings demonstrate that collection bins enhance public waste separation, especially those with images of pristine nature (Gangl et al., 2022b).

### 5.4.2. Higher education and research, NGOs, and civil society

Higher education and research organizations are important agents for change through educating people and building relevant competencies in new generations (see Section 6.8.3 for other educational contexts), allocating research funding to societal challenges, and through their leadership and role model function in society (*medium evidence, high agreement*). Taking the example of higher education, these function much like other big organizations (see Section 5.4.1), albeit in a different, less commercial context (at least in Europe) and their governance and goals are different from commercial organizations (Kezar, 2001). Leal Filho et al. (2014) describe a drive for integrated, interdisciplinary, and transversal application of sustainability in the higher education sector in areas ranging from education to operations, but important gaps were identified (e.g., in business schools, see Csillag et al., 2022) and also between the strategies expressed and actions taken (e.g., Brennan et al., 2015). In Austria, as of January 2024, 20 universities were organized in the *Alliance of Sustainable Universities in Austria* a network to promote sustainability in higher education and society (nachhaltigeuniversitaeten.at).

GHG emission reduction and sustainability initiatives at Austrian universities include introducing emission monitoring and reduction programs (Hölbling et al., 2023). These include reducing air-based business travels, introducing more flexibility by combining or extending business trips to reduce the distance traveled or the number of flights, increasing the choice of plant-based options at university canteens, offering only plant-based options at university and student events, encouraging commuting via public transportation or bikes, as well as investing in renewable energy harvesting facilities in university buildings, and reducing overall emissions in heating, cooling, and electricity. Some of these initiatives were initiated by student groups and as a result of student protests at universities. The Climate Change Center Austria (CCCA) is a network of universities and non-university research organizations founded in 2011 that serves as a joint contact point for science, politics, administration, and the public, sharing climate change knowledge and expertise and has produced a national energy and climate reference plan in 2019 (NECP). Besides operational activities of universities, endeavors to reform research and education have the potential to multiply knowledge and competencies and trigger action, e.g., the certificate of the Alliance on Education for Sustainable Development (nachhaltigeuniversitaeten.at/zertifikat) or university internal working groups on Sustainability Science (e.g., boku.ac.at/en/nachhaltigkeit/sustainability-in-research/wg-sustainability-research).

Pioneering roles can also be played by citizen groups, NGOs, and other civil society organizations (see Section 6.4.2) (*medium evidence, high agreement*). For example, Fridays for Future has been active in Austria since 2018. Further examples for initiatives include co-housing groups, energy communities (see Section 5.4.3), and other forms of initiatives organized around sharing and mutual support principles. These are discussed in more detail in the subsequent sections (Komendantova, 2021). An interesting example can be found in the City of Graz, which launched the KLIMAEURO+ Program in 2024. This program provides small amounts of funding for groups and organizations, enabling them to organize local initiatives and events that directly reduce GHG emissions or provide information and training (Stadt Graz, 2024).

At the national Austrian level, two programs ought to be mentioned in this context because they complement and foster action by community groups and citizens. Climate and energy model regions (Klima- und Energiemodellregionen, KEM) and climate change adaptation model regions (Klimawandel-Anpassungsmodellregionen, KLAR!) are administered by the Austrian government's climate and energy fund. KEM is focused on decentralizing and defossilizing the energy supply, whereas KLAR! is focused on climate adaptation. The KEM approach integrates governance and implementation elements, combining top-down and bottom-up dynamics for multi-level energy transitions through partnerships across scales and societal learning (Irshaid et al., 2021). Komendantova et al. (2018) highlight that KEM activities appear to focus on informing and awareness-raising measures but are limited in participation in actual decision making. This is an important starting point but leaves room for more sophisticated participation forms according to Arnstein's (1969) ladder of participation. Within the KLAR! portfolio of activities, Babcicky and Seebauer (2021) have investigated the interplay of physical and social factors in determining flooding outcomes and demonstrated the value of adding psychological indicators on top of traditionally used socio-demographic proxies. In sum, integrating multi-level perspectives from psychological to systemic and building on the existing awareness-raising initiatives holds great potential for achieving actual energy and climate transitions.

### 5.4.3. Energy communities

Community-based, bottom-up initiatives have an increasing potential in the energy transition and can tap into new low-carbon opportunities (Pathak et al., 2022). Energy community-like initiatives have appeared in Europe sporadically, such as energy efficiency cooperatives in the UK or small-scale wind and biomass projects run by communities in the 1970s in Denmark and Austria (Walker et al., 2010). Individual intentions are often driven by collective willingness or actions, as described in Section 5.3.2. The business case has improved with the legal foundations established recently at the EU level (Fina and Monsberger, 2023; Wierling et al., 2023) (*limited evidence, medium agreement*). The end-user is expected to become a key actor in future energy systems and to contribute to the levels of generation, aggregation, distribution, storage, and consumption, as well as supply of the energy itself or energy services (e.g., by providing electric mobility or other energy services). Energy communities establish space and structures that fulfill these functions and/or help stakeholder cooperation.

The EU has defined 'energy communities' since 2019 as collaborative citizen-driven energy actions that contribute to the clean energy transition, advancing energy efficiency or the renewable energy supply within local communities (Roberto et al., 2023). These must be available for participation and effective control by citizens, local authorities, and SMEs. Citizen energy communities (CECs) are mandated in Article 2(11) of the Internal Electricity Market Directive

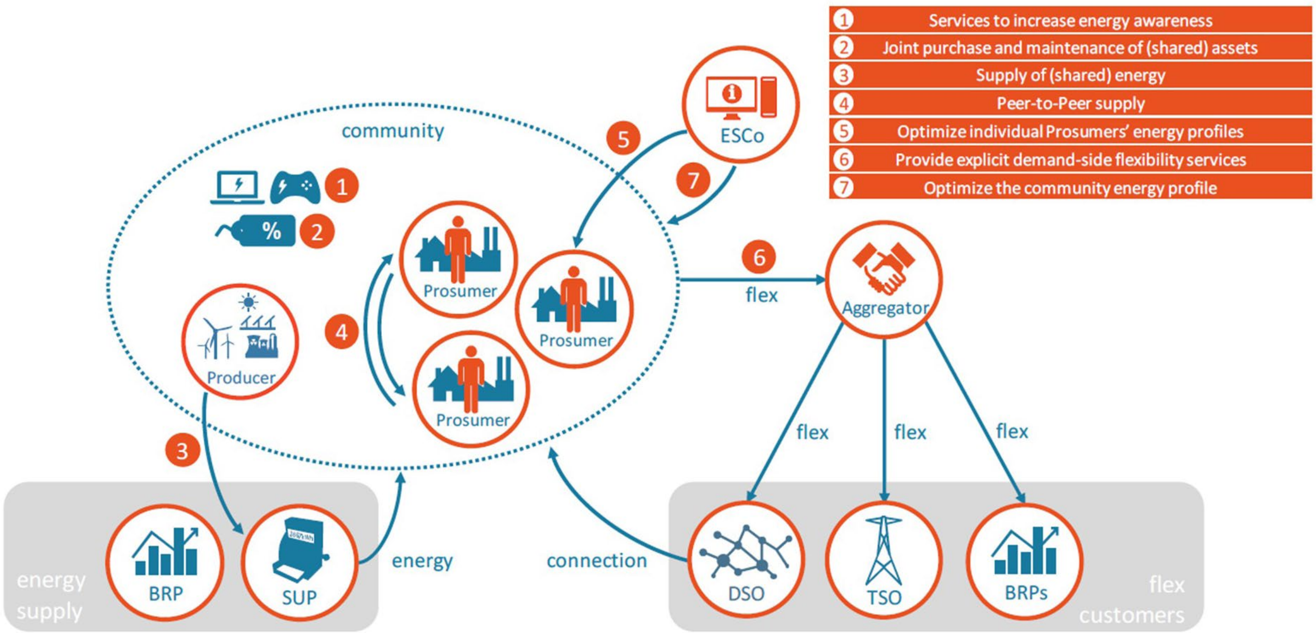


**Figure 5.5** Integration of energy communities in the energy systems (Klaassen and Van der Laan, 2019).

(Directive (EU) 2019/944) and in Article 2(70) of the Recast Internal Gas Market Directive (COM/2021/803). Renewable energy communities (RECs) are defined and regulated in Article 2(16) of the recast Renewable Energy Directive 2018/2001 (COM/2021/557 final). The participants' main economic activities cannot be in the energy sector, and, as such, they can enter and withdraw their affiliation at any time. The differences between CECs and RECs are based on a few features, however, they are largely similar. CECs have a wider scope, allowing citizen participation across the electricity sector, and there is no limit to their size, while RECs focus on renewables only, and types of stakeholders are limited, as they are expected to be located in the vicinity of the project. RECs must be autonomous, leading to a more democratic set-up in decision-making, while this is not a requirement for CECs (REScoop.EU, 2019).

## Primary objectives and benefits

Upscaling demand-side technologies depends on addressing the technical, financial, regulatory, and structural barriers at a local level and with public engagement, processes in which RECs and CECs are instrumental (Von Wirth et al., 2018; Fouladvand et al., 2020; Cabeza et al., 2022). According to the Directives, the main objective of creating and operating these communities is to generate social and environmental benefits rather than financial profits. Several authors find that potential participants are motivated by an economic argument in Europe and beyond (Rogers et al., 2008; Komendantova, 2021; Hackbarth and Löbbe, 2022) (*medium confidence*). The price provided by a locally owned system can often be lower than general market prices, depending on the agreements between community members. Citizen energy communities often join for joint bulk purchases or combined activities, such as building renovation. This allows them to negotiate better prices. At the same time, others emphasize the prevalence or co-occurrence of the pull-effect of social factors (Masson and Fritsche, 2021; Vesely et al., 2021), social norms, trust, and environmental concerns (Kalkbrenner and Roosen, 2016; Sloot et al., 2019). A willingness to participate in or support the local community can also drive projects (Fischer et al., 2021) (*medium evidence, high agreement*). As summarized in Figure 5.5, citizens can enter the energy system at any level, become part of the energy communities and cooperate in them in varied ways. These bottom-up local organizations not only implement projects directly, but have a demonstrative effect, raising public awareness and monitoring value (Azarova et al., 2019).

## Status of energy communities in Austria

Austria had already introduced the concept of energy communities before the EU mandates. Collective self-consumption (CSC) was already provisioned in 2017 in the amendment of the Electricity Act (ElWOG) (BGBl. I Nr. 110/2010). This law enabled private and non-private CSC to be established and operated (Frieden et al., 2020), with a limitation placed on the participation by large companies and energy companies (Gemeinschaft schafft Energie, 2023). Austria was a frontrunner in enacting the final legislative transposition of the EU Directives in summer 2021. As a result, for example, owners of multi-apartment buildings can share electricity, which was previously hardly possible. Wierling et al. (2023) identified 384 energy communities in Austria, applying a slightly broader understanding than that of the legal text, which makes it the fifth most abundant country in Europe after Germany, the Netherlands, Denmark, and Ireland.

The Coordination Office for Energy Communities was set up in 2021 in Austria. This collaborates with public advisory institutions in the federal provinces, helping them set up energy communities. Energy communities in Austria can access funds to increase energy efficiency and the penetration of renewables. Some municipalities and federal provinces have transformed their support schemes for single installations (e.g., PV in general) to support either larger (usually commercial) scale investments or energy community solutions. The Austrian government provides up to four million Euro to support the establishment of energy communities. On federal province level, energy communities are supported (e.g., in Styria) locally. For instance, the City of Graz introduced financial support in 2016 that extended to 2020 (Frieden et al., 2020).

Compliance is monitored with reference to the legal requirements for energy communities. The energy community should provide data and information to the regulatory authority, which performs random or case-by-case compliance checks. The regulatory authority should publish an annual report on the energy communities established in Austria, and in particular on the number and regional distribution of energy communities.

Despite the empowerment potentials of decentralized energy systems, not all societal groups are equally positioned to benefit from energy community policies, with issues of energy justice taking place within initiatives, between initiatives and related actors, as well as beyond initiatives (Villavicencio Calzadilla and Mauger, 2018; Van Bommel and Höffken, 2021).

Energy communities are seen as essential elements of a future-proof, sustainable energy system (Cabeza et al., 2022; Pathak et al., 2022) and particularly in Austria (Azarova et al., 2019; Cejka et al., 2021; Fina and Monsberger, 2023; Wierling et al., 2023) (*limited evidence, high agreement*). However, whether this will effectively be the case is dependent on their uptake during the next years, as this will define their system-wide impact.

## 5.5. Circular and sharing economy and the role of digitalization

Circular economy (CE) and sharing economy (SE) are overlapping business models that benefit climate mitigation by providing for personal needs with reduced amounts of energy and material. CE "designs and manages both, processes and outputs to maximize ecosystem functioning and human wellbeing" (Murray et al., 2017, p. 369) (see Cross-Chapter Box 5). SE refers to an 'economic system in which goods are not necessarily owned by consumers, and services are not necessarily offered by an enterprise, but can be shared between different consumers and used by other consumers' (Heinrichs, 2013; Acquier et al., 2017). Austria's level of circularity is slightly better than global average (9.7 % vs. 8.6 % respectively), which could be increased four-fold with relevant technological and structural changes (de Wit et al., 2019), but its ultimate success depends on consumer commitment (Ghisellini et al., 2018; Holzer et al., 2023) (*medium confidence*). CE and SE are also attractive, because they offer opportunities for new investments as well as redesigned lifestyles (Hörtenhuber et al., 2010; Aigner et al., 2023a) (*limited evidence, high agreement*). In this chapter, we focus on the aspect of the end-users, such as on the private and business consumers, as opposed to the suppliers as in Chapter 4 (Section 4.2). This aspect complements the assessment of how to achieve circularity (see Sections 4.2, 3.3.2 and 3.4.4) with the involvement of the users, whose role is not explored enough (BMNT, 2019) (*medium evidence, high agreement*). Building on the European and Austrian strategies (e.g., European Commission, 2020; BMK, 2022), various behavioral changes and changes in social norms and practices are necessary to actually achieve emission reductions. Austria adopted the 10R framework (Potting et al., 2017) in the Austrian Circularity Strategy (BMK, 2022) as presented in Table 5.1. The ten levels of circularity indicate how to retain raw materials optimally in the cycle with R1 'refuse' highlighting the importance of simply consuming nothing. Thereby, these strategies are in line with the ASI framework (Cross-Chapter Box 4), where the R1 and R2 levels **avoid** a demand for energy and materials at the design phase, the R6–R10 levels **shift** the system level efficiency by changing products or services, and the R3–5 and R7 levels **improve** the efficiency of the product and service by reducing the energy/material input necessary. Related individual behaviors and practical examples in Austria are also indicated in Table 5.1. In this sub-chapter, we highlight the current lack of methodological strong research, which implies that more research funds are needed to study how to encourage end-users to adopt new consumption habits and decisions.

Although all Rs are relevant for the user side, the consumer behavior most commonly associated with the circular economy is the correct disposal of waste and recycling. In the micro census, 94.4 % of Austrians report that they collect waste separately (Neubauer, 2020). Generally, the public perception (in contrast to the mixed discussion in the media) of the circular and sharing economy is positive (Hartl et al., 2024). However, the amount of waste is increasing, and waste is not collected perfectly. In particular, concerning food waste (about 1/3 of food is wasted in Austria), regular public outrage occurs although the amount of food waste is not declining, indicating a high intention-behavior-gap in the society (Schanes et al., 2018) (*high confidence*). Although evidence on the determining attitudes of food waste and possible interventions is still rare, the existing evidence suggests that saving money is more important than environmental attitudes (Schanes et al., 2018).

Concerning ways to define individual behaviors related to the sharing economy, these can be distinguished between (a) business-to-consumer models (e.g., car sharing organized by an enterprise), (b) peer-to-peer exchange via one responsible individual based on a platform (e.g., couch surfing), and (c) consumption within self-regulated communities without a distinct authority (e.g., community gardens) (Hartl and Hofmann, 2019). Whereas pragmatic and economic reasons can be examined to predict the private demand for shared services and products, the identification as an environmentalist can predicts whether a private person supplies shared services or products (e.g., the willingness to share their own car) (Hartl et al., 2020).

Table 5.1 gives a selection of examples of the direct role of consumers in Austria to realize the Rs of the circular and sharing economy. Alaux et al. (2024b) (as detailed in Chapter 3) shows the potential emission reductions from, for example, building materials that can be gained by applying circularity, which can only be achieved if consumer decisions and behavior change occur simultaneously. By transforming both the consumer and production sides, it is possible to capture carbon (e.g., via wood-based construction of passive-housing) with tenants with low-carbon behaviors, which is particularly relevant for Austria (Sikkema et al., 2023).

### 5.5.1. Drivers, barriers, and measures to foster the circular economy and sharing economy

Circular economy is a systems level change, where consumers have a major role to play. It is insufficient to accomplish infrastructural and production-side changes, while it is also not enough for the consumers to be willing to recycle and share more. These need to concur. Almost all Austrians (98 %) believe that consumers have the largest role to play to reduce food waste (European Commission, 2015). Several of the R10 strategies have been in use for decades, for example, recycling, but these might have unexpected incentives and rebounds (Santarius and Soland, 2018; Brock et al., 2021).

Consumers' deliberate choices are preceded by behavioral intentions that, in turn, depend on their attitudes, perceived social pressures, or subjective norms, as well as their perception of control over their behavior (Ajzen, 1991). This explains why, in many instances of the circular economy implementation, there is a positive end-user attitude, but no collectively significant level of action has occurred (*medium evidence, high agreement*). Tröger and Panhuber (2023) found that 60 % of Austrians agree that there should be a ban on destroying clothes that are still in good condition and that these should be available for purchase. Still, secondhand shopping is not a common practice among the population, and sharing clothing is only relevant for luxury apparel (Pantano and Stylos, 2020). A recent study in the Netherlands (Koch and Vringer, 2023) showed that 60 % of the respondents were willing to buy secondhand clothing, but only less than 10 % actually do so. Nonetheless, secondhand business models are believed to generate overall more consumption because of moral licensing. The consumer decides to take advantage of products and services at three key moments: At the points of purchase, use, and disposal (Wastling et al., 2018).

Based on the combination of system preparedness and the intention-behavior approach described above, the key barriers to circular economy strategies in Austria are the following (De Jesus and Mendonça, 2018; Zero Waste Austria, 2021; Zibell et al., 2021; BMK, 2022):

**Table 5.1** Definition of the circular economy levels and their corresponding behavior and practical examples specifically in Austria based on Potting et al. (2017) and BMK (2022). Source: general and food examples own collection; Information and Communication Technologies (ICT) (Zeiss, 2019).

| | Circular economy strategies | Examples of corresponding individual behavior and decision | General practical examples of existing initiatives | Practical examples in food systems | Practical examples of ICT platforms |
|---|---|---|---|---|---|
| R1 | **Refuse:** Abandoning redundant products and services | Anti-consumption attitude: Buying, demanding, gifting nothing | Avoiding packaging: zerowasteaustria.at/verpackungsfrei-einkaufen-in-wien.html | Transformation to vegan or buying nothing or only regional food, e.g., Ama Bio Siegel | Codecheck.info – ecoGator – Evocco app – ToxFox |
| R2 | **Rethink:** Increasing the intensity of the use of products/services | Sharing on peer-to-peer or business level/enhancing multifunctions, e.g., home-office | Peer-to-peer lift-sharing: blablacar.de | 'Host a dinner' initiative: Eatwith.com | Airbnb.at – share-now.com – at.getaround.com – fragnebenan.com – peerby.com – grover.com |
| R3 | **Reduce:** Increasing efficiency in manufacturing or reducing environmental impact | Buying, demanding and giving products and services with lower footprint | Adopting sustainable slow fashion: dariadeh.com/pages/philosophy | Visit vegetarian restaurants; Vienna is among the 6 most vegetarian cities in Europe (McDonagh, 2021)/Purchase energy efficient food processing devices | GreenMeter.eu |
| R4 | **Reuse:** Using a discarded product again in its original function | Buying products in reusable packaging and returning to the service provider | Informal retail (flea markets) and second hand shops attract 20 % of purchases in clothing, 12 % in books and games (no downloads) (Statista, 2023) | Buying milk in glass bottles with return services, reintroduced by Berglandmilch (2020) | Vinted.at – Nebenan.de – peerby.com – Restado.de – Kaputt.de |
| R5 | **Repair:** Correcting a defective product so it can be used in its original function | Repairing broken electronic goods, shoes etc. | zerowasteaustria.at/verpackungsfrei-einkaufen-in-wien.html | Viennese Food Bank guidance on distribution of 'best before' products (Wiener Tafel, 2016) | Shop.fairphone.com – ifixit.com – kaputt.de – Shift.eco – wertgarantie.de – ReplaceDirect.de |
| R6 | **Refurbish:** Restoring an old product to bring it up to date | Collecting and giving away old products, willingness to buy upcycled products | Creating new fashion based on old fashion: Karja.at | TooGoodToGo App where consumers can buy food products that are close to their end-date at a much lower price | Amazon Renewed – Circularcomputing.com – Mudjeans.com – refurbed.at |
| R7 | **Remanufacture:** Using parts of a discarded product in a new product with the same function | Cooking with leftovers, accepting reuse of products from upcycled materials | Remanufacturing of construction materials from demolitions: Restado.de is the largest marketplace for reclaimed construction materials in Europe | The company '2nd chance cereal' produce granola made from unsold bread (Sofia project, 2020) | excessmaterials-exchange.com – Roetz-bikes.com |
| R8 | **Repurpose:** Using a discarded product or its parts to create a new product or service for a new purpose | Using products for a new purpose | Various design handicrafts, e.g., selling on Etsy and promoted by municipalities | Products based on food waste: Unverschwendet.at. Note there are traditional meals that use, e.g., stale bread (French toast) (Peschel and Aschemann-Witzel, 2020) | No example found |
| R9 | **Recycle:** Processing the materials to obtain a new (higher or lower grade) quality | Willingness to pre-sort, recycle at home or collect in separate waste collection system | Large and established businesses in collaboration with municipal services. On the individual level, cost savings benefit those that reduce their municipal waste through waste selection. | Production of compost: wien.gv.at/umwelt/ma48/beratung/muelltrennung/biogener-abfall/kompost.html | Renewi.com |
| R10 | **Recover:** Incinerating materials with energy recovery | Willingness to pre-sort and collect waste in the available system (e.g., bring to a waste park) to incinerate it | Waste incineration though a separation system is also high in Austria (as opposed to landfill) producing heat and electricity. Also complying with the aims of local sourcing. | Food incineration | No example found |

- Technological and infrastructure barriers include the availability of and access to the traditional as opposed to the circular economy alternative, for example, to mobility-as-a-service, public transport, or sharing system (see Section 3.4). Due to the system lock-ins, it is typically easier to use the less sustainable solutions, and these require extra efforts to change (*high confidence*). The distribution of space favors cars, which makes them easy to access. A way to break lock-ins is to ensure that the more sustainable options (e.g., those relevant for CE and SE) become the default options, and thus the decisions to use or apply them become straightforward (Niedderer et al., 2014) (*limited evidence, high agreement*). For example, redesigning city centers with pedestrian areas will make walking self-evident instead of car use (see Section 3.2).
- Legislation also limits the scale of the circular and sharing economy on the consumer side by reducing the opportunity, usually providing for the safety of the consumer (e.g., best-used-before date, obligations of packaging, restrictions on donating food). In the same way, wholesalers and supermarkets establish their own internal rules on, for example, quality criteria (e.g., size, color) and dispose of the low-quality or non-standard products (e.g., fruits and vegetables) before they get to the consumers (*medium confidence*).
- Financial and market barriers limit the purchase of organic and often regional products because only negative (e.g., labor costs) but not positive (e.g., health, environment) costs are factored in, which reduce the competitiveness of the product (*medium confidence*). Economic decisions also affect wholesalers and supermarkets, who optimize packaging and visual appeal (e.g., shiny apples), assuming that this will increase consumer satisfaction (Zero Waste Austria, 2021).
- Consumers are encouraged to purchase and dispose of products through advertisements, peer-pressure, perceived style (e.g., matching colors, seasonal products such as decoration, chocolate Easter eggs, Christmas cookies), and planned product obsolescence. In addition, buying nothing, repairing (e.g., clothes), avoiding (e.g., a car), or reducing (e.g., a small flat) strategies induce shame and involve stigmatization, as others might think one is poor (Anderluh et al., 2023) (*limited evidence, medium agreement*). Making the CE alternatives attractive (e.g., asking celebrities to advertise the sustainable solution) could counteract the traditional triggers. For example, the French government and the French Environmental Agency (ADEME) produced and streamed a national communication campaign to popularize non-consumption and repairing products just ahead of the 2023 Black Friday, titled 'What if we asked ourselves the right questions before consuming?'. However, empirical assessments of the effectiveness of such initiatives are rare.
- Lack of literacy and skills among consumers. Knowledge and skills (e.g., which products can be repaired and how) and the likelihood of using technological systems (e.g., app-based e-bike sharing), as well as opportunities to acquire this knowledge and skills, are often missing (one exemption is a regulation that requires financial advisors to ask investors about their environmental preferences and to inform them accordingly (Seifert et al., 2024)).

Drivers of consumer-adoption of circular economy solutions make it easier for the end-user to carry out the desired behavior and harder to carry out the undesired one (Niedderer et al., 2014) (*limited evidence, high agreement*). Several factors can influence access and ease of using circular or sharing solutions in Austria. (1) Legal and regulatory requirements and standards lead the consumer towards the CE solutions by default. For example, all building and infrastructure development in Austria could be supplied from demolished old building materials (de Wit et al., 2019), which could be mandated by building standards, reducing the need to actually make an end-user decision. (2) Available and easily accessible infrastructure could channel users towards using more circular economy solutions. Presenting environmental food choices as a default option increases, for example, the tendency to make vegetarian choices (Hansen et al., 2021). An increase in density of the public transport infrastructure and closeness of shared mobility (cars, bikes, scooters) has been found to reduce car kilometers traveled. For instance, Mulalic and Rouwendal (2020) provided real-life evidence that the establishment and extension of the underground network in Copenhagen, Denmark, led to a reduction of the total number of cars of 3.4 %, while a certain (most strongly affected) district saw a car ownership reduction of up to 14 %. These findings are in line with the theoretical direct effects found by Holmgren (2020), and may grow to 10–39 % in the long term (*limited evidence, high agreement*). Digitalization has drastically increased the solution spectrum for both business models and peer-to-peer sharing solutions benefitting from faster and more direct involvement (Räisänen et al., 2021). (3) Consumers can be further motivated to use CE strategies (e.g., repair, refurbish, reuse) when it is easy, socially acceptable, and affordable to do. The cost reduction of public transportation shown in field experiments indicated that usage can be increased by cheap or free travel (Gravert and Olsson Collentine, 2021), although this does not necessarily reduce car usage. On the contrary, taxes can boost the uptake of non-environmentally friendly solutions through price signals (Porter and Linde, 1995). Requiring the provision of information on environmentally friendly consumption options at the point of sale can motivate pro-environmental choices (Seifert et al., 2024).

Recognizing the behavioral drivers of circular solutions also increases engagement with these solutions through, for example, attitudes or perceived social pressure (see above). Regarding the first one, providing information in the form of a product signature (e.g., labels) increases trust and knowledge about products (however see the issue of greenwashing). Labels informing people about regional and/or organic food products are well-known to Austrians, and about 61 % of respondents know the AMA Biosiegel and 42 % the EU-BIO-LOGO (Agrar Markt Austria, 2023). Regarding the latter, peer pressure, social norms, and social identity influence purchase choices, product use, or product disposal, as well as the habit of using public transport (Franssens et al., 2021). One promising intervention for reducing litter that needs further investigation is motivating people to pick up litter from others (e.g., during hiking trips or even in cities) (Rosenthal and Yu, 2022). Studies suggest that identification as an environmentalist predicts the willingness of car owners to offer carpooling, whereas economic and pragmatic reasons predict decisions to consume car-sharing services (Hartl et al., 2020). Feedback in combination with gamification (e.g., growing/shrinking tree for slow/fast driving) is also an efficient way to motivate people to use less energy while driving cars (Dahlinger et al., 2018), heating (Carrico and Riemer, 2011; Staddon et al., 2016), or taking long showers (Tiefenbeck et al., 2018).

Successful interventions are based on a thorough high-quality empirical analysis of drivers and barriers of behavior (see COM-B model by Michie et al., 2011). Therefore, the servicing system (e.g., availability of local products) needs to be upscaled, and the intention-behavior gap should be tackled at the same time. Individuals need knowledge and skills (i.e., competence) to perform a specific behavior, and they need to be motivated emotionally and rationally to pursue a specific behavioral goal. Finally, the financial, physical, and social contexts and infrastructure also need to encourage individuals to perform a specific behavior. However, there is currently a lack of rigorous large-scale development of and tests on efficient interventions due to a lack of sufficient financial research funds in the behavioral sciences.

### 5.5.2. Digitalization in a circular and sharing economy

Digitalization is without a doubt seen by many economic actors as a potential silver bullet for solving environmental problems and for achieving net-zero emission economies (Ellen MacArthur Foundation, 2019; Bolton et al., 2022; Schober and Mattke, 2022). For example, digitalization has been said to reduce energy consumption, because it encourages the use of using cloud services (virtualization), the collection, monitoring, and optimization of data flows across all product life cycle levels, and connects people and businesses that would otherwise not have been connected (Zeiss et al., 2021; Bolton et al., 2022). However, even though digitalization might indeed support the move towards CE, it has multiple side effects that can transform efficiency gains into increased resource consumption (Coroamă and Mattern, 2019; Santarius et al., 2020; Pouri, 2021). For example, video streaming results in the consumption of even more video hours, thus increasing energy use (Santarius et al., 2020), which, in turn, increases emissions from data centers (Lord et al., 2022). Even in the case of teleworking, where the $CO_2$ savings from reduced commuting appear to be large, a number of rebound effects have been reported, such as short-term effects (e.g., increases in ICT consumption) and long-term effects (e.g., larger houses, greater distance to work, other energy-intensive purchases) that offset or even eliminate the energy savings (O'Brien and Yazdani Aliabadi, 2020). Thus, the most important guiding principle for using digitalization to reduce $CO_2$ impacts is 'digital sufficiency', which Santarius et al. (2022, p. 2) describes as "any strategy that directly aims at decreasing the absolute level of resource and energy use by reducing the levels of production and consumption" for the dimensions of hardware, software, user, and economy. As such, the issue is not only to produce fewer devices and make them more energy-efficient, but also to reduce the energy footprint of software, increase users' sustainable behavior when using digital devices and, finally, to support a transition to sufficiency-oriented business models that promote public and community goods (Santarius et al., 2022).

After a summary of ICT opportunities, this section provides a much-needed counter-perspective to the many overly optimistic accounts in practice-oriented reports by consultancies such as Deloitte and McKinsey, which see innovative ICTs such as artificial intelligence (AI) and Big Data as a panacea for many environmental problems. To obtain a realistic picture of the overall effects of digitalization efforts on CE, the following sub-section briefly reviews the current state of the use of ICT in the circular economy and the corresponding debate on its effects, placing a special focus on digital rebound effects (Coroamă and Mattern, 2019; Schmelzle et al., 2022).

In the circular economy, managing information flows (market, actor, material object, and activity-related information flows) (Zeiss, 2019) is the key for leveraging positive impacts (Kirchherr et al., 2018). For example, extending the life of products through repair requires a knowledge of their condition, location, and repairability. Recent advances in IT, such as sensor-based technologies that generate information or predictive analytics, can leverage such information and offer opportunities to integrate information into material flows that can be highly transformative in CE application scenarios (Zeiss, 2019). In the following section, typical ICT support for such information flows is reviewed.

- **Big Data analytics and artificial intelligence** which be used to analyze large sets of data can reveal insights and patterns that help identify opportunities for circular practices, such as recycling or refurbishment (Berg and Wilts, 2018; Ellen MacArthur Foundation, 2019). Information systems can provide decision-makers with real-time data and insights and report key circular economy performance indicators, helping organizations set targets, monitor progress, and improve their circular practices (Saidani et al., 2019). As such, these tools help actors make sense of the smarter use and lifespan extension of material objects by providing relevant information at the right time (Zeiss, 2019). One example is GreenMeter.eu, an app designed to educate people about biodiversity in their backyard and to provide directly applicable recommendations for biodiversity conservation or restoration in specific locations. Furthermore, approaches taken to assess individual consumption habits are increasingly digitalized. Examples are personal carbon accounting, which records and calculates $CO_2$ amounts and other GHGs that a person or household emits into the atmosphere through their daily activities and consumption patterns. The aim of personal carbon accounting is to raise awareness for the individual carbon footprint and to encourage more environmentally friendly behavior (Bolton et al., 2022).
- **Product lifecycle information systems** capture data in areas ranging from design and manufacturing to usage and disposal. These data help businesses optimize product design for durability, repairability, and recyclability (Berg and Wilts, 2018; Zeiss et al., 2021; Bolton et al., 2022). For example, information systems can support virtual simulations and modeling for circular product design, analyzing factors like recyclability and disassembly. These can simulate product lifecycles, material choices, and end-of-life scenarios to optimize for circular outcomes. For example, digital twin technology creates virtual replicas of physical products, enabling the real-time monitoring, maintenance, and optimization of product performance throughout the lifecycle (Zeiss et al., 2021). This helps create products that are more conducive to the circular economy (Bolton et al., 2022). ICT can also aid in the proper collection, dismantling, and recycling of electronic waste, ensuring that valuable resources are recovered and hazardous materials are handled safely. ICT can facilitate efficient reverse logistics processes, ensuring that the products and materials used are collected, sorted, and transported to appropriate recycling or refurbishment facilities (Bolton et al., 2022; Wilson et al., 2022).
- **Task-supporting information systems** support the transformation of material objects to extend their lives or the lives of their components and raw materials. CE practices, however, expect actors to actively participate in complex and cognitively demanding tasks, such as repairing a smartphone or recycling manufacturing waste (Zeiss, 2019). For example, platforms such as kaputt.de help stakeholders identify the defect, find suitable solutions (e.g., self-repair, professional repair service, replacement/disposal), and carry out the actual repair by providing activity-based information, such as repair and disassembly instructions, cost estimates, or a list of required tools (Zeiss, 2019).
- Integrating **Internet of Things (IoT)** into CE will provide means to track and monitor the condition and performance of products throughout their lifecycles (Wilts and Berg, 2017; Zeiss et al., 2021). These data can be used to optimize maintenance schedules and extend product lifespans by facilitating the return, repair, or recycling of products (Berg and Wilts, 2018; Bolton et al., 2022). Against this backdrop, information systems can create material passports that document the composition and origin of materials in products. These passports facilitate easier recycling and support the use of recycled materials in new products, but also facilitate predictive maintenance, optimizing resource use and reducing waste (Hoosain et al., 2020).
- Information systems can also be used to **optimize inventory levels**, reducing overstocking and waste. By tracking

product usage and demand, businesses can better plan production and distribution. In the supply chain, information systems provide transparency, allowing stakeholders to track the flow of materials, products, and components throughout their lifecycles. This visibility helps identify potential points of waste generation and supports responsible sourcing. These tools can also be used to support waste management and recycling processes by optimizing collection routes, tracking recycling rates, and identifying opportunities for improvement (Zeiss et al., 2021). Blockchain technology can enhance transparency in supply chains, allowing consumers to trace the origin and lifecycle of products. This may help in verifying sustainable and circular practices (Wilts and Berg, 2017). For example, the Dutch start-up Circularise (circularise.com) created a decentralized communication protocol based on blockchain to improve data quality and availability in circular value networks without releasing datasets or actor identities (Zeiss et al., 2021).

- Information systems can enable the **creation of digital platforms and marketplaces** that support circular business models such as sharing and renting (rethinking), and remanufacturing (Berg and Wilts, 2018; Wilson et al., 2020). These platforms connect consumers and businesses interested in circular practices. For example, online marketplaces for reuse facilitate the exchange or resale of used products and materials by connecting sellers and buyers, making it easier to find secondhand goods and extend the life of products. ICT enables the shift from traditional ownership models to 'Product-as-a-Service' models. Instead of buying products outright, consumers can access products and services on-demand. This encourages manufacturers to design for durability and easy repair, since they retain ownership of the product.
- **Matchmaking information systems** for CE practices help stakeholders find and compare supply and demand for physical material objects and negotiate and contract terms and conditions of the proposed transaction (Zeiss, 2019). Thus, such systems create transparency, reduce complexity, build trust, and act as legal advisors. Typical examples are sharing platforms, such as Vinted (ex Kreiderkreisel, vinted.at) or willhaben.at, where users can present secondhand clothes and other products with the aim to sell, exchange, or give away items for free (rethink and reuse).
- **Collaborative information systems** allow different stakeholders, including businesses, governments, and NGOs, to share knowledge, collaborate on circular initiatives, and drive collective action (Zeiss, 2019). Information systems can be utilized to disseminate information about the circular economy to the public, raising awareness and promoting responsible consumption habits. Cloud-based platforms enable collaborative sharing and access to data, fostering collaboration between stakeholders involved in circular economy initiatives (Bolton et al., 2022). An example is PACE (pacecircular.org) a European-wide platform which serves as a networking and knowledge-sharing hub and brings together various stakeholders from the public and private sectors, including businesses, governments, NGOs, academia, and other organizations. These stakeholders collaborate to exchange best practices, innovative ideas, and solutions related to circular economy practices, policies, and technologies.

The impact of Green IS on environmental sustainability is two-fold (Kranz et al., 2015). Direct effects arise when ICT itself directly contributes to reducing the negative impact on the environment by reducing the consumption of natural resources over the entire life cycle from production to recycling, while indirect effects help societies and companies (e.g., in the areas of production, logistics, energy, and mobility) to operate more eco-efficiently. They can even be systemic, leading to medium- and long-term changes in economic structures and behaviors that support more eco-efficient practices (Henkel and Kranz, 2018). Please note that, due to their novelty, there is little empirical research on the impact of innovative ICT, such as Big Data, AI, and Blockchain, on the environment in various application areas, not only in Austria but worldwide (Lange et al., 2023). As such, it is not surprising that empirical studies on general rebound effects in the Austrian context are also rare, and those with an explicit ICT reference are almost non-existent. For example, a recent review on ICT-induced rebound effects shows that only 4 % of studies are from Austria, 4 % from Switzerland and 12 % from Germany, 14 % from the UK, and 9 % have an EU-wide perspective (Font Vivanco et al., 2022).

### 5.5.3. Risks associated with circular and sharing economy, in particular digital rebound

Business models that engage consumers in behaviors supporting the circular economy also engender backfiring risks. A study from France showed that secondhand fashion offers tempt consumers to buy more than regular fashion offers would; the pro-environmental image of secondhand fashion offers a justification for buying more (Parguel et al., 2017).

Generally, there is a risk that consumers choose one easy sustainable option (e.g., waste separation) to justify their other unsustainable behaviors (Brudermann, 2022). Another risk is, for instance, if car-sharing offers lead to a switch away from public transport instead of a switch away from a private car. However, estimates from Italy suggest that the substitution rate of private cars is five times higher on average than that of public transport (Ceccato et al., 2021). The sharing economy is based on constant financial flows that allow access to goods and services (e.g., rent for a car), which is a risk for households with unstable income flows (Anderluh et al., 2023).

As the use of ICT in the circular economy relies heavily on electronic devices, the increasing use of ICT systems can lead to increasing energy levels. Predictions range from 1.9 % of global electricity use by ICT (Malmodin and Lundén, 2018) to as high as 6.3 % (Andrae and Edler, 2015). While it is difficult to arrive at definite numbers, researchers agree that, despite efficiency gains due to improvements in data centers and devices, energy use for ICT infrastructure could continue to increase (Hittinger and Jaramillo, 2019; Freitag et al., 2021). In addition, environmental and social issues can arise from the production of ICT due to disposal and recycling practices for electronic equipment, the exploitation of limited resources, and insufficient environmental standards (Lange et al., 2023). For example, ICT will also lead to an increase in electronic waste (e-waste), if the products are not managed properly. Although ICT can support the circular economy and recycling in other industries, the hardware is not yet built entirely out of recycled or renewable materials (Santarius et al., 2022). Against this background, digitalization in manufacturing only brings about marginal efficiency improvements (Lange et al., 2023). There are also more optimistic projections, such as the SMARTer 2030 (GeSI, 2020), which states that ICT could contribute to a 20 % reduction in global $CO_2$ emissions by 2030. However, these often do not consider rebound effects (Freitag et al., 2021), such as the following:

- Due to Big Data analysis, AI and video streaming **data volumes are increasing** (Freitag et al., 2021), which, in turn, leads to the exponential growth of data storage, processing, and transmission. Hence, the increasing reliance on IT infrastructure, data centers, and digital technologies leads to higher energy consumption and environmental impacts associated with manufacturing and operating these systems (Morley et al., 2018; Lord et al., 2022; Zhang and Wei, 2022). The massively growing volume of data completely or partially offsets the previous savings potential, even though the energy and resource efficiency of data processing and transmission is constantly being improved (Malmodin, 2020). For example, model training for AI applications and even more so model inferencing (Biewald, 2019) has been predicted to significantly contribute to $CO_2$ emissions (Strubell et al., 2019; Freitag et al., 2021). Thus, calls are increasing for AI to be developed not only for sustainability (Schober and Mattke, 2022), but also so AI itself becomes more eco-friendly (Schwartz et al., 2020; Santarius et al., 2022).
- The **increasing use of IoT** is another factor, which might increasingly contribute to the carbon footprint of ICT in the future (Freitag et al., 2021). There are estimates that the IoT semiconductor production alone could increase 18-fold to 722 TWh in 2025 (Statista 2020, cited by Freitag et al., 2021). For example, in smart home scenarios smart meters are used to provide transparency on energy usage, also with the aim to save household energy due to intelligent redistribution of energy (Pohl et al., 2021). However, smart home technology might also lead to adopting new services (e.g., security services) or intensifying current services (e.g., media entertainment), which, in turn, promotes even more energy consumption (Wilson et al., 2017; Freitag et al., 2021). Against this backdrop, efficiency gains are highly dependent on various context factors, which are difficult to assess in model calculations, such as size of households, adoption patterns due to privacy and security risks (Wunderlich et al., 2019), frequency of data transmissions, and direct effects such as resource consumption in the production process and resource disposal. Thus, in the example of smart meter rollouts, even optimistic assessments tend to show small efficiency gains overall, if any (Gährs et al., 2021), making a 'blind' technological rollout without a thorough impact analysis across the product lifecycle rather questionable (Veit and Thatcher, 2023).
- While IT can enable transparency and traceability in supply chains, it can also contribute to large rebound effects if not managed carefully. An example is **blockchain technology** which is supposed to enhance transparency in the supply chain (Kouhizadeh and Sarkis, 2018), but has serious environmental implications. Many blockchain networks, and especially those that use proof-of-work (PoW) consensus mechanisms (such as Bitcoin), require significant computational power to validate transactions and create new blocks. This leads to high energy consumption, as powerful hardware continuously performs com-

plex calculations, with increasing carbon footprints comparable to whole nations (Freitag et al., 2021). Moreover, the generation of e-waste due to the need to frequently replace hardware, increase the frequency of software updates, and centralize mining activities in regions with cheap electricity are not only problems related to blockchain technology, but general issues of ICT use. Newer consensus mechanisms, such as proof-of-stake (PoS) and other variations, may offer potential solutions that reduce energy consumption compared to PoW. Additionally, efforts are being made to develop more energy-efficient blockchain protocols and to transition existing networks to more sustainable consensus mechanisms, but opinions are mixed about whether these efforts might work (De Vries, 2019).

- As indicated above, while IT may enable new business models and services that extend the life span of products through repair, refurbishment, or sharing, it can also lead to **higher consumption in other areas,** leading to rebound effects that cancel out some, if not all, potential savings (Freitag et al., 2021; Lange et al., 2023). For example, a shared mobility platform can encourage people to travel more frequently, leading to higher overall energy and resource consumption (Lord et al., 2022). Moreover, induction effects may result from the introduction of ICT applications, because they create new options for consumption and production and cause an increase in the demand for energy and resources (Lange et al., 2021). These negative side effects increase economic growth overall, thus increasing energy demands, which offsets potential energy and resource savings (Bieser and Hilty, 2018). The transportation example is a good example of such complex, higher-order effects that introduce new problems in transportation and logistics. These include not only increasing emissions from data centers, but also wider psychological and societal problems, such as de-skilling and a greater supply of low-skilled workers, coordination problems when working with multiple platforms simultaneously, distractions from interacting with a mobile app while driving (Lord et al., 2022), and so on. Additionally, the implementation of IT systems in the circular economy may create lock-in effects, where organizations become dependent on specific technologies or platforms (Lehdonvirta, 2022). This can restrict flexibility and hinder the adoption of more sustainable alternatives in the future (Lange et al., 2023).
- Another area of concern is the **negative impact on society**. Measures applied to track and measure the carbon footprint of products or organizations, or apps and software used by individuals to track and measure their green habits, often involve the detailed, continuous monitoring and collection of various kinds of behavioral data. Therefore, a question arises regarding the appropriate level of such data monitoring and collection measures. This is directly related to issues of surveillance (Zuboff, 2015; Lange et al., 2023), data ownership, security, and privacy (Bolton et al., 2022; Hammi et al., 2022), as well as issues of algorithmic bias (Kordzadeh and Ghasemaghaei, 2022). Recent examples in the UK involve the use of automated ICT surveillance to enforce clean air zones, who has come under criticism due to faulty cameras, scam websites, and automated infringement processes.
- There are also important **side effects on the macroeconomic level** (Gillingham et al., 2016). Such economy-wide rebound effects occur "when the market adjustments and innovation processes after energy efficiency improvements lead to an overall increase in energy use within an economy" (Kulmer and Seebauer, 2019). A recent simulation study with data from Austrian households found that a 10 % efficiency improvement in the fossil fuel consumption may result in an economy-wide rebound effect of 65 %, but a comparatively weak direct rebound effect of 8–12 % (Kulmer and Seebauer, 2019). Thus, studies on rebound effects should not only focus on direct but also on higher-order effects.

To mitigate these rebound effects, it is important to monitor and assess the impact of ICT on the entire life cycle regarding its use in a circular economy. This particularly concerns wider societal implications, such as the perils of surveillance and control (Benlian et al., 2022; Lange et al., 2023).

## 5.6. Distributional justice, social tipping points and social acceptance

We have reviewed how social change happens and what cognitive, emotional, and social principles and dynamics may facilitate or hinder social change processes in order to integrate this vital level of analysis into that of natural sciences, technology and engineering and institutional design. We have adopted a pragmatic approach, tackling the question of 'what can be done and how'. We have intentionally avoided the question of 'what should be done' and the distributional justice implications of taking different approaches to answer this question. We address some of the equity and ethical considerations of climate action below. This is followed by an assessment of social tipping points in Austria towards net zero. We finish by reflecting upon the relevance of the social acceptance of policies for the political feasibility of the net-zero transition.

### 5.6.1. Distributional justice

For the last 30 years, climate action discussions have focused strongly on 'what should be done'. This has led to the definition of the threshold objectives by climate scientists of the +1.5°C or +2°C, and the associated reductions in climate emissions (see, e.g., IPCC, 2018). The question of 'what should be done' is also the question that has received the most attention in economics, with the Nobel Prize going to Nordhaus on the DICE model being a clear highlight. The question is however modified into 'what should be done to maximize social welfare' and has produced estimates of social costs of carbon as a solution (Nordhaus, 2017, 2019). Thus, the analytical framework and answers that economists take are very different from those of other climate scientists, and some commentators have pointed out that our economy is being run on economic models that fundamentally do not consider natural laws (e.g., Stanton et al., 2009; Weitzman, 2009; Kemp et al., 2022; Rising et al., 2022).

The way each of these questions is answered highlights very different ethical stances. The question on 'what should be done' often implies a stronger ethical commitment to the preservation of human lives at 'whatever cost', while the economists typically aggregate human happiness but disregard equity considerations associated with this (which can nevertheless be done by considering more complex social welfare functions than the typical aggregate discounted utilitarian). While the question on 'what should be done' implies as an objective to avoid the loss of human life and suffering in parts of the world that will be badly hit by climate change (e.g., projection of deaths from heat waves in India or displacement of coastal populations in Bangladesh), the question of 'what should be done to maximize social welfare' is answered by creating scenarios of the 'efficient' level of effort that is worth taking. This entails changes in western economies and lifestyles; e.g., is foregoing the idea of owning a car going 'too far' in climate effort? Or is reducing the usage of air conditioning in European countries and therefore potentially have higher heat-wave deaths going 'too far' in climate action? This is not to say that economic analyses do not generally consider the value of human lives, or human lives in countries projected to be more badly hit by climate change. But certainly, there is no common agreement that these need to be preserved at 'whatever cost' in terms of a loss of comfort, change in lifestyle, or aggregation of all efforts in terms of 'reduced social efficiency', as is commonly presented in the economic jargon.

The underlying ethical stances on distributional justice are very different. Distributional justice in economics is a common underdog to social efficiency (aggregating human well-being without considering the equity aspects to it). Distributional justice is at the center of the ethical debate for aiming for thresholds of +1.5°C or +2°C. The disparities between these two views have been a barrier to climate action for decades. The standpoint on distributional justice in Austria ought to be a political decision reflecting social views.

There are also critical ethical aspects of triggering social transformations of any kind, including towards net zero, that need to be explicitly addressed as part of well-functioning democratic systems. Any behavioral intervention should be challenged by asking ethical questions related to how much these modify the choice architecture, individual freedoms, or preferences, and by considering its equity and distributional implications. Reducing information asymmetries by using labels or other information interventions might help citizens make more informed choices and are widely accepted as appropriate (e.g., Sunstein, 2019). Some social welfare enhancing interventions, however, such as using a different default option in new energy contracts or interventions influencing social preferences, might be considered manipulative and ethically questionable by some groups (see, e.g., Bohr, 2016; Küppers, 2024). Indeed, information nudges are more highly accepted than choice architecture nudges (Reynolds et al., 2019; Lohmann et al., 2022), and their acceptance depends on the perceived effectiveness and fairness (John et al., 2023). In any case, studies overwhelmingly indicate that in many countries worldwide, the public largely approve nudges in the environmental, health, and safety domains (Jung and Mellers, 2016; Reisch and Sunstein, 2016; Reisch et al., 2017; Loibl et al., 2018; Hagmann et al., 2019; Sunstein, 2019; Dudás and Szántó, 2021; Krisam et al., 2021; John et al., 2023) (*high confidence*) (see also Section 6.5.1).

Still, open questions exist about the *legitimacy* of such interventions and measures, related to the question of 'who has the right to modify what people desire?'; on the *transparency* of such interventions, referring to 'do people have a right to know that such interventions are in place?'; and on the *accountability* of implementing such interventions, meaning 'how can people call for responsibilities on the outcomes or side-effects of such interventions?'. Increasing transparency has not undermined nudge effectiveness in previous research (Bruns et al., 2018) and, if anything, has improved nudge acceptance (Lohmann et al., 2022). Some of these concerns are common to other regulatory policies: While command-and-control is coercive, the harms and risks posed by the impacts of global warming provide an ethical and potentially also legal argument for limiting some aspects of individual freedom and choice. However, it is essential that any new policies explicitly build on the principles of legitimacy, transparency, and accountability that build the foundation of the Austrian democratic system. Carefully considering the ethical aspects of interventions to navigate demand-side solutions is a critical factor in determining their social acceptability.

### 5.6.2. Social tipping points

In lifestyle change processes, it is essential to understand how social norms and the spread of new behaviors can lead to reaching social tipping points, where previously minority lifestyles and choices ('early adopters') reach the majority of society. For these changes to occur, they need the support of people who make policies, regulations, set technology standards, and make infrastructural changes enabling climate-friendly lifestyles for all. Social tipping points provide a useful framework for asking where rapid social change in lowering anthropogenic GHG emissions can happen and what kind of interventions can trigger such changes (Otto et al., 2020a). In an expert elicitation process, Nabernegg and Otto (2025) asked climate scientists in Austria from different fields to propose candidates for social tipping elements that are likely to help achieve a climate-neutral society in Austria. The authors synthesized the replies in a workshop with selected scientists and conducted interviews with stakeholders from different fields to assess the plausibility of insights. Overall, 33 scientists and stakeholders participated in the process. The study by Nabernegg and Otto (2025) provides initial insights into the applicability of the concept of social tipping in Austria, but further research is needed to shed light on the specific processes and interventions needed.

The results from Nabernegg and Otto (2025) are presented in Figure 5.6 providing 7 important areas where rapid change in GHG emission reduction is possible. Corresponding 14 interventions that are likely to trigger such changes are provided in Table 5.A.1 in the Appendix, including the number of responses. The most frequent suggestions were in the area of norms and value changes, such as changed aspirations for single-family homes and cars as status symbols to increase the social status of climate-friendly lifestyles, and technology cost reduction for renewable energy production, energy storage and e-mobility. Interestingly, the answers in this area did not concern technology breakthroughs or technologies that have not yet been invented but were about providing sufficient support for the implementation of existing technologies for renewable energy harvesting and the development of decentralized solutions and the corresponding infrastructure. The experts and stakeholders also emphasized the role of legislation and the implementation of a growth independent economic system in Austria that include the recognition of the limits of economic growth as well as the limits of measures related to technological solutions and market-based instruments. Interestingly, the expert elicitation participants were rather confident that the suggested candidates for social tipping elements can lead to a rapid decarbonization in Austria, but they were somewhat less confident that the suggested candidates for social tipping elements would actually be implemented. Figure 5.6 locates the proposed areas for rapid change on structural layers of Austrian society, with a manifestation time that varies from very rapid (<1 year) to very slow (>30 years). Although changes in social norms and customs occur very slowly (Williamson, 1998), some of these changes have already been initiated in Austrian society. Given the rapid emission reductions required to avoid catastrophic climate change, it is necessary to act in each of these areas as soon as possible, regardless of their time of manifestation.

The expert elicitation process identified the following most important barriers or negative social tipping elements that would delay the achievement of climate neutrality in Austria: The possible election of an anti-climate government, a prolonged or geographically spreading war in Ukraine or other world regions, the advertisement of fossil fuel products and the fossil industry lobby, a lack of financial incentives for supporting climate neutral options, climate skepticism and denial, and finally misinformation, a low awareness of the problem, and a prioritization of short-term interests. Finally, the role of public discourse and media was mentioned as an important factor for fostering rapid social change.

On the contrary, failure to achieve a net-zero transition by mid-century at the global level could result in severe disruptions to ecosystems, societies, and economies (Steffen et al., 2018). Gowdy (2020) warns that the unstable climate conditions and massive loss of biodiversity we are currently experiencing could even lead to the end of human civiliza-

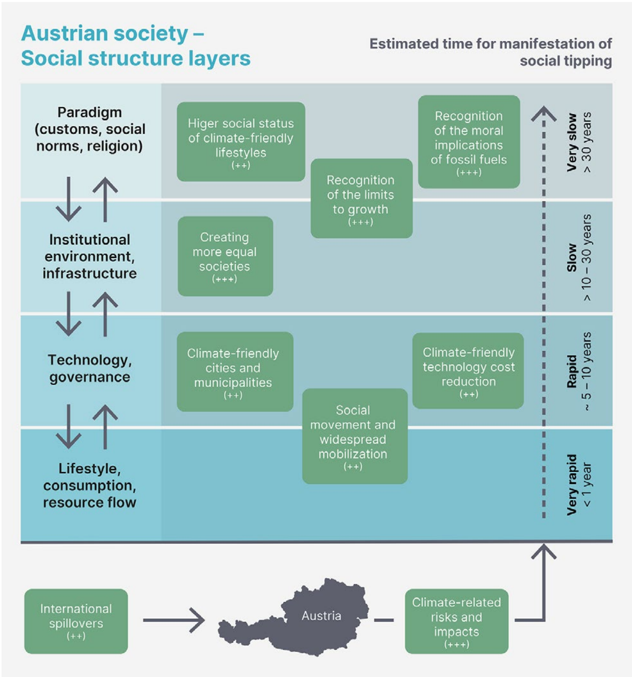


**Figure 5.6** Areas of social tipping with the potential to drive a rapid transition to net zero in the Austrian human society based on Nabernegg and Otto (2025). The processes they represent unfold across levels of social structure on widely different timescales (Williamson, 1998; Otto et al., 2020a), ranging from the fast dynamics of market exchanges and resource flows on sub-annual timescales to the slow decadal- to centennial-scale changes on the level of customs, values, and social norms. Confidence that the described phenomenon is a social tipping area is indicated by (+++) high confidence (>4.5 out of 6), (++) medium confidence (3.0–4.5 out of 6); (+) low confidence (<3.0 out of 6).

tion as we know it. If the atmosphere warms 3–4°C by 2100, and eventually as much as 8°C or more, the planet could return to the unstable climate conditions of the Pleistocene, when agriculture was impossible. Under such conditions, human societies could revert to hunting and gathering (*low confidence*). At present, however, most of the literature on climate-induced social collapse is conceptual (e.g., Steel et al., 2024) or based on literature reviews (e.g., Richards et al., 2021). Comprehensive risk assessment studies are currently lacking.

## 5.6.3. Social acceptability of decarbonization

Social acceptance for socioeconomic changes that accompany the reduction and elimination of GHG emissions is of great importance, as resistance from the public can hinder or slow down such a transition. A majority of Austrians believe that it is the responsibility of national governments to address climate change (European Parliamentary Research Service, 2021; Vlasceanu et al., 2024). Specifically, 64 % of Austrians state that they are in favor of stricter government measures imposing behavioral changes to address the climate emergency, 66 % believe that they are more concerned about the climate emergency than their government, and 83 % say they want to replace short-distance flights by fast, low-polluting trains in collaboration with neighboring countries (European Investment Bank, 2021). Recent survey results indicate a declining relevance of climate change concerns in social and geopolitical developments after 2022 and up to the completion of this assessment report (European Commission. Directorate General for Climate Action., 2023; Hajek et al., 2024; Schwaiger et al., 2025). Therefore, one should be cautious about extrapolating the previous high levels of concern and demand for climate action into the future. For Austria, the transition to reduce emissions and climate neutrality poses several challenges to various sectors in the economy and will also have substantial impact on people's lives, likely impacting various groups in society differently (Meinhart et al., 2022). It could thus enhance the acceptability of climate policies if these adhere to the Just Transition Mechanism as proposed by the European Union, which aims to "ensure that the transition towards a climate neutral economy happens in a fair way, leaving no one behind" (European Commission, 2025) (see Section 6.8.1). Results from Thaller et al. (2023) indicate that the public acceptance of climate policies depends on them being perceived as being fair, effective, and only minimally intrusive.

Many studies suggest that it is important to garner public acceptance and understanding for technologies that can enable the transition to a sustainable future, including renewable energy and low-carbon household technologies. Sposato and Hampl (2018) found that public acceptance and support for renewable energy technologies, such as solar panels and wind turbines, play a crucial role in their successful deployment and widespread adoption. Similarly, Batel (2020) highlighted the significance of public understanding and acceptance of low-carbon household technologies, such as energy-efficient appliances and smart home systems, in achieving sustainable consumption patterns.

In addition to renewable energy technologies, there is growing interest in climate engineering approaches, and particularly carbon capture and storage (CCS) technologies. Arning et al. (2019) emphasized the importance of public perception and acceptance of CCS technologies, which can play a role in mitigating GHG emissions from industrial processes and power generation. Public awareness and understanding of the potential benefits and risks associated with these technologies are crucial for their successful implementation and long-term viability. Pianta et al. (2021) further highlighted the need for effective communication strategies to address public concerns and promote public acceptance of climate engineering approaches. Academic experts perceive the feasibility of CCS technologies as medium-high (Kerner et al., 2023).

Besides the fact that climate neutrality will likely be strongly influenced by technological change, many of those technologies will still involve people, and the extent of abatement will depend on whether technologies are adopted and how technologies are used by individuals. Exadaktylos and van den Bergh (2021) pointed out that various behavioral biases can influence energy-related decisions and, in turn, lead to substantial and harmful rebound effects where energy savings are offset due to incorrect use of the new technologies. A study providing empirical evidence for the proposed hypothesis is that of Brandon et al. (2022), who showed that, against their expectations, smart thermostats had no economically significant effect on the energy use of households due to the inadequate usage of those devices by the individual users (i.e., users were likely to override beneficial default settings of those devices). Ways to overcome such inefficiencies could be effective education for energy efficiency and targeted behavioral interventions which can tackle behavioral irregularities more directly.

There is a large amount of evidence and high levels of agreement that economic incentives in the form of carbon and energy taxes are often rejected by the public (McCright and Dunlap, 2011; Baldwin and Lammers, 2016; Baranzini and Carattini, 2017); consequently, there is growing interest in designing such economic policy instruments to tackle not only efficiency but to increase its social acceptance (Klenert et al., 2018) (see Section 6.5.1). Among others, carbon tax support has been shown to be undermined by fairness concerns (Jagers et al., 2021), beliefs in the ineffectiveness of carbon taxes (Steg et al., 2006), references to the policy as a 'tax' (Kallbekken et al., 2011; Cherry et al., 2012; Baranzini and Carattini, 2017; Carattini et al., 2018) and distrust in the government (Beuermann and Santarius, 2006). The use of the tax revenue is another of the relevant factors for the support of carbon pricing (Baranzini and Carattini, 2017). Acceptability increases if tax revenues are earmarked to environmental spending (Thalmann, 2004; Baranzini and Carattini, 2017; Beiser-McGrath and Bernauer, 2019) or re-distributed similar to the 'Klimabonus' in Austria (Kallbekken et al., 2011; as suggested by Baranzini and Carattini, 2017; Beiser-McGrath and Bernauer, 2019; Carattini et al., 2019; Woerner et al., 2024). But in any case, the visibility of the use of the tax revenue to the public seems to be critical (Mildenberger et al., 2022).

Behavioral interventions have the capacity to induce lifestyle changes indirectly by fostering the social acceptability of ambitious climate policies such as carbon pricing. Tackling effects regarding references to the carbon pricing policies as a 'tax' (Kallbekken et al., 2011; Cherry et al., 2012), persuasive messages (Kaplowitz and McCright, 2015), informational interventions (Dechezleprêtre et al., 2022; Douenne and Fabre, 2022), information about compensatory measures and distributive issues, such as refunding tax revenues (Beiser-McGrath and Bernauer, 2019; Jagers et al., 2019, 2021; Douenne and Fabre, 2022), and learning about the benefits of welfare-enhancing carbon taxes (Janusch et al., 2021) have been shown to potentially influence the acceptability of and support for carbon pricing. Vlasceanu et al. (2024) conducted a 'mega-study' across 63 countries to investigate the effects of behavioral interventions on pro-environmental attitudes, beliefs, and behavior. The authors assessed the influence of 11 expert-crowdsourced interventions based on competing theoretical frameworks in the behavioral sciences on four climate mitigation outcomes: beliefs, policy support, sharing information on social media, and an effortful tree-planting behavioral task. The interventions' overall impacts were very low and mixed, with their effectiveness depending on the types of interventions and outcome measures. Across all countries, writing a letter to a member of a future generation was most effective in increasing support. The overall Austrian sample in this study consisted of 502 participants and was representative of the population in terms of age and gender. In Austria, among the 11 different interventions tested, the dynamic social norms intervention proved to be the most effective for increasing support for climate policies compared to a control group. Specifically, this study informed participants that "more and more people are becoming concerned about climate change" and highlighted changing country-level norms. Almost all of this evidence is based hypothetical scenarios and self-reports, and thus caution should be placed when interpreting the reliability of the findings (see, e.g., Kormos and Gifford, 2014).

Recently, studies on increasing the social acceptance of climate policies have started using real-life measures of policy support and making large data collection efforts in general populations, enhancing the reliability of the evidence. For example, Dechezleprêtre et al. (2022) examined support for climate policies in 20 countries responsible for 72 % of global $CO_2$ emissions. Among others, support for climate policies was measured by examining the willingness of individuals to support a petition for urgent climate action, highlighting the need for immediate emission cuts to prevent environmental harm. Specifically, when respondents were provided with detailed information about the impacts of climate change, their willingness to support this petition increased. On the other hand, explaining climate policies increased their stated (survey measure) but not their revealed support (petition) for policies.

Moreover, command and control policies may be more easily accepted by the public than carbon taxes, which can be seen as more coercive and may therefore be subject to greater public opposition (e.g., Baranzini and Carattini, 2017).

These examples demonstrate the importance of public acceptance and understanding in driving the adoption and effective deployment of sustainable technologies and policies. Building trust, addressing misconceptions, and engaging the public in decision-making processes could contribute to creating a supportive environment for the successful implementation of these technologies and the overall transition to a low-carbon future.

### Engaging the public

Engaging the public entails different dimensions, including communication, deliberation, education, and citizen science. Education and communication as well as the scope for co-creation are crucial for overcoming anxiety, barriers to adoption, and polarization by fostering an understanding for overall well-being (see Section 5.2.1). For example, this understanding may be that a loss of private transport may be compensated by improved public transport options and additional public space in cities or that material restrictions are compensated by immaterial health or the benefits of psychological well-being (Rauch and Steiner, 2006; Brand-Correa et al., 2018; Dür and Keller, 2018; Brudermann et al., 2019). The importance of communicating about climate change and raising public awareness about climate change and climate action has become an active area of research. Climate change communication has to meet the public's needs and help individuals navigate through the inherent complexities of the phenomenon. Moser (2010) mentions three basic goals of climate change communication: To educate and inform, motivate engagement and action, and change social norms and cultural values. One tool that can play an important role in achieving the aforementioned goals is 'framing', that is, describing a problem in different ways to preferentially give rise to different choices or preferences (Tversky and Kahneman, 1981). For instance, a prime example of framing in the context of climate change is given in a study by Lockwood (2011), who investigated how the alternative framing of climate policies would affect public support in the UK. Frames for three different policy areas were tested: Expanding renewable energy, promoting residential energy efficiency, and financial assistance for developing countries. For instance, renewable energy was framed as either a strategy for energy security, as an economic opportunity, or as the 'control frame' of fighting climate change. Among all policy areas, the only significant framing effect was found for promotion of renewable energy. When this topic was framed as a strategy for energy security, it gathered considerably more support than under the climate change frame, while the economic opportunity frame attracted the lowest support. This is a noteworthy finding, since the economic opportunity framing of climate policies has recently gained popularity in the public debate.

Communication is also relevant to adaptation to climate change, such as responding to increased instances of flooding, wildfire, and water shortages. Studies from other countries like Australia and Canada started to develop communication schemes that could prevent human causes of wildfire and prepare residents for the event of a wildfire (Remenick, 2018). Water shortages need to be accompanied by efficient (to-be-developed) communication strategies that motivate citizens to comply with usage schemes or to save energy if a shortage of hydropower occurs (Schultz et al., 2016). Concerning flooding, communication strategies require the efficient promotion of prevention strategies (e.g., purchase of insurances, organization of volunteers) and correct behavior during the event (e.g., compliance with safety regulations).

More generally, many studies show that information campaigns to inform the public how to take concrete action on climate change, such as campaigns on energy conservation, are effective for changing individual behavior patterns in that they help people translate lessons communicated, such as energy tips, into actual use (Farrow et al., 2018; Andor et al., 2022). Although most campaigns strive to change individual behavior, some studies have also shown their effectiveness in influencing community or even national energy consumption (e.g., Carrico et al., 2015).

Moreover, many studies have demonstrated that deliberation can affect how people think about complex societal problems and policy issues, such as climate change and climate policy. For instance, experimental evidence was gathered by MacKenzie and Caluwaerts (2021), who compared support for climate action policies between groups of people (i.e., a group that deliberated the policies with each other and a group that did not). They found that those who deliberated became more supportive of government action, particularly with respect to tax policies (such as a gas tax). One way to implement such deliberation in practice is by using so-called 'Climate Assemblies' in which citizens representing different groups of populations come together to jointly debate climate change policies. Such assemblies have been successfully implemented, for instance, in the UK, Denmark, Germany, Finland, France, Scotland, Spain, and recently also in Austria. In Austria, a hundred randomly selected citizens who were representative of all regions of Austria as well as of different parts of society formed such a Climate Assembly and were tasked with answering the question 'What can Austria do to become climate-friendly by 2040?'. In the Assembly, small groups worked together over six weekends to produce concrete policy proposals for dealing with climate change in Austria. In total, the Assembly developed 93 proposals to address climate change, including a land sealing ban, the abolition of fossil energy subsidies, and higher taxes for climate-damaging vehicles (see Section 6.4.2). Similar comments apply to the design of policy bundles by the public on specific topics, such as transportation (Hössinger et al., 2023). After taking the perspective of a 'task solver' in policy design, citizens propose ambitious bundles of policies, reaching in most cases (60 %) the emission reduction targets of 70 %.

Similarly, education is a strong pillar of public engagement (see Section 6.8.3). Action for climate protection will only be successful when a range of opportunities for different groups in society are provided to improve climate literacy, the understanding of science, awareness, hope, and concern, as well as hopefully and subsequently enable people to make more informed decisions on matters related to climate change. For instance, young people in schools can learn about the science of climate change and understand the impacts of their actions on climate change. In Austria, various educational initiatives have been implemented such as the Austrian Education Energy Initiative (ETSIT) to increase energy literacy and the k.i.d.Z.21 program targeting teenagers to foster climate literacy. Both initiatives were implemented among primary and secondary school students, and the results indicate that they raise awareness and concern about the problem at hand and influence student's intention about energy-saving actions and climate-friendly behaviors (Deisenrieder et al., 2020; Keller et al., 2022).

Lastly, citizen science offers promising opportunities for the future deployment of public engagement campaigns. The European Commission is defining citizen science as 'general public engagement in scientific research activities where citizens actively contribute to science either with their intellectual effort, or surrounding knowledge, or their tools and resources'. This is still developed to only a very limited extent.

### Chapter Box 5.1. Behavioral aspects of responses to climate risks

This box emphasizes behavioral aspects related to responses to climate hazards such as floods, heat waves or wild fires once they manifest. In this way, it can be understood as reflections on adaptation strategies once climate damages manifest. For more information related to climate risks on mental health, please see Section 5.2.1 and Cross-Chapter Box 2, for risks related to migration due to climate impacts in other countries, see Section 6.8.2. For the interested reader, the EU-wide report for responses to crises, including but not restricted to climate-related crises, 'Safer Together – Strengthening Europe's Civilian and Military Preparedness and Readiness' was released in late 2024 (Niinistö, 2024) and is highly relevant when considering responses to climate catastrophes.

Human responses to disasters can either reduce the damages in crisis situations, whenever there is a display of cooperation, coordination, mutual help, etc., or increase the damages if there is a panic response, unleashed conflict, focus on self-interest, panic buying, etc. (Niinistö, 2024). Therefore, it is very important to set the right institutions and governance structures that can facilitate cooperation and coordination during disasters, such as risk management plans, organizational network that coordinate disaster response, communication networks, information and data exchange, etc. This should include adaptation to climate change, for example in urban and rural planning in relation to heat stress or unusual precipitation events.

In the literature, disaster risk reduction (DRR) policies covering, for example, goals, recognition of critical signals, communication and coordination between public and non-profit actors, as well as with citizens are seen to increase successful crisis response (Steigenberger, 2016; Kuhlicke et al., 2020; Krogh and Lo, 2023). Nonetheless, empirical comparisons on a country level show that exposure to frequent and severe disasters does not lead to improved DRR policies (Nohrstedt et al., 2021). Case studies show that the success of these crises plans increases with training, expertise-building, planning and plan enactment, leadership, and personal acquaintance and trust between actors (Steigenberger, 2016; Seebauer and Babcicky, 2018; Krogh and Lo, 2023). Future research should establish more empirical evidence on successful DRR and might adopt more holistic strategies such as adopting the concept of safety culture, also for the context of natural hazards DRRs (Marshall, 2020).

During a crisis, behavioral interventions can be used to enhance compliance with risk reduction policies, e.g., energy saving, water saving (Gangl et al., 2022a; European Commission et al., 2023). There is a high agreement in the literature that cheap informational nudges effectively promote energy savings (Buckley, 2020). Effective communication depends, for instance, on clear and concrete goals, including implementation intentions, i.e., if-then-plans (Ahn et al., 2021), simple heuristics, i.e., rule-of-thumb (Tversky and Kahneman, 1981, 1986) from trusted sources and role-models (Craig and McCann, 1978). Increasing the salience of specific behaviors through visual signals, such as traffic light symbols (Dobber et al., 2023) and reminders which use feedback (Legault et al., 2020) or targeted social norms (Bonan et al., 2020; Kaestner and Vance, 2022) can also increase compliance with rules.

Nonetheless, future behavioral research should test whether announcements or early warning systems also work as expected in acute crisis situations and how positive and negative spill-over effects can be utilized to increase the efficacy of crisis communication. For instance, communication policies can target companies using the strategy to create positive spill-over effects to households (European Commission et al., 2023). The report on preparedness and readiness to crises to the President of the European Commission offers a broad range of recommendations for crisis management within and across EU states, aiming to mitigate the negative effects of crises, including natural hazards and other climate change related events (Niinistö, 2024).

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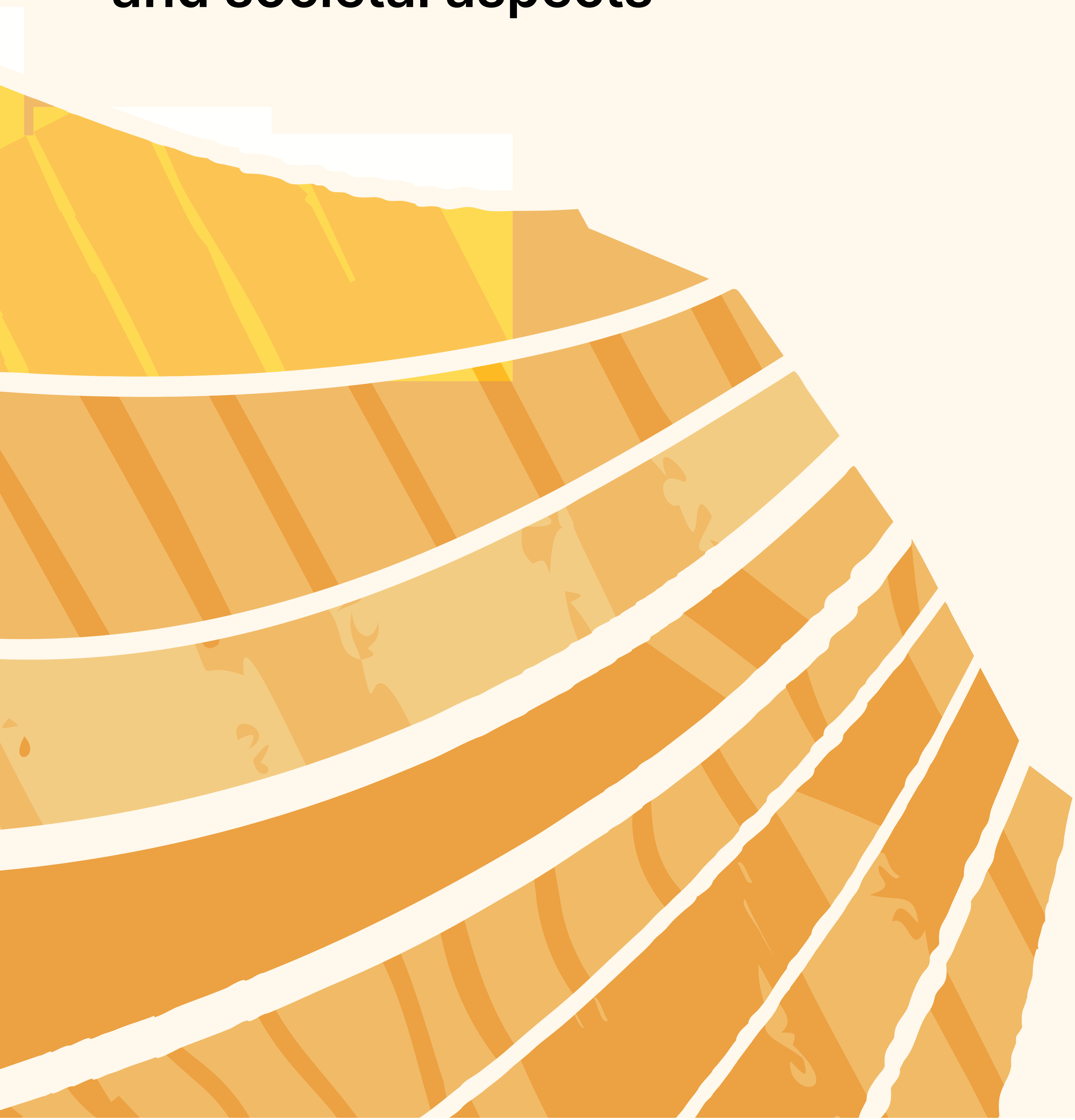
## Chapter 6

# Climate governance: Political, legal, economic and societal aspects



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## EXECUTIVE SUMMARY

**Climate policies currently in place are insufficient to achieve the targets set out for Austria (*high confidence*).** For Paris-aligned policymaking at all levels of government, it is essential to integrate climate policy comprehensively, both vertically and horizontally (*high confidence*). This integration should also encompass a clear prioritization of climate policies in case of target conflicts. In addition to mitigation policies, adaptation instruments are necessary to offset the negative effects of unavoidable climate change. Measures supporting a just transition are crucial for the successful implementation of climate policies. They can alleviate undesired social hardships and improve social and political acceptance (*high confidence*). {6.5}

**The GHG emission reductions achievable through the current policy instruments are insufficient to meet the EU legal targets in line with the Paris climate goals *(high confidence*).** International treaties related to climate protection have no direct effect ('nicht unmittelbar wirksam') on the legal framework for climate protection in Austria. This is evident in the reluctance of Austrian policymakers to implement a Climate Protection Act ('Klimaschutzgesetz'), which would have specified sectoral targets for GHG reduction up to 2030 and beyond. Austria's legally binding GHG emission reduction targets are derived from the effort sharing provisions set forth in EU legislation. The framework of EU energy and environmental law serves as the primary driver for Austrian climate law *(high confidence)*. {6.3}

**It is essential to consider the wider structural context in which climate governance is embedded when assessing Austrian climate governance (*high confidence*).** To enable deep decarbonization, climate policy must address the structural context of climate governance, including the politico-juridical framework and wider societal (nature) relations. Given that such interventions inevitably result in winners and losers and may disrupt established routines, they meet resistance. Failure to address these resulting transformation conflicts could lead to backlash against climate action (*high confidence*). {6.2}

**Although climate governance in Austria includes a large variety of instruments to foster effective mitigation and adaptation measures, these have not been sufficiently implemented by political actors so far (*high confidence*).** This is exemplified by a reluctance of policymakers to phase out climate counterproductive subsidies and to green the tax system. Powerful economic and political interest groups in Austria are obstructing effective climate action and thus preventing the full potential of climate governance from being realized (*high confidence*). As a result, an implementation gap has emerged – ambitious climate targets exist without sufficient measures and instruments in place to achieve them (*high confidence*). Implemented instruments do not alter existing power relations, growth logics, and the dominant mode of production and living (*high confidence*). This is reflected in the lack of sufficiency-oriented 'avoid' policy instruments capable of significantly reducing demand for energy, materials and land. {6.4}

**The significant and rising costs associated with climate inaction will exceed the budgetary costs of effective climate action (*high confidence*).** Reaching net-zero and adequate adaptation will require considerable investments, with the projected benefits exceeding the costs (*high confidence*). The additional investment required is estimated at between 1.3 % and 4.8 % of GDP per year. Public budgets, in terms of both revenue and expenditure, are a crucial lever in this process. However, they are currently underutilized and undermined by counterproductive measures such as climate harmful subsidies (*high confidence*). In addition, effective climate action also requires the mobilization of private funds to bridge the investment gap. This can be achieved by providing adequate standards for green finance and reducing the carbon exposure of the economy (*high confidence*). {6.7}

**Climate change losses in Austria, currently averaging $EUR_{2019}$ 2 billion annually, are projected to rise significantly by 2030 ($EUR_{2019}$ 2.5–5.2 billion) and by 2050 ($EUR_{2019}$ 4.3–10.8 billion) (estimates from 2020) (*limited evidence, high agreement*).** Austria is currently impacted by climate-related damage and loss, and future climate change along with socioeconomic development will intensify these effects (*limited evidence, high agreement*). {6.7.2}

**Just transition policies should address the asymmetric impacts of climate policy on employment and workers across sectors and regions. Furthermore, they must consider the wider inequalities and vulnerabilities exacerbated by the transition to climate neutrality (*high confidence*).** While the concept of a just transition, retaining its labor-centric origin, remains a point of contention, with interpretations spanning from narrow socio-technical shifts to comprehensive social-ecological transformations of the social relations of production, the introduction of such policies is crucial to secure public acceptance and support for rapid decarbonization (*high confidence*). {6.8.1}

**The links between climate change and migration are largely disregarded in the political debate in Austria, and significance is mainly attributed when climate change results in increased international migration to Austria (*limited evidence, high agreement*).** The evidence base remains limited, revealing ambiguous effects on whether climate change will drive increased migration to Europe, with no clear indication of its specific impacts on Austria. {6.8.2}

**Education is universally recognized as a key instrument for achieving all SDGs, and this is particularly true for Climate Change Education and SDG 13 'Climate Action' (*high confidence*).** However, education itself needs to be transformed in order to fully exploit its transformative potential for sustainable and climate-friendly living in Austria. This applies to the entire educational spectrum, starting in early childhood and extending through adulthood, in both formal and non-formal settings. The contributions of all players and stakeholders to climate change education must be promptly and fundamentally transformed and strengthened (*high confidence*). {6.8.3}

**Media representation of climate change likely increased in Austria since the mid-2000s. While dominant frames focus on the negative economic consequences of climate action, parts of the media represent climate change-skeptical positions.** In contrast, several perspectives, such as the need for fundamental transformation of economy and society beyond market-based approaches and individual responsibility, as well as the question of social inequality tend to be underrepresented in the media discourse (*limited evidence, high agreement*). {6.8.4}

## 6.1. Introduction

Effective climate action combines legal, economic, political and societal aspects. This chapter assesses these aspects from an interdisciplinary perspective. It begins with the structural context of climate governance (Section 6.2). In a second step, the legal framework and the international commitments for Austrian climate policy are addressed (Section 6.3). The following section (6.4) assesses the role of institutions and actors. This is followed by an integrated assessment of existing policy instruments for climate change mitigation and adaptation (Section 6.5).[1] Section 6.6 assesses the legal remedies of climate liability by reviewing selected climate lawsuits. Public finances, investment requirements[2] and costs of (in)action for mitigation and adaptation are addressed in Section 6.7. The final section (6.8) examines the literature on various societal aspects, such as distribution and justice, migration, education, and media in the context of the climate crisis.

## 6.2. The structural and dynamic context of climate governance

Climate governance refers to the various interactions of political, economic and social institutions to steer social systems towards climate change mitigation and adaptation. These interactions are embedded into societal structures, such as political and legal frameworks, societal (nature) relations, and the political economy of modern societies, as well as the conflict dynamics and antagonisms that arise within them. Achieving the deep decarbonization necessary to meet the goal outlined in the Paris Agreement requires addressing these structures and dynamics that both enable and hinder such efforts (Novy et al., 2023a) (see Section 8.3.3) (*robust evidence, medium agreement*). The literature on sustainability transformations points to *three core problem complexes* that need to be addressed in order to understand which aspects of society need to be changed and why deep decarbonization is such a contested process (Newell, 2015; Scoones et al., 2015; Brand, 2016; Görg et al., 2017; Stirling, 2019; Morgan, 2020; Pichler, 2023):

**(1) The first complex includes deep-rooted structures such as the modern growth economy, unequal and unsustainable societal (nature) relations, and associated mental infrastructures and political institutions that shape and impede transformation (*robust evidence, medium agreement*).**

Political economy and political ecology research show that climate governance is embedded in a broader structural context that encompasses modern society, its economy, and the state (Perreault et al., 2015; Paterson and P-Laberge, 2018). These societal structures comprise both material and ideational dimensions and serve as both facilitators and entrenched obstacles to achieving deep decarbonization (Hirth et al., 2023). First, modern economies are seen as inherently driven by competition, economic growth, and profit-seeking (Feola, 2020; Hausknost, 2020), which poses fundamental challenges to a low carbon transformation (see Fouquet, 2019; Buch-Hansen and Carstensen, 2021) (see Cross-Chapter Box 7).[3] An economy prioritizing profit-seeking over basic human needs is identified as a main driver of ecological disruptions (Görg et al., 2017), mainly because competition forces producers to strive for unsustainable growth in order to maintain competitiveness (O'Connor, 1991; Saitō, 2016; Bärnthaler et al., 2021). This implies an expansionary dynamic that is also considered as a cause of geopolitical and geoeconomic tensions (Arrighi and Silver, 2001; Harvey, 2003; Scheffran, 2023; Brand and Wissen, 2024) and, since the late 18th century, is a driver of and itself driven by the large-scale use of fossil fuels (Malm, 2013; Ortiz, 2020; Christophers, 2022). Second, various forms of intra-societal inequality as well as unequal north-south relations have also been found to be entangled with structures of growth-oriented and fossil-fuel-based economies (Hickel, 2017; Daggett, 2018; Brand and Wissen, 2021). Inequalities such as class and unequal gender relations as well as racist divisions serve as structural features reinforcing and stabilizing unsustainable modes of producing and living, particularly as they enable to shift and thus externalize negative social and environmental impacts of economic activities to other places and populations (Lessenich, 2019; Sovacool et al., 2020; Brand and Wissen, 2021). These very inequalities are also identified as main drivers of vulnerability and lack of adaptation to the effects of climate change (Cappelli,

1 The focus here is on providing a general overview, while more detailed accounts and information on the effects of these policies on GHG emissions are given by the sectoral chapters of this report.

2 Green finance in particular is addressed in Cross Chapter Box 8.

3 This view contradicts standard economics, which sees these very characteristics as key levers for decarbonization (Hawken et al., 2000; GCEC, 2014; World Bank, 2023a).

2023). Third, structural unsustainability also has an ideational dimension, as it shapes widely shared conceptions of modern societies or 'mental infrastructures' (Welzer, 2011), that is, deep-rooted understandings of a good life, freedom (Bergthaller, 2017), progress and emancipation (Blühdorn, 2022). Fourth, different perspectives exist towards the extent structural unsustainability also shapes modern political institutions such as the state and liberal democracy.[4] On the one hand, there is a broad body of literature considering the state as the key for a deep decarbonization (Mazzucato, 2014; Eckersley, 2021; Babić and Dixon, 2023). Due to its capacity to allocate and distribute resources, facilitate innovation, regulate production and consumption, manage free-rider problems, and enforce legal frameworks, the state is seen as essentially capable to steer societies towards sustainability. On the other hand, scholars argue that growth imperatives and related deeply rooted societal relations and orientations shape and stabilize the modern state and liberal democracy. The functionality secured, e.g., by taxes, and legitimacy generated for instance by the welfare state and liberal democratic procedures of states co-evolved with and partially rely on a growth-based fossil economy (Hausknost, 2020; Pichler et al., 2020; Koch, 2022; Mitchell, 2023). Consequently, doubts arise about the state's steering capacity, as it is perceived not as a neutral regulator but as an asymmetric terrain (Jessop, 2007), that tends to favor strategies aligned with the dominant fossil fuel-based growth paradigm (Silvester and Fisker, 2023). This inclination results on the one hand in institutional dependencies on fossil fuels, reinforcing carbon lock-ins (Unruh, 2002). On the other hand, it constitutes a structural limitation of transformative state action to a narrow corridor of ecological modernization (Johnstone and Newell, 2018; Hausknost, 2020). For example, due to the automotive industry's central role in Austria's export-oriented industrial economy, its substantial contribution to the tax basis of the state, its role for the formation of labor relations and wage dynamics, and a persistent connotation of automobility with a good life within the Austrian population, state action to move beyond car-centered mobility systems as well as a conversion and downscaling of the automotive industry is relatively difficult to achieve (Pichler et al., 2021a). Therefore, climate governance as an issue specific arrangement embedded in these wider institutional arrangements is not only reactive and responsible for developing solutions to respond to the risks caused or compounded by climate hazards but is also constitutive of them and contributes to the emergence of risks (see Cross-Chapter Box 1). This implies that the state and other institutional contexts vary in their openness to ambitious climate action. For example, Austria's membership in the EU means that the structures and processes of climate governance in Austria are embedded in the European legislative architecture. This framework would allow for more ambitious climate governance objectives and measures than what has been pursued by Austrian governments so far (Nash and Steurer, 2019).

**(2) The second complex entails more dynamic aspects such as interest and power constellations, as well as resulting conflicts that arise over deep decarbonization (*high confidence*).**

Actors are differently positioned within unsustainable and unequal societal (nature) relations. As a result, they have different, sometimes even conflicting, interests, visions and policy preferences with regard to climate governance, and different capacities to shape it (van der Ven, 2016; Marquardt, 2017; Schneider et al., 2023). Accordingly, social science research on sustainability transformations pays much attention to the contested nature of climate action. First, the obstructive and delaying role of incumbents and (more recently) other powerful actors (e.g., in politics and the media) has been well studied (Geels, 2014; Meckling et al., 2015; Newell, 2019; Turnheim and Sovacool, 2020; Ekberg et al., 2022; Brulle et al., 2024; Plehwe et al., 2024). Sociological research highlights, e.g., how the strategies of powerful actors interact with dominant non-transformative attitudes and unsustainable practices within societies characterized by cleavages and class divisions (Fritz and Eversberg, 2024). Popular perseverance is at times seen as a major obstacle. This includes a protracted tendency of large parts of the citizenry to prefer the convenience of unsustainable lifestyles and to reject climate policy proposals, partly despite growing awareness of the climate crisis (Blühdorn, 2020; Beckert, 2024). Scholars of International Relations and International Political Economy highlight the international and global dimensions of contested transformations and show how manifest geopolitical and geoeconomic tensions shape climate governance (Paterson, 2020; Scheffran, 2023; Brand and Wissen, 2024). This multifaceted contestation of climate action is reflected in a burgeoning literature on transformation conflicts at multiple sites and scales (Brand and Wissen, 2024; Dörre et al., 2024; Eversberg et al., 2024; Fritz and Eversberg, 2024; Herring et al., 2024; Kalt, 2024),

[4] The state is treated in more detail than other aspects here because much of the recent literature emphasizes its central place in governing the climate crisis.

and on how these conflicts may lead to backlash against climate action (Patterson, 2023).[5]

**(3) The third complex includes the structurally and power-shaped, and inherently conflictive character of policies and policymaking (*robust evidence, medium agreement*).**

The prioritization, formulation and implementation of climate-related policies, as well as their content, are framed and shaped by structural inequality, unsustainability, power and conflict. This is highlighted by critical policy studies (Pichler, 2023; Schneider et al., 2023) and has three main consequences: First, policies are understood as the outcome of conflicts and compromises between diverging interests and visions. Contestations between forces of inertia and change implies a conflict orientation of climate policy (Niedertscheider et al., 2018; Plank et al., 2021), as effective climate policy needs to counter powerful interests by building strategic state capacity (Meckling and Nahm, 2022). Second, policies differ in the extent to which they reproduce or transform the structural context of unsustainable societal (nature) relations. This is crucial, because the effectiveness of climate policies depends on their ability to change structures of unsustainability (Novy et al., 2023a). Third, it is highlighted that policymakers are more likely to adopt policies that align with existing societal structures, dominant interests, and power relations than more transformative policies, as these non-disruptive policies avoid challenging dominant growth imperatives and their associated interests (Markusson et al., 2018). Such institutional biases may partly explain the lack of sufficiency or 'avoid' policies in Austria and the EU, i.e., those focusing on reducing demand rather than merely increasing efficiency (Zell-Ziegler et al., 2021; Jarre et al., 2024; Brad et al., 2025) (see also Cross-Chapter Box 4). Fourth, to address popular resistances and increase the acceptability and legitimacy of climate policies, considerations of justice and participation need to be firmly embedded in climate governance. This is all the more important given the unequal distribution of responsibility for climate change, the unequal distribution of its impacts, and the unequal distribution of the means to adapt to it (Newell et al., 2022).

5 However, studies also find evidence for broad popular support for climate policy focused on green investment and industrial policy as well as measures compensating unpopular climate policy instruments like carbon pricing in different European countries (Abou-Chadi et al., 2024).

## Cross-Chapter Box 7. Degrowth and other beyond growth concepts: The desirability and feasibility of (limiting) growth

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### Context

Critiques of relentless economic growth have a long history. Active academic debates on steady-state economics (Daly, 1973) and attempts to model and illustrate the limits to growth (Meadows et al., 1972) are already more than half a century old. The debate is fierce and continuing, discussing the feasibility and desirability of different elements of growth (Meadows et al., 1992; Nordhaus et al., 1992). Here, the core question is what kind of economic structures are conducive to improving well-being while achieving ecological stability and sustainability (Hickel and Hallegatte, 2022). A strong consensus exists on the need to leave behind GDP as an indicator of social progress (Stiglitz et al., 2009; Costanza et al., 2014), but there are different frameworks to analyze what this means for policymaking and the organization of economies around the world. It includes recognizing that while more energy use is required to provide decent living standards for all that are currently deprived (Kikstra et al., 2021), there is a large potential for simultaneous reduction of energy demand, which can bring multiple interacting benefits (Grubler et al., 2018; Creutzig et al., 2022). Moreover, moving beyond growth requires replacing the existing economic growth paradigm with alternative social imaginaries and narratives (Fournier, 2008; Latouche, 2009). Skepticism towards green-growth strategies is widespread among climate-policy researchers (King et al., 2023), and resource and emissions decoupling in the past decade have been highly insufficient to be on track to meet climate targets, both global targets and targets for Austria (Haberl et al., 2020; Vogel and Hickel, 2023), across many biophysical pressures (CCBox 7 Figure 1).

### Beyond growth frameworks

Beyond growth frameworks see most current economic systems as unsustainable and unable to sufficiently increase human well-being within a socially just transition process unless they address perverse growth incentives. Approaches to structural economic changes, tools, and preferred policy interventions differ between frameworks. Definitions used here are in CCBox 7 Table 1. This box focuses on degrowth, a prominent growth-critical approach (Kallis et al., 2018). Degrowth and green growth are contrasted as alternative climate mitigation strategies (CCBox 7 Table 1) to identify common and differing insights on what type of growth is feasible and desirable. A key distinguishing feature is the role of 'avoid' and sufficiency strategies for climate mitigation, which are valorized much more heavily in degrowth (see also Cross-Chapter Box 4).

**CCBox 7 Table 1** Overview of relevant terms.

| Framework | Definition |
|---|---|
| Agrowth | An argument that sees GDP as an unreliable indicator for progress and argues that we should not focus on it. |
| Beyond growth | An umbrella term for terms and approaches that are critical of continued economic growth. |
| Decent Living Standards | "A set of *material* requirements that are essential for human flourishing" (Rao and Min, 2018). |
| Degrowth | A research field and socio-political movement focusing on a targeted, redistributive and democratically planned downscaling of production and consumption, primarily in industrialized countries, as a way to achieve sustainability and well-being, while minimizing key risks. |
| Doughnut economics | "A multi-criteria boundary tool to support economic planning by identifying environmental limits and social thresholds and is agnostic towards GDP growth" (Raworth, 2017), as it does not see GDP as a good indicator for environmental or social progress. |
| Feminist ecological economics | An approach to economics that centers household and community (re)production and interrelations with nature, for instance through care and unpaid work, and justice related to gender, ecological degradation, decolonization, and global inequities. |
| Foundational economy | An approach to restructuring the economy to prioritize the provisioning of everyday human needs like food, housing, health services and transport within planetary limits. |
| Green growth | A set of policies that aim to bring together and simultaneously stimulate sustainable development and economic growth. |
| Post-growth | A broad set of approaches that challenge the necessity, feasibility, and desirability of continuous economic growth, especially in advanced economies. |
| Steady-state economics | A concept focused on maintaining a sustainable non-growing economy, including a constant level of resource use, population, and capital stock, with a focus on social welfare not economic growth. |
| Sufficiency | A set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human well-being for all within planetary boundaries. |
| Well-being economy | A set of measures that delivers on five core needs for ecological and human well-being: Dignity, connection, nature, fairness, and participation. |

### (De)growth in the context of climate change mitigation and broader sustainable development

Many proposals have attempted to quantify what might be considered 'enough' and 'too much'. Proposed minimum requirements for human flourishing have been based on theories of the human needs (Max-Neef, 1991; Sen, 2012; Lamb and Steinberger, 2017) that "avoid serious harm and are universalizable, objective, empirically grounded, non-substitutable and satiable" (Gough, 2015). For one example, the Decent Living Standards (Rao and Min, 2018), minimum energy requirements are less than half of current global energy use (*medium confidence*) (Millward-Hopkins et al., 2020; Kikstra et al., 2021). Total levels consistent with decent living standards for all are higher due to inequality (Millward-Hopkins, 2022) but can be lowered with improvements in service provisioning systems and reduced within-country inequality (Kikstra et al., 2024a). The minimum material footprint to support decent living standards has been estimated at 3–13 t per capita per year (Vélez-Henao and Pauliuk, 2023) (*medium confidence*), which is also less than half of the current annual material footprint, estimated at 24–33 t per capita in Austria pre-COVID (Giljum et al., 2019; Eisenmenger et al., 2020; Lenzen et al., 2022; Plank et al., 2022; UNEP IRP, 2023; Statistik Austria, 2024) (*high confidence*). The federal government's Circularity Strategy has recently set a 7 tMF/cap target for 2050, which expresses the intention to lower resource use levels (see Cross-Chapter Box 5).

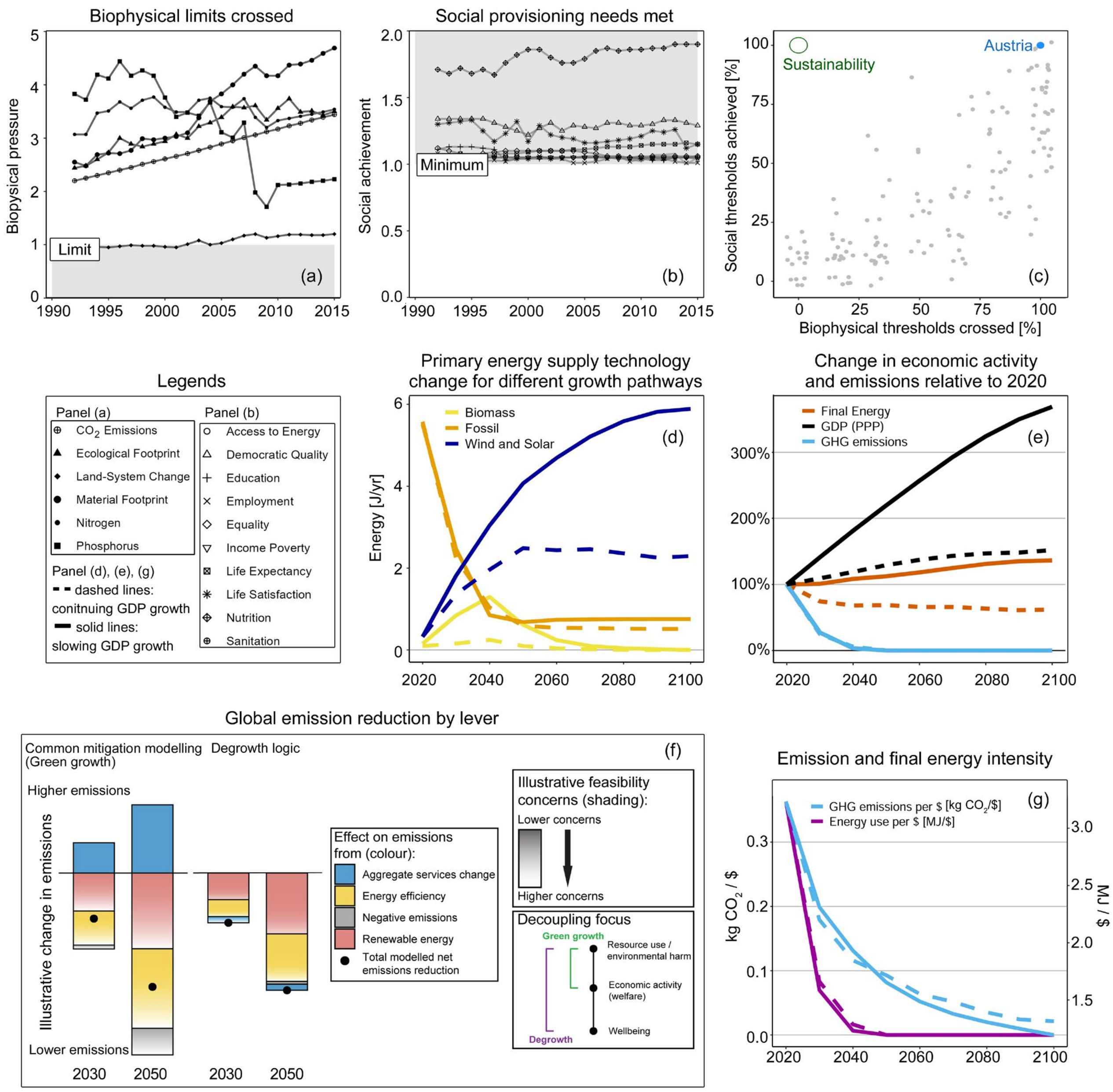
Ceilings on activity are more often linked to large-scale environmental thresholds and risks such as planetary boundaries, tipping points, and climate impacts more broadly. Maximum activity levels are then most often linked to carbon budgets corresponding to global warming levels (see Chapter Box 1.1), through estimates of carbon intensities of certain activities, and through the concepts of consumption and production corridors (Di Giulio and Fuchs, 2014; Bärnthaler and Gough, 2023). Additionally, ethical arguments have been made to determine upper limits based on preferences and perceptions of fair levels of income inequality (Osberg and Smeeding, 2006), and a recent survey distinguished the 'rich' from the 'super-rich' in the Netherlands at between EUR 1 million and 3 million total personal wealth (Robeyns et al., 2021).

Whether it is desirable and feasible for climate mitigation strategies to downscale a particular activity depends strongly on the sector and country, noting different levels of development, inequality, and needs. Less necessary, and ecologically destructive sectors may include short-distance flights (Dobruszkes et al., 2022) and other inefficient and harmful mobility (Muller et al., 2011; Cattaneo et al., 2022), housing-as-asset (zu Ermgassen et al., 2022), leisure (Smetschka and Wiedenhofer, 2023), fast fashion (Niinimäki et al., 2020), affluent energy overconsumption (Büchs et al., 2023), and animal-based foods (Kozicka et al., 2023). At such a policy level, many of these proposals are supported by both degrowth and green growth analyses, although the approaches to identifying and embedding them differ.

While advocates for degrowth strategies typically call for a clear break with standard economic doctrine, there are elements of agreement with conclusions from standard economic analyses. A full accounting of the external costs of energy calls for rapidly shrinking fossil-based energy production (Muller et al., 2011). Induced technological change explicitly calls for a shift from 'dirty' to 'clean' sectors (Acemoglu et al., 2012), with demand reduction playing a significant role. IEA (2020), for example, shows how, by 2050, 50 % of global steel demand could be met by reuse and recycling, under a 1.5°C decarbonization pathway.

Challenges to green growth strategies have been more extensively researched than challenges to degrowth. For example, efficiency improvements can lead to rebound effects, i.e., induce increased demand, partially offsetting environmental gains (Gillingham et al., 2016; Moshiri and Aliyev, 2017; Raimund, 2023). Much less is known about how strong challenges, including possible rebound effects (Sorrell et al., 2020), to achieving a beyond growth pathway could be, with limited evidence available about the effects of systematically targeted downscaling on employment and productivity, on international competitiveness and financial stability in the case of unilateral or cooperative implementation, or on the financial ability to finance the energy transition, or on the extent to which the transition to renewables induces productivity gains and resulting economic growth (Arkolakis and Walsh, 2023).

From a macro-perspective, to achieve sustainability, economic activity needs to be sufficiently decoupled from emissions as well as from material, energy, water and land resources. To mitigate climate change, the emission intensity of economic activity and energy consumption needs to decline faster with higher economic growth and the same emission reduction target, which may be an indicator of a higher macroeconomic challenge. At the same time, to stabilize at any temperature, $CO_2$ emissions need to go to zero, ultimately requiring full decoupling. Even if a degrowth scenario achieves absolute decoupling from economic growth in both GHG emissions and final energy, this does not necessarily mean that the year-on-year change in emissions intensity or final energy intensity is different from a green growth scenario (CCBox 7 Figure 1f). At the same time, higher energy demand in a green growth scenario requires a larger energy supply system, which requires more energy and metals such as copper for the energy system itself (Granier et al., 2007; Lesk et al., 2022; Slameršak et al., 2022; Wang et al., 2023), as illustrated by the scenario highlighted in CCBox 7 Figure 1f, and may thus come with higher environmental pressures beyond emissions, potentially lowering feasibility of decoupling from all environmental pressures (*limited evidence, medium agreement*). Economic growth is also related to biodiversity loss through greater resource consumption and higher emissions (Otero et al., 2020), while the combination of degrowth and efficiency gains can lead to simultaneous emissions and health benefits (Bodirsky et al., 2022).




**CCBox 7 Figure 1** Past trends in (a) Biophysical pressures and the exceedance of ecological thresholds for Austria; (b) Trends in social provisioning and the meeting of social minima for Austria; (c) Share of thresholds crossed in 2015 across all countries with Austria highlighted compared to a state where sustainability would be achieved. All data from panel a–c is from Fanning et al. (2022). (d, e, and g) A modeling example comparing the need for upscaling renewables (d) under a 1.5°C consistent target for Australia for a 'continuing GDP growth' versus a 'slowing GDP growth' scenario, with their respective (e) total energy use, GDP, and emissions pathways, and (g) emissions and energy intensities. All data from panel (f) based on Kikstra et al., (2024b). (g) Theoretical representation of a degrowth logic for climate change mitigation compared to common mitigation modeling approaches, based on Li et al. (2023).

Integrated modeling approaches that adequately reflect the dynamics of a global degrowth transition across sectors in coherent global integrated frameworks with high regional detail do not yet exist, but many partial studies have provided explorations and preliminary quantifications. Exploratory country-level modeling indicates that an emissions reduction can be combined with reductions in consumption and increases in social prosperity (D'Alessandro et al., 2020), while lowering the challenges of upscaling renewables and carbon prices fast enough to meet ambitious climate targets (Kikstra et al., 2023) (CCBox 7 Figure 1f). Global studies are few, and range from simplified energy-emissions modeling, to illustrate the space for developing new process-based mitigation pathways (Keyßer and Lenzen, 2021), to first versions of process-based modeling of the conflict between economic growth, climate policy and resource sustainability, with a green-growth scenario failing to meet climate goals and a post-growth scenario meeting emissions objectives (Nieto et al., 2020). For food and land systems, a modeling study showed the possibility of achieving a steady-state, net-zero GHG food system that improves nutritional outcomes (Bodirsky et al., 2022). A few studies have also looked at post-growth modeling using stock-flow consistent models (Victor, 2012; Jackson and Victor, 2020; Sers, 2022). While these models tend to remain conceptual rather than empirically calibrated, one recent working paper described the possibility of finding higher inflation in 'the North' and somewhat slower economic growth in 'the South' due to reduced international trade if 'the North' unilaterally shifted to degrowth while 'the South' continued to focus on economic development (Leoni et al., 2023).

As discussed above, qualitative literature exists on the feasibility, desirability, and economic dynamic effects within and across countries for a transformation beyond growth (Kallis et al., 2018; Kerschner et al., 2018; Hickel et al., 2022). However, attempts to quantify feasibility and desirability are mainly explorative (D'Alessandro et al., 2020; Jackson and Victor, 2020; Nieto et al., 2020; Keyßer and Lenzen, 2021; Moyer, 2023; Kikstra et al., 2024b). Instead, quantifications demonstrate the need for 'avoid' strategies by showing the shortcomings of green growth strategies (Vogel and Hickel, 2023) or by comparing high and low resource demand scenarios (Grubler et al., 2018; Sugiyama et al., 2024).

### Key elements

In short, the degrowth approach:

- Emphasizes empirical evidence on the difficulties of decoupling GDP-growth from growth in emissions, energy, and material footprints, and is concerned about the speed and scale needed to achieve climate targets without the relying on speculative levels of deployment of negative-emission technology;
- Problematizes the limited number of mitigation strategies available due to growth imperatives and concerns about rebound effects without concurrent sufficiency-based policies;
- Links emission and resource-use reductions in the spheres of consumption and production;
- Aims at guaranteeing and potentially expanding necessary forms of consumption/production, for instance through collective forms of service provisioning, while downscaling less necessary and ecologically destructive forms of production/consumption, for instance through sufficiency and 'avoid' strategies;
- Raises a key question for democratic deliberation and democratic planning: What do we – as a society – need more of and what do we need less of to live a good life within planetary boundaries?
- Takes a eudaimonic approach to well-being and welfare, assuming universal objective basic needs or decent living standards, whose fulfilment 'for all' is prioritized over growth to satisfy wants or preferences when the two conflict;
- Centers on national and international justice implications, problematizing the disproportionate share of the Earth's resources that richer countries appropriate both in terms of common resources such as carbon emissions into the atmosphere, and through processes of unequal exchange (e.g., Dorninger et al., 2021);
- Intends to move our socio-economic-ecological system from scarcity to (radical) abundance by re-connecting humans to each other, land, nature, and a culture of care, while de-commodifying and de-colonizing the socio-economic system.

For climate mitigation, compared to green growth, degrowth approaches:

- May reduce geophysical and technological feasibility concerns, and therewith enable faster emissions reductions, due to a reduced speed and scale of upscaling renewables for the same emissions reduction target compared to a green growth approach;
- Reduce environmental pressures beyond climate change due to reduced resource needs (*high confidence*);
- Come with a stronger focus on improving eudaimonic human well-being and focus less on preferences;
- May come with higher sociopolitical feasibility concerns due to rapid economic, sociocultural, and economic breaks with past trends.

## 6.3. Regulatory framework of adaptation and mitigation

### 6.3.1. International: Requirements of the Paris Agreement

The Paris Agreement is currently the central international treaty for combating climate change, committing signatories to limit global warming to well below 2°C and possibly to 1.5°C above pre-industrial levels. Unlike its predecessor, the Kyoto Protocol, it contains neither numerical reduction targets nor a sanction mechanism (Binder and Ritter, 2023). It is not directly applicable in Austria. Other treaties and conventions also have an indirect impact on climate protection in Austria, such as the General Agreement on Tariffs and Trade (Mayr et al., 2021) or the Convention on International Civil Aviation (Karimi-Schmidt, 2019).

Article 3 of the Paris Agreement requires all parties to contribute to the reduction targets. These contributions are to be determined by the states themselves but must be based on an ambitious level and include a steady increase with the aim of achieving the objectives of the agreement. The EU and its Member States submitted a joint Nationally Determined Contribution and updated their initial commitment in December 2020 to a net domestic GHG emission reduction of at least 55 % by 2030 compared to 1990. The EU Effort Sharing Regulation (ESR) partially transfers this commitment to Member States by setting separate binding annual GHG emission targets for each Member State for emissions not covered by the EU Emissions Trading System (EU ETS) (Handig and Stangl, 2023).

Among other commitments, Article 7 of the Paris Agreement sets out the goal of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change in order to contribute to sustainable development and ensure adequate adaptation in the context of the temperature goal.

### 6.3.2. The EU regulatory context

The European Climate Law (Regulation (EU) 2021/1119) establishes a framework for reducing GHG emissions by sources and increasing removals of GHG by sinks. It sets a binding interim target of climate neutrality by 2050. At the same time, it aims to make progress in implementing adaptation strategies. In order to achieve the binding target of climate neutrality, the binding target within the EU is to reduce GHG emissions by at least 55 % by 2030 compared to 1990 (Frenz, 2022; Handig and Stangl, 2023). The European Climate Change Act is a central part of the EU's Fit for 55 package, a set of proposals to revise and update EU legislation. Most proposals have already been adopted (see Table 6.1). EU law is the driving force behind Austrian national climate legislation (Ennöckl, 2020; Hofer, 2024a) (*high confidence*).

The EU's climate change strategy is based on reducing GHG emissions, increasing the share of renewable energy and energy efficiency, and addressing the climate change impacts of land use and land-use change. The overall GHG emission reduction target is divided between sectors covered by the EU ETS and sectors covered by the ESR. The EU ETS currently covers emissions from energy-intensive industry, energy utilities and domestic aviation, and will be extended to include emissions from maritime transport in 2027. These sectors are subject to an EU-wide reduction target of 62 % for 2030 compared to 2005 (Directive (EU) 2023/959) (see Section 6.5.1). For the ESR sectors, an overall emission reduction target of 40 % applies for 2030, and specific targets have been defined for individual Member States. Austria is obliged to achieve a reduction of 48 % by 2030 compared

Table 6.1 Overview of Fit for 55 legal measures

| Measures | New legal measure / Revision of existing legal measure (n/r) | Legal act |
|---|---|---|
| Stronger emissions trading system including aviation | n/r | Directive (EU) 2023/959 |
| Extending emissions trading to maritime, road transport, and buildings | n/r | Directive (EU) 2023/959 |
| Restructuring taxation of energy products and electricity (not adopted) | n/r | COM/2021/563 final |
| New Carbon Border Adjustment Mechanism (CBAM) | n | Regulation (EU) 2023/956 |
| Updated ESR | r | Regulation (EU) 2023/1319 |
| Updated Land Use, Land Use Change and Forestry (LULUCF) Regulation | r | Regulation (EU) 2023/839 |
| Updated Renewable Energy Directive (RED) | r | Directive (EU) 2023/2413 |
| Updated Energy Efficiency Directive (EED) | r | Regulation (EU) 2023/955 |
| Stricter $CO_2$-performance for cars and vans | r | Regulation (EU) 2023/851 |
| New infrastructure for alternative fuels | n | Regulation (EU) 2023/1804 |
| ReFuelEU: more sustainable aviation fuels | n | Regulation (EU) 2023/2405 |
| FuelEU: Cleaner maritime Fuels | n/r | Regulation (EU) 2023/1805 |
| Reduction of methane emissions in energy sector | n | Regulation (EU) 2024/1787 |
| Updated energy performance of buildings | r | Directive (EU) 2024/1275 |
| Social Climate Fund | n | Regulation (EU) 2023/955 |
| Decarbonization of gas markets and promotion of hydrogen | r | Directive (EU) 2024/1788 |

to 2005 (Regulation (EU) 2023/857). EU law provides for a governance mechanism in this area (Dederer, 2021). Integral to this are integrated national energy and climate plans for ten-year periods, which the Member States are required to prepare and report to the European Commission. They are obliged to implement effective instruments to reduce GHG emissions, often based on European directives on buildings, vehicles, energy efficiency, renewable energy, etc. In addition, a separate EU-wide emissions trading system ('ETS 2') will be introduced in 2027 for buildings and transport, as well as for energy supply and manufacturing not covered by the EU ETS. A Social Climate Fund (SCF) will be established, including revenues from ETS auctioning, with the general objective of supporting vulnerable households as well as measures and investments to reduce emissions in the road transport and buildings sectors (Regulation (EU) 2023/955). An EU-wide legislative framework to reduce methane emissions in the energy sector complements efforts to achieve significant GHG emission reductions (Regulation (EU) 2024/1787).

Article 5 of the European Climate Change Act requires the European Commission and Member States to develop strategies for adaptation to climate change. The new EU Adaptation Strategy was adopted in 2021 and aims to achieve a climate-resilient Union by 2050 by promoting smarter, faster and more systemic adaptation and strengthening international action on adaptation. Through 'smarter adaptation', the EU aims to improve data and risk assessment tools to advance knowledge on adaptation and manage uncertainty. Under the goal of 'faster adaptation', the EU focuses on the need for faster and more comprehensive adaptation by accelerating the development and deployment of adaptation solutions. The objective of 'more systemic' adaptation refers to the need for policy developments at all levels and sectors, taking into account the cross-cutting priorities of local resilience, integration of adaptation into macro-fiscal policies and implementation of nature-based solutions for adaptation (COM/2021/82 final).

### 6.3.3. The national regulatory context

The Austrian legal framework for climate protection is largely based on EU legislation, which is mainly determined by the European Climate Change Act, the ETS Directive, the ESR and the LULUCF Regulation, and supplemented by numerous sector-specific regulations and directives. Purely national regulations are of secondary importance. Member States have policy space mainly in those sectors that are currently not covered by the EU ETS (transport, buildings, agriculture). It is precisely in these areas that national legislative measures have so far been taken only selectively (Ennöckl, 2020).

Within the existing division of powers between the federal government and the federal provinces in the Federal Constitutional Law, there is no explicit area of responsibility for climate protection measures. Climate protection, as well as environmental protection in general, is a cross-cutting issue (Handstanger, 2022; Ennöckl, 2023a) (*high confi-*

*dence*). The Constitutional Sustainability Act ('BVG Nachhaltigkeit') (BGBl. I Nr. 111/2013) contains a constitutional commitment to sustainability and thus to climate protection in all areas of government action. It sets a mandate for action for all responsible actors in legislation and implementation (Sander and Schlatter, 2014). Insufficient efforts in these areas have not yet been taken up by the courts. The legal effectiveness of the Constitutional Sustainability Act is therefore considered to be very low (Ennöckl, 2023a; Kirchmair and Krempelmeier, 2023) (*medium confidence*). In Austria, an appropriate design of the legal framework can make a significant contribution to the transition to a climate-neutral society and economy. However, this requires addressing and resolving deeper structural problems of the law, including the reorganization of the legal institutions and infrastructures that co-constitute and regulate the political economy. Thus, necessary legal changes affect not only environmental law, but also essential parts of economic law in general and the overall legal order of fundamental socio-economic structures (Lachmayer and Müller, 2023) (see Section 6.2).

In 2011, Austria was an early adopter of a Climate Protection Act ('Klimaschutzgesetz') at the national level. The Climate Protection Act does not include any competences, strategies or instruments for the reduction of GHG emissions, but rather consists of a mere mechanism to distribute the emission reduction targets in 2020 set by EU and international law to different sectors (Ennöckl, 2023b). The law is therefore mainly described as a 'mandate or negotiation law' (Ennöckl, 2020; Schulev-Steindl et al., 2020). Adaptation to climate change plays a minor role in the Austrian Climate Protection Act.

Since the GHG reduction targets contained in the law expired in 2020, Austria has been de facto without a functioning nationally determined climate protection act. The Federal Energy Efficiency Act (BGBl. I Nr. 72/2014) provides for energy efficiency targets at the national level, which should contribute to achieving climate neutrality by 2040 (Suchanek et al., 2023). Although the goal of achieving climate neutrality by 2040, as envisaged in the Government Program 2020, has not yet been explicitly enshrined in legislation, some legal provisions refer to this target. For example, § 35 (12) (a) of the Federal Energy Efficiency Act states that the goal is to contribute to achieving climate neutrality by 2040.

Concerning the expansion of renewable energies, Austria has set a target of producing 5 TWh of renewable gas and raising electricity production from renewable sources on a yearly balance[6] to 100 % until 2030 (Ennser, 2022). It has introduced a set of measures to accelerate the deployment of renewable energy production. Regarding energy efficiency, Austria aims to achieve a linear decrease in final energy consumption up to a maximum of 920 PJ in 2030. Various laws, e.g., on renewable gas are under consultation but not yet decided or will have to be amended once the directives from the Fit for 55 directives come into force.

## 6.4. Institutions and actors of climate governance in Austria

This section assesses Austrian climate governance strategies, their institutional design and the actors involved. It analyses the interests and power relations involved in governance processes that may limit their effectiveness. The concept of governance refers to a mode of political steering that includes, but is not limited to, state actors. It can involve multiple scales (from local to international) and a variety of private, public and civil society actors and institutions. It is typically conceived as a consequence of the failure of states to 'govern' complex societal problems, such as climate change, through vertical 'top-down' regulation alone (Jordan et al., 2003; Biermann et al., 2012; Brand, 2016; Bäckstrand and Kronsell, 2017). Climate governance often focuses on technological (and sometimes social) innovations and their diffusion across economies and societies. However, as the climate crisis is a time-bound problem, a complementary focus on *exnovation*, i.e., the "intended dismantling of practices, products, technologies and infrastructure" (Krüger and Pellicer-Sifres, 2020, p. 117) becomes ever more important. This includes, for example, phasing out fossil energy infrastructures such as coal-fired power generation, as well as phasing out fossil subsidies and socio-technical systems such as the internal combustion engine and its various applications. In this report, the relationship between innovation and exnovation in climate policy and governance is systematically reflected in the Avoid-Shift-Improve (ASI) framework (see Cross-Chapter Box 4). Governance of exnovation is necessary to shift societies from fossil to sustainable socio-technical systems. It is also essential to implement forms of climate governance that aim to avoid unnecessary and harmful consumption patterns (*robust evidence, medium agreement*).

[6] This means that the percentage is to be determined based on the total quantity of energy consumed in a year and does not have to be achieved in all hours, days or months of the year.

Austria has long had a reputation as a leader in environmental policy (Lauber, 1997). However, despite this reputation, Austria's weak climate policy record contrasts with its strong declared climate ambitions (Melidis and Russel, 2020). Therefore, there is a strong mismatch between Austria's (powerfully produced) self-image as a country with relatively high environmental standards and the actual unsustainability in many sectors. The general climate policy consensus in the Austrian state apparatuses is to deal with climate change in a mode of 'ecological modernization', i.e., to change the energy and resource base without changing social structures and power relations as well as the prevailing modes of production and consumption. This ties in with the clientelist character of Austrian climate policy, in which certain state apparatuses often act in favor of certain groups, e.g., farmers or the business sector (Steurer et al., 2020; Nash and Steurer, 2023) (*medium confidence*).

In the last 20 years, the Austrian government and parliament have formulated three climate strategies and a Climate Protection Act (Nash and Steurer, 2023) (see Section 6.3.3), which has been amended several times. However, climate policy in Austria remains fragmented and incremental and has so far failed to achieve its goals (Niedertscheider et al., 2018; APCC, 2023; Tebecis, 2023). Climate governance has not been a coherent government priority (Scherhaufer and Clar, 2021). As in other European countries, climate governance in Austria has so far mainly relied on 'soft' measures – so-called 'New Environmental Policy Instruments' – which include voluntary measures and market-based instruments, that do not constitute deep interventions in the economic structure of society or in consumer practices (Wurzel et al., 2013; Feichtinger et al., 2021). It remains deeply committed to a perspective of technological change and market-driven innovation to stimulate 'sustainable' or 'green' growth, while there is no vision for sufficiency-oriented governance, i.e., policy frameworks and governance mechanisms that address the systemic drivers of the climate crisis (Novy et al., 2023b). So far, climate governance has not attempted to steer the scale, nature or scope of final consumption (e.g., through mandatory carbon labeling or choice editing) (Maniates, 2010). The incremental nature of Austrian governance can be exemplified by the automobile sector, where government responses to the climate crisis have so far relied on market-based solutions, technological fixes (e.g., shifting to electric vehicles instead of public transport), international competitiveness, and technological innovation, and have failed to achieve the much-needed downscaling and conversion of production and consumption (Krenmayr et al., 2020; Pichler et al., 2021b) (*robust evidence, medium agreement*).

### 6.4.1. Institutions

In this chapter, 'institutions' refers to the political, legal, and economic rules and forms of organizing climate governance. Institutions are located at and traverse multiple levels of scale, from local/municipal to regional, national, European, and international (Pierre and Peters, 2020). Here we focus on the national and federal provincial level. At the national level, the establishment of a Ministry for Climate Protection, Environment, Energy, Mobility, Innovation and Technology (BMK) in 2020 was a symbolically important step for climate governance in Austria (Nash and Steurer, 2023), both because climate was explicitly mentioned in the title of the ministry and because it was given priority over the other areas covered by the ministry. Moreover, the integration of the key sectors of transport and energy into the ministry's remit brings important levers for climate change mitigation (Eberl et al., 2020).

#### Federalism

The fragmented structure of the Austrian government and its respective agencies remains an obstacle for the realization of ambitious climate policies at the national level. In particular, Austrian federalism is more of a hindrance than an enabler for the formulation and implementation of ambitious climate policies. Conflicting interests between the federal and federal provincial levels favor either agreements with unambitious targets, unclear responsibilities, a lack of sanction mechanisms, or no agreement at all (Steurer et al., 2020; Scherhaufer and Clar, 2021) (*medium confidence*). The recently adopted Fiscal Equalization Agreement for the period 2024–2028 does not provide for substantial reforms to strengthen intergovernmental climate governance in Austria (Bittschi et al., 2024). In terms of institutional design, national climate councils, as provided for in the European Climate Change Act, can play an important role in convening stakeholders and providing expert scientific advice on climate policy to relevant authorities (Evans and Duwe, 2021). They can also monitor relevant policy developments (EEA, 2021a). Despite the encouragement to do so, not all Member States have yet established an independent climate advisory body.[7]

[7] These are ESABCC, Denmark, Estonia, Finland, France, Germany, Greece, Ireland, Luxembourg, the Netherlands, Slovenia, Sweden, Iceland and the United Kingdom.

### Social partnership

The Austrian social partnership, an important mechanism for well-designed economic and social policies, has not yet reached the heights of climate policy (Tobin, 2017; Niedertscheider et al., 2018; Brand and Niedermoser, 2019) (*medium confidence*). The social partnership was designed to reconcile conflicting social interests in an era of rapid fossil-based economic and socio-metabolic expansion, and as such may not be ideally suited in its current form to manage the decarbonization of a complex economic structure. Empirical research has even identified the Austrian social partnership as a force obstructing climate action (Brand and Pawloff, 2014). However, in recent times, important initiatives have been launched to 'green' the Austrian social partnership, e.g., the initiative 'Growth in Transition' that started in 2008 or a more recent initiative to strengthen the perspective of a comprehensive social-ecological transformation within the Chamber of Labor (Arnecke, 2024).

### Institutional focus on climate change adaptation

There is evidence that Austria's governance system is better suited to enabling effective adaptation to climate change than mitigation (Clar and Steurer, 2014; Steurer and Clar, 2018) (*medium confidence*). Clar and Steurer (2014, p. 23), for example, argue that Austrian federalism "could prove helpful in mediating between national guidance and local adaptation". However, the existing institutional set-up seems to be more geared towards conventional strategies to help individual and collective actors cope with or gradually adapt to climate change (Fekete et al., 2022), e.g., via sophisticated disaster risk management systems or adapted building standards (Nordbeck et al., 2019). In contrast, it seems much less prepared for what Fedele et al. (2019, p. 116) call "transformative adaptation", that is "fundamental systems' changes that address root causes of vulnerability to climate change" (cf. Brand and Wissen, 2024) (*high confidence*).

Natural hazard management and climate change adaptation – internationally, but also in Austria – are currently largely uncoordinated in dealing with some of the same climate-related risks (see Cross-Chapter Box 1). In terms of risk analysis and decision making, natural hazard management focuses strongly on experience, while climate change adaptation focuses mainly on possible future developments (Schinko et al., 2017; Leitner et al., 2020) (*high confidence*). As climate change impacts intensify in the future and adaptation limits may be reached, current incremental risk management measures may no longer be sufficient to maintain societal goals and values (Dow et al., 2013; Preston et al., 2013; Schinko et al., 2024) (*high confidence*). To improve the effectiveness and efficiency of climate-related risk management, the two currently largely independent approaches need to be more closely integrated into a holistic approach – a concept known as 'climate risk management' (Jones et al., 2014; Mechler et al., 2014; Schinko et al., 2017) (*high confidence*). In order to achieve this integration, it is crucial to first understand the current, often isolated governance structures in specific countries or regions and thus identify the potential synergies, but also conflicts, at the interface between these two policy areas (Leitner et al., 2020) (*high confidence*).

Moreover, historically, risk management strategies have been developed for single hazards (Leitner et al., 2020), while advancing climate change will increasingly cause compound climate-related risks (e.g., Zscheischler et al., 2018) (*medium confidence*). To overcome existing path dependencies (Hanger-Kopp et al., 2022; Seebauer et al., 2023) of single-hazard risk management arrangements, which may ultimately cause barriers to transformative adaptation efforts and lead to the intensification of existing societal inequalities, Thaler et al. (2023) argue for a compound risk governance system and management practice (*medium confidence*).

The various institutional deficits with regard to both mitigation and adaptation point to the need for substantial changes, not only in existing policies, but also in the polity, i.e., the (political, legal and economic) institutional framework within which mitigation and adaptation policies are formulated and implemented (Pichler, 2023).

## 6.4.2. Actors

Actors relevant to climate policy and policymaking can be found both inside and outside institutions and can be collectively organized in institutions such as political parties. As in many other democratic industrialized countries today, the existing constellation of actors in Austria harbors the danger of 'climate delay' or 'climate policy dismantling', i.e., the possibility of obstructing and delaying already agreed climate policies and decarbonization targets, as well as cutting, reducing or abolishing existing policies (Lamb et al., 2020a; Ekberg et al., 2022; Paterson et al., 2024) (see Section 8.5.1). After a phase of progressive climate policy formulation starting around 2019, the EU and many of its Member States, including Austria (Arnecke, 2024), are currently facing an era of reluctance and restraint with regard to the further development of climate policy (Plehwe et al., 2024) (*high confidence*).

## Political parties

The positions and strategies of political parties on climate change in Austria vary greatly. In the legislative period of 2019–2024, the government has set the target of climate neutrality by 2040. There are, however, substantial differences among parties when it comes to concrete measures to achieve this goal, despite a formal commitment of all parties to the overall objective of climate neutrality (Kirchengast et al., 2019a) (*high confidence*).

Ambitious climate action – mostly within the corridor of ecological modernization – is demanded primarily by the Austrian Green Party. Accordingly, it is also the party most clearly identified with the issue of climate change in Austria, by experts and the electorate (Dolezal, 2016; Abstiens et al., 2021). While the Green Party has benefited considerably from the issue salience of climate change in the parliamentary elections of 2019 and in several regional elections, more recent elections, e.g., to the European Parliament, have seen Green losses in an atmosphere of increasing societal polarization and strong gains of far-right parties across Europe, including in Austria (Cunningham et al., 2024; Schwörer, 2024). While this provides an ambiguous picture of the impact of polarization and far-right popularity on the salience of climate change as an electoral issue and the performance of the Green Party (Buzogány and Scherhaufer, 2018), it also suggests that the salience of the climate change issue in recent years positively influences the Green Party's performance, both on the European (Pearson and Rüdig, 2020) as well as the national level, where the Greens entered a governing coalition as the junior partner of the conservative People's Party (ÖVP) after the snap elections in 2019 (Eberl et al., 2020) (*medium confidence*).

Representing business as well as agrarian interests, the ÖVP is located at the blocking end of the party spectrum when it comes to ambitious climate action. With an emphasis on the principles of voluntariness and 'technology openness', a construal of the climate crisis as a question of technological innovation and a framing of more binding and far-reaching measures as a threat to the national economy and prosperity, it has repeatedly hindered the implementation of more ambitious climate policy. In recent years, it has done so from a powerful position, leading two governments and dominating key state apparatuses such as the BMF and the Chancellery (Steurer et al., 2022; Auel and Schmidt, 2023; Pearson, 2024) (*medium confidence*). One area of climate policy where the ÖVP has recently taken a more proactive role is Carbon Capture and Storage (CCS) and Carbon Capture Utilization (CCU). In spring 2023, the ÖVP-led BMF initiated the development of a carbon management strategy, aimed at establishing a regulatory and subsidy framework for CCS and CCU in Austria. This integration of CCS and CCU into Austria's climate strategy is in line with the party's inclination towards techno-solutionism. It poses crucial political challenges in terms of addressing the risk that unwarranted expectations of CCS and CCU undermine other mitigation efforts, in terms of limiting CCS to residual emissions that are truly hard-to-abate, and dealing with the persistent risks and uncertainties of these technologies (Brad et al., 2024).

On a programmatic level, the Social Democratic Party (SPÖ) is committed to global or European multilateral agreements and stresses that global responsibility requires local action. It sees climate protection as a challenge that requires a profound restructuring of modes of production and consumption as well as the economy and society at large. However, in a 2019 analysis of party positions on climate change, the alignment of the SPÖ's climate policy with the Paris Agreement was rated as "unclear", partly due to shortcomings in spatial planning (Kirchengast et al., 2019b). An infamous example of these shortcomings is the Lobautunnel, a proposed underground segment of a bypass highway beneath a Viennese nature reserve. The tunnel not only represents the SPÖ's reluctance to abandon emission and resource-intensive pathways like car-centered mobility, but it is also emblematic of how climate-related issues are still highly contentious within the party. While the Viennese party stands firmly behind the project, others in the party, including the federal chair and the party youth, intermittently opposed it. Looking beyond mobility, the federal chair has introduced plans for a climate transformation fund ('Klima-Trafo') in early 2024. This fund is intended to foster and secure sustainable investments, e.g., in renewables or innovative start-ups (Arnecke, 2024).

For the resurgent far-right Austrian Freedom Party (FPÖ), the protection of nature and immediate environment is a salient and fundamental component of ideology and legislative activity. This is nourished by a long-established ethno-nationalist ecological framework of anti-anthropocentrism and organicism (Voss, 2019), and sometimes serves more strategic ends (Tosun and Debus, 2022). It also entails a programmatic embrace of a domestic green energy transition as a way to strengthen national sovereignty (Selk and Kemmerzell, 2022) and sometimes even seems to extend to climate mitigation (Ruser and Machin, 2019; Ćetković and Hagemann, 2020). However, climate policy sceptic positions in the guise of economic pragmatism and even outright denial of anthropogenic climate change are still firmly anchored within the party (Forchtner, 2020; Malm, 2021) (*medium evidence, high agreement*). This is reflected not only on the programmatic level (Kirchengast et al., 2019a), but also in parliamentary decision making – both at the national and EU level – where the FPÖ has repeatedly opposed mitigation measures (Ćetković and Hagemann, 2020), most infamously in its vote against the Paris Agreement (Austrian Parliament, 2016). While this can be interpreted as an act against multilateralism rather than climate obstruction (Selk and Kemmerzell, 2022), there are also domestic issues where the FPÖ has positioned itself against measures that allegedly harm the so-called 'common man', symbolized, e.g., by the figure of the car driver, who is claimed to suffer from increasing restrictions imposed by climate change policies (Ruser and Machin, 2019). This points to a populist strategy dividing the political space into a self-righteous (urban) and climate-conscious 'elite', imposing their climate agenda on a victimized 'people'. Climate action thus appears as an elitist project directed against the majority in the FPÖ's discourse (Buzogány and Mohamad-Klotzbach, 2022). This also points to a more general characterization of right-wing parties as unbridled defenders of a resource and emission intensive 'imperial mode of living' (Eversberg, 2018; Brand and Wissen, 2024).

The liberal party Neos is strongly committed to multilateral and transnational efforts to mitigate climate change in which it wants Austria to lead by example. Crucially, Neos claims that effective climate protection can best be achieved within an ecologically modernized market economy that promotes technological innovation. While the party perceives state regulation as an obstacle to economic development in many respects, climate protection measures form a notable exception here. For Neos, the decarbonization of the market economy does also require regulatory action by the state, e.g., in the form of a restructuring of subsidies. Importantly, however, this does not imply an expansion of the current regulatory framework or the state's ability to intervene in the economy. Instead, climate protection measures such as a $CO_2$ tax should be 'revenue-neutral', i.e., accompanied by deregulation measures that offset the additional costs for Austrian companies. Many of the climate protection measures proposed by the federal government are supported by the Neos. While they joined the Greens in opposing the Lobautunnel, Neos supported the Renewable Energy Act and the Energy Efficiency Act (Arnecke, 2024).

### Organized interest groups

The neo-corporatist character of Austrian politics places specific interest groups in a key position in climate policymaking, by formally establishing links between the state and a limited set of social partner organizations (Tálos and Hinterseer, 2019). While the social partnership is strong when it comes to economic and social issues, it is weak when ambitious climate policies need to be formulated and implemented (Brand and Pawloff, 2014; Niedertscheider et al., 2018). However, there is a range of positions on climate change among the social partners. The Chamber of Labor is the most ambitious social partner trying to pursue ambitious climate policies, despite its occasional advocacy for the expansion of fossil infrastructure to secure employment (Arnecke, 2024) (*high confidence*).

Historically, the relationship between trade unions and environmentalists in Austria has been complicated and conflictive (Brand and Niedermoser, 2019). In the past, trade unions have repeatedly opposed climate protection measures, which they believed would hinder economic development and undermine their bargaining power. In doing so, they have even joined forces with energy companies to secure cheap energy prices (Soder et al., 2018). Despite the complex relationship between trade unions and environmental goals, newly emerging alliances between trade unions and environmental groups have been identified as potential new societal alliances for social-ecological transformation (Soder et al., 2018). It should also be noted, that some 'traditional' trade union policies, e.g., working time reduction, can be considered as 'implicit climate policy', as they are not understood as measures to combat climate change but can contribute to climate-friendly living (Brand and Niedermoser, 2017; Liebig, 2019) (see Section 4.7.3).[8] In recent years, the climate crisis has become an increasingly central issue for the Austrian Trade Union Federation (ÖGB), whose 2023 program includes fourteen pages on climate change and a 'just transition'. Here, the ÖGB emphasizes the risks of climate change itself (e.g., working in increased heat) as well as its mitigation (e.g., layoffs due to stricter regulation). Despite their warnings, they also point out the potential long-term synergies between their fundamental goals of improving wages, working conditions and job security on one side and climate protection on the other.

[8] The potential positive contribution of a (wage) worktime reduction to enabling climate-friendly living depends on the design and mix of respective policies (Hardt et al., 2020, 2021).

However, it is important to note the sectors and class fractions represented by the ÖGB. While some branches, such as the sectoral union for transport and services (vida), have common interests with climate movements like Fridays for Future (FFF) and in fields like public transport even engage in a joint campaign called 'We ride together', conflicts exist in individual cases such as plans for airport expansion. In other sectors, climate politics is even more contentious. The sectoral union for construction and wood, for example, has also entered into a coalition with FFF, demanding, among other things, subsidies for renovation. In response to the severe crisis in the construction industry, however, the union has since joined the WKO in calling for an economic stimulus package that includes resource-intensive measures such as subsidies for single-family homes (Arnecke, 2024). Meanwhile, in sectors such as the automotive industry, the contradiction between the immediate interests of workers and environmentalists is even more obvious (Pichler et al., 2021a). Where they exist, union's climate strategies tend to remain within the corridor of ecological modernization, as they tend to support climate action only if the primary goals of employment, competitiveness, and economic growth are not compromised (Brand and Niedermoser, 2019) (*medium confidence*).

The Austrian Economic Chamber (WKO) and the Federation of Austrian Industries (IV) represent different business factions with different interests regarding climate policy. For instance, oil and gas producers and renewable energy producers are both represented by the WKO, yet they have conflicting interests regarding an energy transition. However, WKO and IV have been identified as powerful veto players, blocking the implementation of ambitious climate policy (Abstiens et al., 2021) (*high confidence*). A concrete example is the development of the 2011 Climate Protection Act, where the WKO played a central role in limiting ambition, especially of GHG emission reduction targets (Brand and Pawloff, 2014; Nash and Steurer, 2021). This obstructive role is also reflected in the perceptions of the members of the Citizens' Climate Council. Evaluations of the body show that members were disappointed with the IV and the WKO, who were late in submitting their inputs, were the only stakeholders not to attend in person but online, and attended only one round of discussions with the citizens, while all the other stakeholders stayed for two rounds (Buzogány et al., 2022). A more ambivalent role seems to be played by the Austrian Chamber of Agriculture. While sometimes described as 'pro-environment', it sided with the other social partners in slowing down the transition to renewable energies. In support of agribusiness interests, it favored subsidies for biofuels and lobbied against feed-in-tariffs for wind or solar power (Tobin, 2017; Arnecke, 2024).

## Climate organizations and movements

Although Austria has established environmental organizations, policymakers and social partners only partially view them as legitimate partners in policymaking (Hermann et al., 2015). However, in recent years, as in many other countries around the world, the FFF movement has become a key civil society actor in Austrian climate politics, ushering in a new phase in the history of the Austrian environmental and climate movement (Daniel and Deutschmann, 2020; Arnecke, 2024). In Germany, FFF has been identified as supportive of representative liberal democracy, but also critical of incumbent power relations (Buzogány and Scherhaufer, 2022). Although putting pressure on politicians was the main motive for participants taking part in a 2019 FFF demonstration in Austria (Daniel and Deutschmann, 2020), they also showed little trust in the government to act appropriately to counter climate change (Buzogány and Mikecz, 2019). As well as demanding from politicians to make decisions in-line with climate science and international agreements such as the Paris Agreement, FFF Austria has been involved in specific conflicts, opposing fossil infrastructure projects such as the Lobautunnel and the proposed third runway at Vienna Airport, and supporting the expansion of wind farms in the Waldviertel region of Lower Austria (Arnecke, 2024).

The Lobautunnel conflict also led to the founding of the Austrian branch of the Last Generation protest movement, which is best known for its civil disobedience (Arnecke, 2024). As with the German branch of the movement (Rucht, 2023), Last Generation's strategy has been highly conflictual and has led to polarized responses, including repressive measures against climate activists (Simsa, 2024). The movement ceased its activities in 2024.

In addition to demonstrations, NGOs and movement actors have also used climate litigation as a strategy to influence climate policy change (see also Section 6.6). For example, a 2017 court case to prevent the construction of a third runway at Vienna Airport was initiated by individuals together with an NGO, the Anti-Aircraft Noise Society (Setzer and Bangalore, 2017). In 2020, Greenpeace and numerous other plaintiffs filed a human rights lawsuit with the Constitutional Court based on preferential tax conditions for air travel compared to train travel. The case is currently pending before the European Court of Human Rights (Wallner, 2022).

A central mainstream actor in recent years has been the 'Klimavolksbegehren'. Using a formal direct-democratic instrument for citizens to bring issues to the attention of parliament, which is obliged to consider and report on the issue, climate activists initiated a popular petition on climate policy in 2020. It was signed by 380,590 Austrian citizens (5.9 % of the population entitled to vote), making it the 20th most-supported public petition in Austrian history and leading to its subsequent consideration in parliament (Wallner, 2022). Of the four demands made by the petition – binding and sector-specific $CO_2$ budgets, a constitutional amendment guaranteeing climate protection, eco-social tax reform, and a citizens' climate assembly – the last two were taken up (Arnecke, 2024).

The Citizens' Climate Assembly was a representative mini-public initiated in 2021. Although designated independent and impartial, the assembly was associated with the minister for climate action from the Green Party from the outset (Buzogány et al., 2022). A key output of the assembly was a set of policy recommendations that demanded more ambitious climate policy than the status quo across a very comprehensive range of policy areas, although these have not been discussed in parliament and the main feedback loop in the political process has been a detailed response from the relevant ministries (Clar et al., 2023). The assembly was praised as a good example of a deliberative forum at the national level (Clar et al., 2023). It was built upon important procedural aspects – specialized facilitation, a scientific advisory board, and possibilities for participative deliberation by participants on both procedural and substantive aspects (Buzogány et al., 2022), all of which were highlighted as beneficial by participants (Praprotnik et al., 2022). The extent to which participants were concerned about climate change did not change over the course of the assembly, which participants put down to being able to direct their concerns in a meaningful direction (Praprotnik et al., 2022). This empowerment continued after the assembly concluded, with former members founding an official organization to continue their work. Criticism of the assembly was that the stakeholder board lacked meaningful engagement (Buzogány et al., 2022). Furthermore, despite the intention to constitute a representative proxy of the Austrian population, the assembly members were found to be more concerned about climate change and more interested in politics than the general population (Praprotnik et al., 2022). In particular, the exclusion of people who had not been vaccinated against COVID-19 from participation excluded a group overrepresented among FPÖ supporters (Arnecke, 2024).

## 6.5. Policy instruments for climate change mitigation and adaptation

This subchapter addresses policy instruments for climate mitigation and adaptation in Austria, offering only a brief overview of specific instruments, with detailed discussions provided in the sector-specific Chapters 2, 3 and 4.

Effective climate policies enable structural change towards climate-friendly living and producing, and increase resilience in the face of unavoidable climate change. This includes transforming unsustainable consumption and production patterns (see Section 6.2). Key levers to achieve this goal are demand-side mitigation policies, and associated instruments focused on increasing sufficiency, i.e., reducing demand for energy, materials and land while ensuring high levels of well-being within planetary boundaries. These policies, also characterized as 'avoid'-instruments, work by preventing demand altogether, distinguishing them from instruments that 'shift' demand to other means or merely 'improve' existing provisioning structures (see Cross-Chapter Box 4).

'Avoid' instruments span across various categories (regulatory, economic, etc.) and sectors. In the transport sector, for instance, teleworking incentives such as subsidies for energy bills, help reduce commuting needs. Some instruments contribute both to avoiding and shifting demand, e.g., banning domestic flights can reduce (air) travel while also shifting traffic from air to rail. Evidence from Austria and other EU countries indicates that such 'avoid' instruments are significantly underrepresented in both current policy mixes and medium- to long-term policy plans (Zell-Ziegler et al., 2021; Novy et al., 2023b; Jarre et al., 2024; Olesen and Vikkelsø, 2024; Brad et al., 2025).

Moreover, the design of policy instruments is subject to a variety of problems, including imperfect information, undefined property rights, multiple externalities, market power, vested interests, unobservable or immeasurable behavior, monitoring problems, uncertainty, lack of stakeholder support, and constraints on available administrative capacity (Bennear and Stavins, 2007). This motivates a second-best policy framework using a combination of regulatory, economic and other instruments to address the identified problems and explains the widespread use of climate policy packages. EU Member States reported 2,052 climate change policies or measures in 2021, of which 44 % were economic instruments and 41 % regulatory instruments (EEA, 2021b).

Table 6.2 Summary table on the status of policy instruments in Austria (content based on expert estimations by the Lead Authors of AAR2).

Part A: Mitigation

<table>
<tr><th></th><th>Agriculture / forestry / other land use</th><th>Transport (excluding aviation)</th><th>Buildings</th><th>Non-ETS industries</th><th>ETS industries</th><th>Energy supply</th><th>Aviation</th></tr>
<tr><td rowspan="8">Economic instruments: taxes and ETS</td><td colspan="4">National emission trading system</td><td colspan="3">EU ETS</td></tr>
<tr><td colspan="5">Energy taxes</td><td></td><td>Fuel taxes</td></tr>
<tr><td>Carbon border adjustments</td><td colspan="3"></td><td colspan="2">Carbon border adjustments</td><td></td></tr>
<tr><td>EU level border-meat-adjustment tax</td><td colspan="4"></td><td>VAT exemption for PV systems</td><td>VAT on international flights</td></tr>
<tr><td>Elimination of reduced VAT or higher taxes rate for meat and dairy products</td><td>Road pricing trucks</td><td>Vacancy fee</td><td colspan="2">Resource taxes</td><td></td><td>Passenger taxes</td></tr>
<tr><td>Higher taxes for emission-intensive products</td><td>Road pricing cars / city toll</td><td>Secondary residence fee</td><td colspan="4"></td></tr>
<tr><td>Fertilizer tax</td><td>Vehicle taxes</td><td>Real estate tax</td><td colspan="4"></td></tr>
<tr><td>Soil sealing taxes</td><td>Parking fees</td><td colspan="5"></td></tr>
<tr><td rowspan="9">Economic instruments: subsidies</td><td colspan="7">R&D subsidies</td></tr>
<tr><td>Investment subsidies</td><td>Subsidies for low emission mobility</td><td>Subsidies for change of heating systems</td><td colspan="2">Environmental protection subsidies</td><td>Investment subsidies</td><td></td></tr>
<tr><td>(Restructuring of) subsidies</td><td></td><td>Subsidies for thermal refurbishment</td><td colspan="2"></td><td>Feed-in premiums</td><td></td></tr>
<tr><td>Payments for eco-system services</td><td colspan="6"></td></tr>
<tr><td>Premiums for the reduction of livestock</td><td colspan="6"></td></tr>
<tr><td>De-sealing premiums</td><td colspan="6"></td></tr>
<tr><td>Earmarked compensation payments directed to re-naturation</td><td colspan="6"></td></tr>
<tr><td></td><td>Commuting subsidies</td><td colspan="5"></td></tr>
<tr><td></td><td>Subsidies for company cars</td><td colspan="5"></td></tr>
<tr><td rowspan="6">Planning instruments</td><td>Reduction of rezoning of green spaces</td><td colspan="5">Spatial planning</td><td></td></tr>
<tr><td></td><td></td><td>Energy planning</td><td colspan="2"></td><td>Energy planning</td><td></td></tr>
<tr><td></td><td>Unsealing / greening</td><td>Re-densification</td><td colspan="2">Re-naturation of industrial sites</td><td colspan="2"></td></tr>
<tr><td></td><td>Expansion and electrification of public transport</td><td>Adaptation of infrastructure</td><td colspan="2"></td><td>Expansion & adaptation of grid infrastructure</td><td></td></tr>
<tr><td></td><td>Infrastructure for e-mobility</td><td colspan="5"></td></tr>
<tr><td colspan="3"></td><td colspan="2">Product passes</td><td colspan="2"></td></tr>
<tr><td rowspan="7">Other instruments</td><td colspan="7">Non-Financial disclosure regulation</td></tr>
<tr><td colspan="7">Qualification programs</td></tr>
<tr><td colspan="7">Information campaigns</td></tr>
<tr><td colspan="3">Fiscal equalization</td><td colspan="2"></td><td>Fiscal equalization</td><td></td></tr>
<tr><td colspan="3">Labeling</td><td colspan="4"></td></tr>
<tr><td>Reform of communal tax</td><td colspan="6"></td></tr>
<tr><td>Guideline for fertilizer applications</td><td colspan="6"></td></tr>
</table>

Not implemented / missing | 11%  Implemented but insufficient | 77%  Implemented and (fairly) sufficient | 9%  Counterproductive instrument | 3%

| | Agriculture / forestry / other land use | Transport (excluding aviation) | Buildings | Non-ETS industries | ETS industries | Energy supply | Aviation |
|---|---|---|---|---|---|---|---|
| Regulatory instruments | LULUCF regulation | $CO_2$ fleet emission limits / ban of fossil drives | Building codes | Product design standards | | Renewable quotas | Ban of short flights |
| | Feedstuff regulation | Speed limits | Moratoria on expansion of natural gas network | Obligatory energy audits | | Regulations for energy communities | Ban of private jets |
| | Supply chain responsibility regulation | Vehicle access restrictions | Ban of fossil heating systems (new buildings) | Obligatory waste heat utilization | | Sustainability standards for biofuels | |
| | | Environmental impact assessment | | Environment impacts assessment | | | |
| | Regulation on deforestation-free products | Parking space management | Ban of fossil heating systems (old buildings) | | IPPC standards | | |
| | Afforestation obligation | Obligatory shift of longer freight transport to rail | Adaptation of residential property law | | CCU/S regulation | | |
| | Fertilizer regulations | Obligatory transport on rail for certain goods | Adaptation of heritage protection | | | | |
| | Restrictions regarding menus in public canteens | Mobility budgets | Adaptation of tenancy law | | | | |
| | Conservation of biodiversity, nature restoration law | Adaptation of building regulations | | | | | |
| | Regulation on the sustainable use of plant protection products | Moratoria on building of high-ranking roads | Refurbishment of public buildings | | | | |
| | Maximum livestock-to-land ratio | Right to telework | | | | | |
| | Re-naturation of forests through reduced timber extraction | | | | | | |
| | Guidelines for soil protection | | | | | | |
| | Advertising bans for meat | Advertising bans for cars | | | | | Advertising ban for airline |
| | Public procurement | | | | | | |
| | Change in the forestry act | | Parking space obligation | | | | |
| Just transition instruments / compensation instruments | Coupons for vulnerable consumers | Subsidies for public transport for low-income households | Subsidies for changing heating systems and refurbishment for low-income households | Financial support for affected regions | | | |
| | | Lump-sum payments ('Klimabonus') | | Reductions in corporate taxes | | | |
| | | | Energy efficiency programs | Reductions in labor taxes | | | |
| | | | Consumer protection and information | Employment subsidies | | | |
| | | | Preferential loans / energy efficient mortgages | Active labor market policies | | | |
| | | | Curbing monthly back payments of tenants for renovation measures | | | | |

Not implemented / missing | 11%  Implemented but insufficient | 77%  Implemented and (fairly) sufficient | 9%  Counterproductive instrument | 3%

Part B: Adaptation

<table>
<tr><th></th><th>Agriculture / forestry / other land use</th><th>Transport (excluding aviation)</th><th>Buildings</th><th>Non-ETS industries</th><th>ETS industries</th><th>Energy supply</th><th>Aviation</th></tr>
<tr><td rowspan="3">Economic instruments</td><td>Subsidies for resilient crops</td><td></td><td>Subsidies for passive cooling</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Subsidies for water-saving management systems</td><td></td><td>Subsidies for renovation</td><td></td><td></td><td></td><td></td></tr>
<tr><td>Subsidies for cover crops</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="5">Regulatory instruments</td><td colspan="6">Consideration of adaption issues in EIA</td><td></td></tr>
<tr><td>Heat protection (labor law)</td><td></td><td></td><td colspan="2">Heat protection (labor law)</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Adaption of tenancy law (Responsibility and Entitlement)</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Adaption of residential property law</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td>Adaption of heritage protection</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="8">Planning instruments</td><td colspan="6">Spatial planning</td><td></td></tr>
<tr><td></td><td colspan="5">Heat protection (passive & active cooling, unsealing)</td><td></td></tr>
<tr><td colspan="6">Flood protection</td><td></td></tr>
<tr><td></td><td colspan="5">Avalanche protection</td><td></td></tr>
<tr><td></td><td colspan="5">Torrent control</td><td></td></tr>
<tr><td colspan="7">Resilient water management: upgrade of drainage infrastructure, stormwater harvesting and re-use</td></tr>
<tr><td></td><td></td><td></td><td colspan="2">Supply chain diversification</td><td></td><td></td></tr>
<tr><td>Strip cropping (“Begrünungsstreifen / Agroforststreifen”)</td><td></td><td>Cooling and water retention through greening, de-sealing, and implementation of “sponge cities”</td><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="4">Other instruments</td><td colspan="6">Insurance obligation</td><td></td></tr>
<tr><td colspan="6">Information</td><td></td></tr>
<tr><td colspan="6">Qualification</td><td></td></tr>
<tr><td colspan="7">Non-financial disclosure regulation</td></tr>
</table>

Not implemented / missing Implemented but insufficient | 97% Implemented and (fairly) sufficient | 3% Counterproductive instrument

For both mitigation and adaptation, this subchapter focuses on regulatory, planning, economic and other instruments such as information and behavioral instruments. Regulatory instruments are highly sector-specific, ranging from building codes to feedstock regulations to fossil fuel bans. For planning instruments, this section focuses on energy planning. Regarding economic instruments, the focus is on instruments that aim at mitigation and adaptation by steering relative prices.[9] Regarding mitigation, instruments to compensate for potentially negative distributional impacts of mitigation policies are also addressed.

Table 6.2 provides an overview of important climate policy instruments in Austria in different sectors, distinguishing instruments according to their implementation status and their alignment with climate policy objectives. Instruments are further divided into different types (economic, regulatory, planning, just transition and other instruments). Table 6.2 (A) displays mitigation instruments while Table 6.2 (B) presents adaptation instruments.

### 6.5.1. Mitigation instruments

#### Regulatory instruments for climate change mitigation

There are numerous examples in policy practice where regulatory instruments have been used effectively, e.g., to increase energy efficiency, control toxic substances, or manage natural resources such as forests or fisheries (Bennear and Stavins, 2007). Furthermore, regulatory instruments such as bans and limits have been identified as key levers to achieve phase-out and exnovation of unsustainable structures and practices (Heyen et al., 2017; Green, 2018; Rosenbloom et al., 2020; Pichler et al., 2021b; Rinscheid et al., 2021).

[9] Economic policy goes beyond measures to influence prices and, consequently, shape economic activities. It encompasses a wide range of measures of government interventions to proactively steer structural change. While some types of measures merely alter the framework conditions under which producers and consumers act (i.e., they do not aim at direct intervention), others intend to intervene more directly into economic activities (Peters, 2015). Many recent studies highlight the contribution of economic policy to the transformation to a climate-friendly economy (Blanchard et al., 2022). This includes, for example, trade policy (Wolf, 2021), industrial policy (Rodrik, 2014; Eder and Schneider, 2018; Pichler et al., 2021b), financial and monetary policy (Krogstrup and Oman, 2019; Cahen-Fourot, 2021), (re-)distributional policy (Theine et al., 2022; Kapeller et al., 2023), and labor market and employment policies (Bohnenberger, 2022; Hofbauer et al., 2023).

However, regulatory instruments also come with general policy issues (see introduction of Section 6.5). This is illustrated by the mixed track record of the European Union's Corporate Average Fuel Economy (CAFE) targets. Political influence from car manufacturing lobbies (Oki, 2021) has played a role in undermining the standard's effectiveness (for more information on the influence of obstructive actors, see Sections 6.2 and 6.4.2). This interference contributed to missed emissions targets in the mobility sector and ultimately led to a reduction in overall welfare (Reynaert, 2021).

Standardization is crucial for both market and non-market interactions among individuals or groups for two key reasons: (i) without a basic level of standardization, it becomes highly costly for individuals to compare goods and services, making informed purchasing decisions difficult (standards are therefore essential for reasonable price formation); and (ii) even in the absence of formal or centralized regulation (laws, directives, etc.), implicit or decentralized forms of regulation still emerge through social interactions, including habits, customs, and practices (Pindyck and Rubinfeld, 2018).

*Transport*

The legal framework for the transport sector in Austria has not yet been adapted to the requirements of sustainable transport in passenger and freight transport (see Section 3.4). There is a lack of regulatory instruments in transport law aimed at avoiding $CO_2$ emissions. Current measures, such as speed limits and driving bans, are mainly directed at reducing local emissions, e.g., particulate matter, and thus can only contribute indirectly to the reduction of GHG emissions (Schulev-Steindl et al., 2021). In permit procedures for construction of new road infrastructure, GHG emission reduction aspects only play a minor, if not negligible, role (Graber, 2023). There are also few legally binding requirements for public transportation (Fitz, 2023a). Amendments to building codes in some federal provinces have introduced requirements for the installation of EV infrastructure (i.e., charging infrastructure) in new buildings (Cejka, 2024) and have also facilitated the installation of charging infrastructure in apartment buildings (Fidler, 2023). Furthermore, an amendment to road traffic law introduced provisions to promote cycling and walking (Hugeneck, 2023).

Currently, certain waste shipments must be made by rail or by other means of transportation with equal or lower pollutant or GHG potential. However, this obligation does not apply equally to primary raw materials. Therefore, evaluating the instrument in terms of its impact on the recycling of secondary raw materials could be an important step in reducing the use of natural resources (Krasznai, 2023).

*Industries and energy supply*

GHG emissions from installations are primarily regulated through the economic instrument of emissions trading (see Chapter Box 6.1). Whether Member States can take additional measures in the context of the EU ETS is controversial (Hofer, 2023a). The GHG intensity of installations currently plays little or no role in plant permit procedures (Ennöckl and Sander, 2023; Hofer, 2023a). Regulatory instruments currently focus mainly on energy efficiency and GHG emissions of households and individuals; for industrial emissions and electricity generation, economic instruments are currently favored by policy makers. One exception is the Environmental Impact Assessment (EIA) Act: For example, projects subject to EIA must be designed to limit GHG emissions according to the state of the art or best available techniques. However, for plants included in the EU ETS, no emission limits for direct GHG emissions of GHG subject to emission trading apply (Baumgartner and Niederhuber, 2023; Hofer, 2023b).

The ban on geological storage of $CO_2$, which came into force in 2011 and is currently under discussion, does not apply to the sequestration and transport of $CO_2$ or to research projects, and the storage volumes permitted for research projects are so small that this also hampers the implementation of research projects (Tiefenthaler, 2022).

*Buildings*

Various regulations on EU, national and federal provincial level regard energy efficiency, electricity and heating of buildings. For example, the Renewable Heat Act ('Erneuerbare-Wärme-Gesetz') bans the installation of gas heating in new buildings (BGBl. I Nr. 8/2024). The building regulations of the federal provinces integrate mitigation aspects, e.g., by establishing the principle that buildings and all their parts must be planned and constructed in such a way, that the amount of energy required during use is limited according to the state of the art. Most regulations on sustainable and low-emission buildings have been implemented because of EU legislation. More comprehensive, possibly nationwide, regulations are needed to strengthen mitigation efforts (Häusler and Schlenk, 2021) (see Section 3.3.3). Concerning the energy-efficient renovation of buildings protected by heritage law, the competent authority has to consider aspects of ecological sustainability in general and energy efficiency and renewable energy sources in particular when deciding on permits to modify such buildings.

*Agriculture*

In the agricultural sector, too, the national regulatory framework is largely determined by EU law (The Common Agricultural Policy, CAP) (Eckhardt, 2022). According to EU law, the Austrian CAP strategy must include agri-environmental and climate commitments as well as voluntary schemes for climate, environment and animal welfare ('eco-schemes'), and is complemented by fertilizer regulations and afforestation obligations.

## Planning instruments for energy and climate change mitigation policies

Spatial planning laws of the federal provinces either directly address climate protection as a spatial planning objective or implicitly include mitigation aspects by referring to the protection of the environment and natural resources in general. In addition, some provinces explicitly refer to the expansion of renewable energies as a primary objective in their spatial planning laws (Stöglehner, 2023a). Nevertheless, land consumption in Austria is high (Pories and Pfeiffer, 2024). This section focuses on energy planning, while spatial planning is addressed in detail in Section 3.2.

*Energy Planning*

In addition to lengthy permitting processes, inconsistencies resulting from a lack of coherent nationwide spatial planning for renewable energy infrastructure are barriers to the rapid expansion of renewable energy. Both federal provinces and municipalities are required to designate areas for renewable energy development and infrastructure according to their competencies (Storr, 2024). Efficiency losses thus may result from varying spatial capacity designated for renewable energy projects at different levels. The amended Renewable Energy Directive (Directive (EU) 2023/2413) requires Member States to identify potentials and define areas for accelerated approval of renewable energy projects in order to accelerate the transformation process (Handig and Rathmayer, 2024). Additionally, based on an amendment to the EIA Act and only for wind turbines, in the absence of both local and supra-local spatial energy planning in the federal provinces with regard to the designation of sites for wind turbines, the consent of the municipality alone is now considered sufficient for the granting of a permit for a wind turbine. This means that the lack of designated areas for wind turbines is no longer a legal obstacle to accelerating the expansion of wind turbines (Altenburger et al., 2024).

The legal framework aims to resolve the tension between the expansion of renewable energy and the protection of biodiversity by, among other things, compensating for biodiversity losses through the designation of specific compensation areas, i.e., areas that must be designated and permanently secured as compensation for biodiversity interventions. However, there is currently no detailed legal framework for compensation areas (Wagner and Ecker, 2013).

Currently, Austrian spatial planning legislation does not consistently and comprehensively address the spatial dimensions of energy consumption and energy supply (Stöglehner, 2023a, 2023b). In 2014, the Austrian Conference on Spatial Planning (ÖROK) developed an expert paper that contains the relevant action requirements for the transition to renewable energies. Here, improving the legal framework for spatial planning has great potential to support the energy transition (see Section 3.2.2).

*Strategic Environmental Assessment*

A Strategic Environmental Assessment (SEA), i.e., the assessment of the environmental impacts of a project at the planning stage[10], must be carried out for major planning projects and programs with significant expected environmental impacts (Alge et al., 2019). This includes significant effects of the plan or program on climatic factors (Stöglehner, 2023b).

Without further specifying the scope and depth of the assessments, the European legal framework for the acceleration of renewable energy (Council Regulation (EU) 2022/2577) strongly emphasizes the role of SEAs in energy planning. According to Article 6 of the EU Acceleration Regulation, the EIA and the assessment of species protection under Article 12 (1) of the Habitats Directive (Council Directive 92/43/EEC) can be omitted if a project is carried out in an area designated for the expansion of renewable energies, provided that this area has been designated for this purpose after an SEA has been carried out (Handig and Rathmayer, 2024). It is therefore important that the SEA adequately addresses all environmental issues that would otherwise have been considered at project level (e.g., $CO_2$ emissions) and that public participation in the process is ensured (Stangl, 2024).

*Nature Impact Assessment*

As biodiversity and climate protection are inseparably linked (see Section 1.6.4), the Nature Impact Assessment (NIA) resulting from Article 6 of the Habitats Directive (Council Directive 92/43/EEC) provides an instrument for balancing interests and defining compensatory measures effectively and uniformly in all Member States when expanding renewable energy (Wagner and Ecker, 2019).

The current EU framework for the expansion of renewable energies provides for exemptions from NIAs for renewable energy installations by affirming the overriding public interest in the expansion of renewable energies and allowing compensation for biodiversity losses, while ensuring that the design of compensation areas is consistent with the overall system of EU habitat and species protection law (Handig and Rathmayer, 2024; Stangl, 2024).

## Economic instruments for climate change mitigation

Economic instruments encompass fiscal and other economic incentives and disincentives to incorporate environmental costs and benefits into household and firm budgets. They include pricing instruments (e.g., carbon taxes and emissions trading), subsidies and fiscal transfers.

Carbon pricing instruments are used specifically to influence the incentive structures of production and consumption activities. They focus on market interactions and the efficient allocation of scarce resources. In the presence of negative externalities, pricing instruments are theoretically the most efficient policy intervention to internalize negative external costs that would otherwise be borne by the public (Metcalf and Weisbach, 2009; Ellerman et al., 2010; Pigou, 2013). Second order implications, such as distributional or leakage effects, require additional instruments. Economic instruments are increasingly used internationally in climate policy and have proven to be effective (Bayer and Aklin, 2020; Gugler et al., 2021; Koch et al., 2022; World Bank, 2024) (*medium confidence*). However, available evidence shows that the degree of environmental effectiveness varies across sectors and countries, suggesting that a policy mix of pricing instruments and command and control approaches is needed (Haites, 2018; Shmelev and Speck, 2018; Green, 2021; van den Bergh et al., 2021) (*high confidence*).

[10] While the EIA assesses the environmental impact of a specific project (project level), the SEA examines effects of plans and programs on the environment (planning level).

The scope, stringency, coherence and timeframe of the use of economic instruments for climate change mitigation in Austria can be strengthened considerably (COM/2021/555 final; OECD, 2021a; Steininger et al., 2024) (*high confidence*). Also, the menu of readily available and affordable low-carbon substitution possibilities in response to the use of economic instruments is moderate to high as well as steadily increasing due to social and technological innovation.

Implementing economic instruments – in particular carbon pricing in the form of emissions trading or emission taxes – faces trade-offs due to other potentially conflicting policy objectives (e.g., economic competitiveness) and unintended consequences such as negative distributional impacts. Carbon pricing approaches require additional measures to minimize or compensate for these impacts, for which robust strategies exist (e.g., the Austrian 'Klimabonus'). Analyses for Austria (Kirchner et al., 2019; Eisner et al., 2021; Mayer et al., 2021) show the importance of revenue recycling to compensate for the regressivity of carbon taxes (see Section on compensation instruments) (*high confidence*).

Carbon pricing instruments have limits. These can be structural, when flexible response options are not (sufficiently) available (e.g., public transport in rural areas), or informational, when affected actors lack sufficient knowledge about relevant data, such as underestimated total cost of ownership of private cars (Andor et al., 2020), when actors exhibit present bias (Heutel, 2015)[11], or in the presence of principal-agent problems, e.g., between landlords and tenants (Seebauer, 2021), or due to lack of public trust in carbon-pricing mechanisms and general distrust of policy (Ewald et al., 2022). Thus, the presence of other types of market failures beyond externalities requires the use of further specifically designed instruments formed into policy packages (*high confidence*).

Carbon pricing instruments have the advantage of generating revenues that can be used either to mitigate negative impacts on competitiveness or income distribution, or to subsidize investments and research and development (R&D), etc. Both auctioning revenues from ETS and ESR could be substantial sources of public revenue to support just transition and modernization funds, and transparent earmarking could increase public acceptance (Klenert et al., 2018).

Setting price signals is a normative endeavor with significant distributional impacts and prone to creating resistance from political opponents, incumbent firms or (parts of) the public. This may result in decisions to weaken the stringency of the political intervention (Michaelowa, 1998; Segerson et al., 2024).

Although subsidies can provide important incentives and can result in societal benefits in the case of positive externalities (e.g., R&D, nature conservation) compared to carbon-pricing instruments, they represent a second-best solution. While they are politically easier to implement, they also have several shortcomings – they burden public budgets, the additionality of the funded investments is not ensured, they may have negative distributional impacts; by reducing prices, they may lead to increased production and consumption, and there are significant barriers to subsidy removal, due to the vested interests of beneficiary groups (Michaelowa, 1998; Kärnä et al., 2020; Renström et al., 2021; Heyl et al., 2022; Segerson et al., 2024). Reducing environmentally counterproductive support measures is the other side of the coin and is necessary to correct the pricing of externalities, not only to bring prices closer to the true social cost of carbon, but also to avoid conflicting and inefficient use of several policy instruments (OECD, 2005; Skovgaard and van Asselt, 2018; Elgouacem, 2020; Kletzan-Slamanig et al., 2022). This underlines the dual role of economic instruments, which not only correct externalities, but can also preserve or transform (market) structures (Segerson et al., 2024).

Emissions from the non-ETS sectors (especially buildings and transport) are currently addressed by various types of instruments at EU and Member State level. While the building sector is mainly addressed by regulatory instruments (regional building codes; see Section on regulatory instruments for mitigation), economic instruments like subsidies for thermal renovation and the substitution of fossil heating systems also play a role in combination with incentives provided by energy taxation or exogenously caused energy price increases. In 2027, both sectors will be included in the new emission trading system (ETS 2). GHG and air-pollutant emissions of mobile sources (passenger cars, duty vehicles) are addressed with economic instruments, especially pricing approaches (registration and circulation taxes, mineral oil tax, tolls, parking fees). In addition, investment subsidies and tax benefits for electric vehicles have been increasingly provided in recent years. The combination of various economic instruments for transport is justified by affecting not only the regular use but also investment decisions, thus

11 Present bias is the tendency to settle for a smaller present reward rather than wait for a larger future reward, in a trade-off situation.

compensating the present bias of consumers (Heutel, 2015) and also considering other externalities. Additionally, EU directives regulate fleet fuel efficiencies.

However, the rate of change in the building sector to date has been insufficient, and for the Austrian transport sector the use of economic instruments had no statistically significant impact on GHG emissions (Koch et al., 2022), due to a lack of (effective) regulation, rebound effects overcompensating fuel efficiency gains, and the existence of opposing incentives provided by fossil fuel subsidies and other counterproductive measures (e.g., commuter subsidies, company car taxation). The latter is particularly relevant for aviation, where regulation is either insufficient (inclusion of only intra-EEA flights in the EU ETS, mostly free allocation of allowances, too moderate airline ticket levies) or non-existent (general tax exemption for international aviation for fuels and VAT). Furthermore, efficiency gains have been overcompensated by the continuous growth in air traffic.

Industry and energy generation have been included in the EU ETS since its introduction. Emissions from these sectors in Austria have decreased by 7.2 % between 2005 and 2022 (Umweltbundesamt, 2024), indicating a certain effectiveness of the instrument, at least regarding emissions from energy generation. The price incentive from the ETS was complemented by other policies like energy taxation (albeit with tax refunds for energy intensive industries), subsidies for renewables, energy efficiency and R&D. From 2026 onwards, a new instrument on EU level, the CBAM, will apply a carbon price on emission-intensive goods entering the EU in line with the reduction/phase-out of free allowances in the EU ETS.

In the agricultural sector, the only economic instruments currently aimed at reducing GHG emissions are subsidies for those agri-environmental measures within the Austrian rural development program that have been shown to effectively reduce GHG emissions (Freudenschuß et al., 2010; Foldal et al., 2019; BML, 2024; Kraxner et al., 2024) (*medium confidence*), i.e., greening of arable land, reduced tillage and mulching, reduced application of mineral fertilizer, environmentally friendly and biodiversity-promoting management, and organic agriculture. However, the overall impact of all subsidies in the rural development program may lead to a rebound effect, as they can result in increased production output and consequently higher GHG emissions.

## Chapter Box 6.1. Carbon pricing in the EU and Austria

### The EU Emissions Trading System (EU ETS)

The EU implemented the EU ETS as its flagship climate policy instrument in 2005 (Directive 2003/87/EC). Initially the scheme only covered $CO_2$ emissions from energy supply and emission-intensive industry.[12] However, in 2012, it was expanded to include domestic aviation (Directive 2008/101/EC), and by 2027 maritime shipping will also be integrated into the system (Directive (EU) 2023/959). In 2021, the EU ETS covered approximately 38 % of the EU's GHG emissions. In addition to EU members, Norway, Iceland and Liechtenstein have been participating directly in the EU ETS since 2008 (EEA Joint Committee, 2007), and the Swiss ETS has been linked to it since 2020 (European Commission and Swiss Confederation, 2017). The EU ETS is a cap-and-trade system: First, an emission limit ('cap') is set for the regulated entities, and then emission allowances (certificates) are distributed to them, either through free allocation or auction. These allowances must be surrendered to cover emissions and can be traded between entities, which, according to economic theory, leads to least-cost abatement.

The design of the EU ETS has been adjusted several times. While the definition of the cap and the allocation of emission allowances to sectors and installations was initially the responsibility of the Member States, there has been an EU-wide cap and allocation process since 2013. This cap decreases by an annual linear reduction factor, which has been increased twice to reflect the increasing ambition of the EU's climate targets. Moreover, the allocation process has shifted towards auctioning, particularly for the electricity sector. For this sector, allowances are generally auctioned, while emit-

[12] The set of industry activities covered by the EU ETS has increased since 2013. Moreover, in addition to $CO_2$ emissions for certain activities also other GHGs were included (e.g., nitrous oxides from the production of certain chemicals).

ters in sectors potentially exposed to carbon leakage receive free allocation based on benchmarks. For all other sectors, a mix of free allocation and auctioning applies. In the future, the CBAM will gradually replace free allocation (Regulation (EU) 2023/956). For a long time, the EU ETS was characterized by low allowance prices due to an oversupply of allowances following the economic crisis in 2009. As a result, quantity management provisions (the 'Market Stability Reserve', MSR) have been introduced in the EU ETS to create a stable and continuously increasing price signal (Decision (EU) 2015/1814; Directive (EU) 2023/959). In case of an oversupply of allowances in the market, allowances will be placed in the MSR. If the oversupply does not decrease, these allowances will eventually be canceled. Conversely, in case of a shortage of allowances in the market or if the price increases excessively, allowances are released from the MSR.

### The national emission trading system in Austria ('Nationale $CO_2$-Bepreisung')

To reduce energy-related $CO_2$ emissions not covered by the EU ETS, 17 European countries have so far implemented carbon taxes (World Bank, 2023b). Austria has, however, followed the approach of Germany and introduced a national emission trading system for these sectors in October 2022 (BGBl. I Nr. 10/2022), in the context of the Recovery and Resilience Facility. As in Germany, the carbon price follows a pre-defined pathway increasing from EUR 30/t$CO_2$ in 2022 to EUR 55/t$CO_2$ in 2025. However, in Austria the price is automatically adjusted in case of substantial price fluctuations. This adjustment led to a price of EUR 32.5/t$CO_2$ in 2023 (instead of the initially planned EUR 35/t$CO_2$) due to energy price increases caused by the war in Ukraine. In contrast to the downstream approach of the EU ETS, the design of the national ETS follows an upstream approach, which means that the suppliers of fuels will ultimately have to surrender the certificates and pass on the costs to their consumers. As there is no emission cap in place, the national ETS functions like a carbon tax.

For households, revenues from the national ETS are recycled via regionally differentiated lump-sum payments ('Klimabonus'), distinguishing between four types of regions according to the quality of public transport and settlement density.[13] For companies, hardship and carbon leakage provisions apply. Agriculture is currently exempt from the national ETS. In 2027, the national ETS will be replaced by a newly established European emissions trading system ('ETS 2') covering energy-related $CO_2$ emissions from transport and buildings as well as from energy supply and manufacturing not covered by the EU ETS.

[13] In 2023, adults received a payment between EUR 110 and EUR 220. In 2022, all adults (independently of their area of residence) received payment of EUR 250 to also compensate for the strong energy price increases. Children receive(d) half the amounts of adults.

## Other policy instruments for climate mitigation

### *Information instruments*

Information-based instruments address the consumption side of mitigation and aim to support consumers in making sustainable choices (Jordan et al., 2013; van den Bergh et al., 2021). They include labels, education, ratings, rankings, and campaigns.

Environmental labeling and information schemes (ELIS) are a set of instruments aiming at 'empowering' consumers by providing information on the environmental impacts of products and services (Gruère, 2013; Klintman, 2016). ELIS in Austria are largely harmonized with EU and OECD standards and with the International Organization for Standardization (ISO) 14020 series of labeling standards. Many ecolabels have an implicit link to climate mitigation (organic agriculture, wood and fiber sourcing, etc.), but there are few (if any) third-party ecolabels in Austria certifying a low carbon-footprint. Recently, first-party claims of climate neutrality by companies have mushroomed and increasingly face accusations of 'greenwashing' or 'carbonwashing' (In and Schumacher, 2021; Kubat and Tokić, 2024) (*high confidence*).

Beyond organic farming, which is based on an EU regulatory framework, evidence of environmental effectiveness of ecolabels is scarce (Meis-Harris et al., 2021). Recent NGO criticism blamed eco-certification schemes of being weak, ineffective and in some cases fraudulent (Vogt, 2019; Greenpeace International, 2021). Ecolabels typically generate market niches, but do not contribute to transforming the respective market segment as such. A general criticism of information-based instruments is that they help create sustainable options, but do not eliminate unsustainable ones (Hausknost, 2014; Bärnthaler, 2023).

Government-sponsored mandatory climate score labeling schemes have been proposed as a more effective alternative to voluntary labeling (Lemken et al., 2021). However, this would cross the line to being a regulatory instrument. Overall, evidence suggests that substantial changes in consumption-based emissions and individual behavior will require regulatory frameworks and strong public policies rather than reliance on voluntary labeling (Dubois et al., 2019).

*Behavioral instruments*

Behavioral public policy, as understood here, includes all means and modes of public policy aimed at influencing human behavior by using insights from behavioral economics, behavioral sciences, psychology or neurosciences (Straßheim, 2020) (see Section 5.3.1). Nudges are the most prominent type of behavioral public policy. Nudging has been criticized for targeting individual behavior only, and for neglecting the societal determinants of choice (Mock, 2023). Understanding (market) behavior as 'social practice' that is embedded in and constrained by societal structures suggests the need for policy instruments that intervene in these structures (rather than addressing individual behavior) and, as a result, "restrict or eliminate choice" (Mock, 2023, p. 381) where necessary. Examples include the reduction of automobile-centered infrastructure and the sustainable reorganization of interconnected social domains like work, housing, education, and food. This category also includes regulatory experiments, which are "an instrument which deliberately deviates from the existing regulatory framework to try out new rules in a real-world setting" (Bauknecht and Kubeczko, 2024, p. 45). The idea is to create a legal free space in which new ways of regulating technological and social innovations can be tried out. This can take the form of 'regulatory sandboxes' that provide legal exemptions to experiment with new ways of doing things, or of 'regulatory innovation experiments' that aim to adapt an existing regulatory framework to new societal (and technological) challenges. In Austria, an example of the latter is the *Energy.Free.Room* program created by the BMK (Bovera and Lo Schiavo, 2022). For the European energy sector, the EU has published a *state of play of regulatory experimentation in the EU* (Gangale et al., 2023). In Germany, the planned *Real-world Laboratory Act* (BMWK, 2023) aims to provide a legal basis for experimenting with new approaches. Regulatory experimentation could be a crucial instrument for expanding and mainstreaming niche innovations, but also for adapting existing regulatory frameworks more quickly to the challenge of the climate crisis.

*Enabling instruments*

Enabling instruments aim to facilitate the transformation of social practices by providing the respective material, organizational and legal infrastructures for new ways of doing things (e.g., recycling schemes, new legal forms of shared ownership or use of products and utilities) (Grubb et al., 2020). Enabling instruments are essential for experimenting with and implementing social innovations and structures for climate-friendly living (APCC, 2023).

### Instruments compensating negative distributional effects of climate policies

The necessity of compensation measures is mostly addressed in the literature regarding the introduction or increase of environmental taxes in general and carbon taxes in particular, which are often shown to be regressive in high-income countries, particularly when electricity and heating are taxed (less regarding fuel taxes) (*high confidence*). Such compensation measures aim to mitigate undesirable distributional effects of climate mitigation measures, which has also been shown to be an important determinant of their public acceptance (see Köppl and Schratzenstaller (2023) for an overview of recent empirical research regarding carbon taxation). Regulatory and planning instruments will also have distributional impacts that may require compensation measures (*limited evidence, high agreement*).

The section is based on empirical findings for Austria regarding the incidence of the burden of climate measures (Kirchner et al., 2019; Eisner et al., 2021; Kettner-Marx et al., 2021; Mayer et al., 2021; Six and Lechinger, 2021; Budgetdienst des Österreichischen Parlaments, 2022) and regarding the effects of potential compensation measures for Austria (Kettner et al., 2024). Simulations of social-ecological tax reform scenarios in Austria confirm, on the one hand, that carbon pricing can contribute to reducing $CO_2$ emissions, spur renewable energy use and improve energy efficiency (*medium evidence, high agreement*). On the other hand, this literature confirms a trade-off between equity and efficiency with respect to revenue recycling (see Table 6.3) (*medium evidence, high agreement*): Reducing labor costs increases GDP and employment, but does not increase low household incomes or improve equality. The opposite is true for lump-sum payments. One potential compensation measure not considered in Table 6.3 are green vouchers. Their distributional effect is likely similar to that of direct payments, but may reduce potential rebound effects better (Büchs et al., 2021). Currently, no study exists that assesses the impact of using carbon tax revenues for green vouchers for Austria.

In its 2022 social-ecological tax reform, the Austrian government has opted for lump-sum payments ('Klimabonus') to compensate households for the introduction of the national ETS. These per capita climate bonus payments do not differ according to household income but according to the region of residence (with the exception of the first year, 2022, when all adults received equal payments of EUR 250 to also compensate for the strong increase in energy prices due to the war in Ukraine); children receive half of the payments of adults (BGBl. I Nr. 10/2022; BGBl. I Nr. 11/2022).

In addition to studies focusing on carbon pricing, there is a growing literature on compensation measures regarding housing and increasing energy prices in general, with a particular focus on energy poverty. Interestingly, not much research in this area seems to be currently available for the sector of private mobility.

Regarding the housing sector, most research focuses on how to mitigate burdens on energy poor or low-income households (see also Section 5.6.3). While many compensation measures exist in the housing sector such as financial interventions, energy efficiency programs, consumer protection and information (Pye et al., 2017), research highlights the challenge of financing retrofits and/or energy efficiency measures and the impact of these measures on energy use and energy poverty (Berger and Höltl, 2019; Seebauer et al., 2019; Bertoldi et al., 2021; Bourgeois et al., 2021; Seebauer, 2021; George et al., 2023). There is agreement on the need for compensation measures that can alleviate the burden of both upfront costs, financing costs and the tenant/landlord dilemma (*medium evidence, high agreement*). Studies show that targeting energy poverty may require (i) public funding schemes that operate at the building level (to avoid displacement) and focus on energy-inefficient buildings with households at poverty risk (Berger and Höltl, 2019); (ii) addressing the tenant/landlord dilemma by implementing personalized support, limiting tenant's back payments for renovation measures, higher subsidies for retrofitting measures for buildings with poor households, and a better coordination of climate change initiatives to target energy-poor households (Seebauer et al., 2019; George et al., 2023); and (iii) combining a polluter-pay principle with an ability-to-pay approach for low-income tenants (Seebauer, 2021).

The recent increase in energy prices, especially for natural gas, due to the war in Ukraine has resulted in numerous compensation measures in Austria and other European

**Table 6.3** Effects of carbon pricing with different compensation mechanisms in Austria.

<table>
<tr><th>SDG-Targets</th><th>No compensation</th><th>Direct payment (dividend)</th><th colspan="2">Reduced value added tax</th><th>Reduced labor costs</th><th>Investments for climate mitigation</th><th colspan="2">Multiple compensation measures[1]</th></tr>
<tr><td>13.2 Reduced $CO_2$ emissions</td><td>[6], [8]</td><td>[2], [3], [5], [4], [6]</td><td colspan="2">[4], [5], [6]</td><td>[5], [6]</td><td>[3], [7]</td><td colspan="2">[1], [2], [3], [8]</td></tr>
<tr><td>7.2 Renewable energies</td><td>[6]</td><td>[6]</td><td colspan="2">[6]</td><td>[6]</td><td>[7]</td><td colspan="2">No data</td></tr>
<tr><td>7.3 Energy efficiency</td><td>No data</td><td>No data</td><td colspan="2">No data</td><td>No data</td><td>No data</td><td colspan="2">No data</td></tr>
<tr><td>8.1 Economic growth</td><td>[6], [8]</td><td>[3], [4], [5], [6]</td><td>[4]</td><td>[5], [6]</td><td>[5], [6]</td><td>[3], [7]</td><td colspan="2">[1], [2], [3], [8]</td></tr>
<tr><td>8.5 Employment</td><td>[6], [8]</td><td>[3], [5], [6]</td><td>[6]</td><td>[5]</td><td>[5], [6]</td><td>[6]</td><td>[1], [2], [3]</td><td>[8]</td></tr>
<tr><td>10.1 Income of low-income households</td><td>[6]</td><td>[2], [4], [5], [6]</td><td>[4]</td><td>[5], [6]</td><td>[5], [6]</td><td>No data</td><td colspan="2">[2]</td></tr>
<tr><td>10.4 Increase equality</td><td>[6]</td><td>[2], [4], [5], [6]</td><td>[4]</td><td>[5], [6]</td><td>[5], [6]</td><td>No data</td><td colspan="2">[2]</td></tr>
</table>

**Evaluation scheme:** Strong negative | Medium negative | Weak negative | Neutral | Weak positive | Medium positive | Strong positive

[1] Multiple compensation measures refer to comprehensive climate mitigation packages

Sources: Authors' own visualization based on [1] Goers and Schneider (2019); [2] Großmann et al. (2019); [3] Großmann et al. (2020); [4] Mayer et al. (2021); [5] Kettner et al. (2024); [6] Kirchner et al. (2019); [7] Kratena and Schleicher (1999); [8] Schneider et al. (2010).

countries. For Austria, Kettner et al. (2023) show that most of the implemented compensation measures have negative effects on climate mitigation, especially those that directly reduce energy prices. Only energy efficiency subsidies, investment subsidies for energy independence and support of climate-friendly mobility show synergies between climate protection and mitigating social burdens. A study by Baumgartner et al. (2022) recommends compensation measures that have synergies with climate mitigation, i.e., investment subsidies for building retrofits and heating boiler exchanges, alternative energy supply and energy use (e.g., anergy, geothermal), promotion of public transport and active mobility, town center revitalization, and energy efficiency subsidies. Baumgartner et al. (2022) argue that the Austrian commuter allowance should not be increased to avoid disincentives.

## 6.5.2. Adaptation instruments

### Regulatory instruments for climate change adaptation

Article 5 of the European Climate Law requires the European Commission and the Member States to develop strategies for adaptation to climate change. Member States must adopt national adaptation strategies and implement them (Handig and Stangl, 2023). Every five years, starting in 2023, the European Commission will assess the compatibility of national measures with the integrated national energy and climate plans and the biennial progress reports to be prepared under the Governance Regulation (Regulation (EU) 2018/1999).

The Austrian Climate Protection Act only refers to adaptation issues in § 4 (2): The National Climate Protection Committee shall, among other things, advise on adaptation to the unavoidable consequences of climate change (Ennöckl, 2023b). Otherwise, only a few areas of law explicitly address adaptation to climate change (Bertel, 2023, 2024).

In 2024, the BMK published the third Austrian Strategy for Adaptation to Climate Change (BMK, 2024a). The document provides a framework for adaptation policy in 14 fields of activity: Agriculture, forestry, water balance and water management, tourism, energy (with a focus on the electricity sector), construction and housing, protection against natural hazards, disaster management, health, ecosystems and biodiversity, transport infrastructure including mobility aspects, spatial planning, economy, cities (urban open and green spaces). Recommendations for action to achieve climate change adaptation are given for each area of activity. However, these are hardly reflected at the legal level. Only in exceptional cases does legislation take climate change adaptation into account. Legal research on adaptation issues is also scarce.

One example, relevant for certain projects in the Non-ETS and ETS industries, energy supply and transport sector, is the EIA Act. According to § 6 (1) and § 3 (5), the environmental impact declaration or individual decision of the competent authority must consider a project's vulnerability to the impacts of climate change, especially due to its location (Baumgartner and Niederhuber, 2023). Also, the Water Act obliges the competent authority to include the projected impacts of climate change on the occurrence of floods in its flood risk assessments and flood risk management plans.

Furthermore, some legal provisions at national or federal state level address climate change adaptation in their objectives, e.g., stating that in order to maintain an economically healthy, efficient and comprehensive agricultural and forestry sector in a functional rural area, adaptation to climate change should be taken into consideration according to § 1 (1) Agricultural Act (BGBl. Nr. 375/1992), or that the effects of climate change on electricity supply should be taken into account by appropriate measures as stated in § 1 (3) of the Vienna Electricity Sector Act (LGBl. Nr. 46/2005). § 37 (1) of the Burgenland Spatial Planning Act (LGBl. Nr. 49/2019) further specifies that shopping centers and supermarkets shall be designed to meet the requirements of climate change mitigation and adaptation.

According to the Austrian Adaptation Strategy, measures should be implemented in the transport and energy sectors to strengthen the resilience of infrastructure to the impacts of climate change and to ensure security of supply, e.g., by incorporating adaptation requirements into the relevant regulatory framework. In the building sector, legislative changes are also needed to ensure the consideration and integration of adaptation requirements in the relevant regulatory frameworks. This includes, e.g., amendments to tenancy, heritage and residential property laws to facilitate the transformation of existing buildings.

### Planning instruments for climate change adaptation

Spatial planning law and building regulations as well as disaster control law contain provisions relevant to climate change adaptation, as they provide a legal framework for natural disaster scenarios (e.g., floods, droughts, debris flows), establish warning systems or risk zones (Stöglehner, 2023a, 2023b). However, most legal provisions do not explicitly mention climate change adaptation, nor do they currently emphasize the impacts of climate change.

The Austrian Adaptation Strategy proposes a stronger integration of water management planning and water demand into spatial planning for the purpose of adaptation. Such a proposal has not yet been taken up.

Equally important in terms of this strategy is the planning of ecologically significant open spaces (near-natural spaces, habitat corridors) and the anchoring of cold air corridors in spatial planning.

Introducing a mandatory Nature and Climate Impact Assessment for all legal acts with regard to the adaptation and mitigation goals would contribute to ensuring that climate change adaptation is taken into account in all new laws within the framework of the above-mentioned fields of action (Wagner et al., 2021).

### Economic instruments for climate change adaptation

Economic instruments to promote climate adaptation include market-based instruments (i.e., monetary incentives such as taxes, subsidies or permits), as well as financial and risk-financing instruments. Instruments that have been identified by Bräuninger et al. (2011) as being suitable for climate adaptation include land use taxes to reduce the vulnerability from sealed soil or guarantees to reduce borrowing costs for mitigation measures. Agrawala et al. (2008) focus on insurance, environmental markets and public-private partnerships as viable options to incentivize private action for adaptation. Economic instruments can play an important role and complement and reinforce existing instruments for land use planning and flood protection (Filatova, 2014; Ackerschott et al., 2023). A particular role is played by risk financing instruments, which do not tackle adaptation directly, but pool risks with the aim of redistributing direct losses (e.g., from flooding) and reducing consequential losses such as bankruptcy. A challenge for the use of market-based economic instruments for adaptation is the definition of measurable and tangible adaptation units (such as 'saved wealth' or 'saved health' as proposed by Bräuninger et al. (2011)).

### Other policy instruments for climate change adaptation

In contrast to mitigation, adaptation policy instruments typically do not address individuals as consumers or private decision-makers outside their professional roles. Therefore, the market-related categories of information and behavioral instruments do not apply to adaptation in the same way. In Austria, adaptation measures strongly rely on public action regarding initiation, financing and implementation, and mostly address public authorities, industry actors and practitioners (Knittel and Bednar-Friedl, 2016). At the same time, adaptation measures tend to be voluntary and weakly institutionalized, lacking binding rules of implementation (Clar and Steurer, 2019).

Academic literature increasingly emphasizes that adaptation can no longer be understood as an isolated policy objective, but that the adaptation and transformation of societies are deeply interlinked (Mach and Siders, 2021; Werners et al., 2021; Fekete et al., 2022). Climate change is already beginning to transform the socio-economic structure of Austria, e.g., winter tourism is losing ground as the economic backbone of alpine provinces, and agriculture and forestry are experiencing increasing transformational stress. Adaptation, conceived as an attempt to adjust the status quo to a changing climate, may reach its limits once losses and damages undermine human well-being beyond the local level (Mechler et al., 2020; Schinko et al., 2022). There is a lack of policy instruments reflecting the need for comprehensive and transformative climate risk management in response to a rapidly changing alpine and lowland climate (Schinko et al., 2022) (*high confidence*).

Researchers have proposed some ideas to strengthen the effectiveness, scope, reach and depth of adaptive measures in Austria and their transformative potential:

- The establishment of a 'National Climate Risk Council' to create missing decision-making structures (Leitner et al., 2020)
- The extension of the Austrian Disaster Fund ('Katastrophenfonds') to include private sector anticipatory adaptation (Leitner et al., 2020)
- The strengthening of participatory adaptation instruments, including participatory budgeting, which has yielded successful adaptation measures in Vienna (Thaler and Seebauer, 2019; Ahn et al., 2023)
- Greater reliance on nature-based solutions (including restoration and protection of ecosystem functions) (Dubo et al., 2022; Schinko et al., 2022; Turner et al., 2022)

## 6.5.3. Climate Policy Integration

Climate policies are more effective when they are part of policies in the respective policy fields (e.g., agriculture, transport, buildings) than when they are separate policies. Climate Policy Integration (CPI) is primarily concerned with the integration of climate change into all policy areas (Adelle and Russel, 2013). Four different categories of analysis have been identified for CPI: (i) normative CPI, (ii) CPI as a process of governing, (iii) CPI as a policy outcome (Jordan and Lenschow, 2010), and (iv) CPI through reflexive learning, given that diverging interests – which need to be acknowledged – and the often contentious nature of politics and the fragmented nature of the polity (i.e., political institutions) require complex processes to enable CPI (Plank et al., 2021) (see Section 6.2). The CPI label, however, risks glossing over this conflictual nature of substantive decarbonization, as has been shown in the literature for Austria and the EU (Kettner and Kletzan-Slamanig, 2018; Niedertscheider et al., 2018; Plank et al., 2021) (*high confidence*).

Social science literature shows that coherent climate policies face a structurally fragmented apparatus, which formulates and implements policies, as well as competing policy targets and often unsustainable policies. Therefore, climate policy integration is much more a question of political priorities and power than of well-designed policies (see Sections 6.2 and 6.4).

With regard to climate mitigation, Austria's federal structure has been identified as a factor hindering CPI (Steurer and Clar, 2015; Steurer et al., 2020) (see Section 6.4.1), with the challenge of vertical coordination compounding the already difficult challenge of horizontal CPI. Successful CPI requires the institutional prioritization of decarbonization as an overarching policy goal, for example by elevating climate protection in a constitutional framework or introducing climate protection as a human right.

No analyses of CPI in the context of adaptation in Austria are available so far. However, a mapping of adaptation governance for Switzerland (Braunschweiger et al., 2018) shows that while strategic decisions and funding are usually located at the federal level, the actual implementation takes place at the regional or local level, underlining the common division of labor in multi-level governance systems.

Using the national adaptation strategy as a framework, all federal provinces have developed regional adaptation strategies following a dialogue process and the involvement of federal province's representatives in the development of the national strategy. The implementation of adaptation measures, however, is not obligatory or mandated by law. Thus, policy-making for adaptation involves to a large extent informal, cooperation-oriented, 'soft' governance modes and coordination formats, and vertical cooperation or the adherence of stakeholders to non-binding agreements (Probst et al., 2019). Actual implementation seems to be particularly driven by problem pressure, i.e., experienced climate change impacts, rather than governance arrangements (Clar and Steurer, 2019).

### 6.5.4. Integrative perspective on Austria's climate policy instruments

Austria's official emission scenarios (Umweltbundesamt, 2023a, 2023b) show that the country's climate neutrality target for 2040 cannot be achieved through existing and currently planned policy measures alone. This illustrates the need for comprehensive policy mixes and that climate issues must be mainstreamed across all policy areas to enhance effectiveness of climate policy. Achieving this requires attention to the interactions and overlaps among various measures (*high confidence*) (see Section 6.5.3). With the window to reach the Paris Agreement goals rapidly closing, climate governance and policy must prioritize not only the objectives of (technological) innovation, but also the goals of 'exnovation', that seek to rapidly phase out fossil-based technologies, products and practices (David, 2017; Davidson, 2019). Austrian climate governance to date is mainly oriented on adding sustainable technologies to an unsustainable structure, rather than implementing a targeted strategy of 'creative destruction' (Kivimaa and Kern, 2016) (see Section 6.5.1). This points to a lack of transformative ambition within the current Austrian climate governance, which is further highlighted by the absence of sufficiency instruments that could avoid energy and resource demand by transforming provisioning systems (Zell-Ziegler et al., 2021; Jarre et al., 2024; Brad et al., 2025) (see Section 6.5.1).

The preceding sections assessed low hanging fruits, challenges, and barriers for Austrian climate policy from an interdisciplinary perspective. Achieving targeted climate action calls for balancing various policy objectives, in particular effectiveness, justice, and efficiency.

## 6.6. Climate policy litigation

Climate policy litigation denotes legal remedies aimed at obliging the state and/or corporations to reduce GHG emissions. These lawsuits often aim not only to achieve legal success in court, but also to raise public awareness and initiate political developments to strengthen efforts in climate change mitigation (Fitz, 2023b). So far, in Austria there has been a clear focus on lawsuits against the state, a recent example being the case of twelve children and adolescents who invoked their constitutional children's rights.

### 6.6.1. Human rights, climate lawsuits and environmental proceedings

The Austrian constitution does not explicitly refer to climate change or climate protection (Ennöckl, 2023a). However, comprehensive environmental protection forms a state objective[14], and there is widespread agreement that climate protection is covered by this provision. The legal consequences of this state objective are still controversial (Kirchmair and Krempelmeier, 2023), culminating in the much-criticized decision of the Constitutional Court, which qualified the refusal of a permit for a third runway at Vienna's airport on the grounds of climate protection as arbitrary and unlawful (Madner and Schulev-Steindl, 2017; Merli, 2017). Moreover, human rights, as enshrined in the Austrian constitution (e.g., the right to life and the right to respect for private and family life), oblige the state to take sufficient measures to protect humans from the consequences of climate change, as the European Court of Human Rights confirmed in a lawsuit against Switzerland (Ennöckl et al., 2024; Hofer, 2024b; Hollaus, 2024) (*high confidence*).

To date, the Constitutional Court has not ruled substantively on the existence and scope of positive state obligations regarding climate change. Most lawsuits failed on formal grounds. Moreover, the court ruled that there was no constitutional claim for issuing an ordinance regarding a ban on sales of fossil fuels and heating oil (Gärner et al., 2023). Due to the high formal hurdles for filing a climate-related lawsuit, there is a deficit in legal protection under the Austrian constitution that may violate the European Convention on Human Rights (Hofer, 2024b; Hollaus, 2024) (*high confidence*). A pending case with potentially far-reaching consequences is Müllner vs. Austria before the European Court of Human Rights, in which a person with multiple sclerosis is demanding climate protection on the grounds that their disease symptoms increase with rising temperatures.

The right to participation in environmental proceedings according to the Aarhus Convention, especially for NGOs, has – despite the 'Aarhus-Beteiligungs-Gesetz' from 2018 – not yet been fully implemented in the Austrian legal framework, both at the level of administrative proceedings and in court trials (Handig, 2023). The question arises as to whether and by whom deficits in climate protection can be claimed against the state in general and in individual procedures for the approval of GHG-intensive projects. So far, climate change as a public interest (Üblagger, 2024) has mostly gained importance in administrative and judicial decisions on the expansion of renewable energy, when balancing different public interests affected by a renewable energy project, e.g., the construction of wind turbines.

[14] A state objective guides and binds the legislative and the executive, but it does not establish individual rights.

### 6.6.2. Climate liability

The goal of so-called private climate lawsuits is to hold private $CO_2$ emitters liable for their climate-damaging behavior. The private plaintiffs base their claims on their legal rights to life, health and property, which are also guaranteed as human rights. Under the current legal system, such actions are admissible as actions for injunctive relief and damages (Wagner, 2023). However, the success of such actions depends on the requirement of causality (Burtscher and Spitzer, 2017). The action for damages also needs an allegation of unlawful conduct on the part of the $CO_2$ emitter (Perner and Spitzer, 2021). To facilitate litigation by private injured parties, the previous obstacles to actions for damages and injunctions against climate-damaging conduct need to be overcome by presuming causality, allocating responsibility among polluters in the case of proportional liability, and establishing a climate-related right of action for associations (Wagner, 2018, 2019, 2023; Burtscher and Schindl, 2022; Wallner, 2023; Rabl, 2024).

## 6.7. Budget, green public finances, investments and cost of (in)action

### 6.7.1. Investments for climate mitigation and adaptation

So far, only few studies have addressed the necessary (additional) investment costs for the transformation towards a carbon-neutral society (Gupta et al., 2014; Kreibiehl et al., 2022), and most of them focused exclusively on energy investment requirements (McCollum et al., 2018). Nevertheless, there is agreement that large investments (i.e., capital expenditures – CAPEX) are required to meet the 2030, 2040 and 2050 climate mitigation goals (*limited evidence, high agreement*). Notably, while this will require a substantial increase in additional investments, a large share will come from the reallocation of investments, i.e., away from fossil fuels towards renewables (Gupta et al., 2014; Riahi et al., 2022). Investments for climate mitigation are needed in all economic sectors and will need to target both infrastructure (e.g., the electricity grid, district heating, buildings, railways, bicycle lanes, and industrial installations) and technologies (e.g., renewable energy sources such as wind and photovoltaics, heat pumps, electric vehicles, and insulation), as well as R&D and education (Gupta et al., 2014; Kreibiehl et al., 2022). One of the most recent studies on additional investments for decarbonization in Europe, published by Institut Rousseau (2024), estimates that additional annual investments amount to about 2.3 % of European annual GDP until 2050; one important provision is that current fossil investments must be shifted to decarbonization.

Based on the Transition 2040 scenario, sectoral investment costs for climate neutrality and additional cost compared to already required legislative measures and replacement investments were estimated. The results reflect the high investments required in the energy, building and transport infrastructure, from which climate measures cannot be separated. However, the additional investments for climate neutrality are much lower than the total ones (Krutzler et al., 2023; Umweltbundesamt, 2023c). The estimated costs up to 2030 to achieve the Fit for 55 goals for Austria are reported in the National Climate and Energy Plan (NECP) (BMK, 2024b). The estimated costs up to 2040 and 2050 for the WAM NECP are reported in Krutzler et al. (2024).

For Austria, based on the Transition 2040 scenario, there is a recent estimate of the costs of achieving carbon neutrality (Weyerstraß et al., 2024). Additional costs (compared to a baseline scenario without additional measures, i.e., only with existing measures and policies) may amount to $EUR_{2023}$ 6.2–10.9 billion/yr, for the period 2024 to 2040 (see Figure 6.1). This corresponds to about 1.3–2.3 %/yr of the Austrian GDP of 2023 (Weyerstraß et al., 2024). A previous study estimated the total investment potential and gap from 2022 until 2030 on the path to climate neutrality at EUR 169.7 billion (Miess et al., 2022). This corresponds to additional annual investments until 2030 of about 3.6–4.8 % of the Austrian GDP, inducing annual value-added effects between 2–2.7 % of GDP as well as creating and securing between 60,000 and 80,000 jobs annually. This estimate, based on transformation assumptions for all energy sectors, considers the largest investments until 2030 in the energy, building and mobility sectors. Industry enters the transformation process with comparably low investments, which means that most investments in the industry sector will follow after 2030 and towards 2040 and 2050 (Miess et al., 2022). For all sectors and the energy system it is important that climate-neutral and renewable energy becomes cheaper than fossil energy (*robust evidence, medium agreement*).

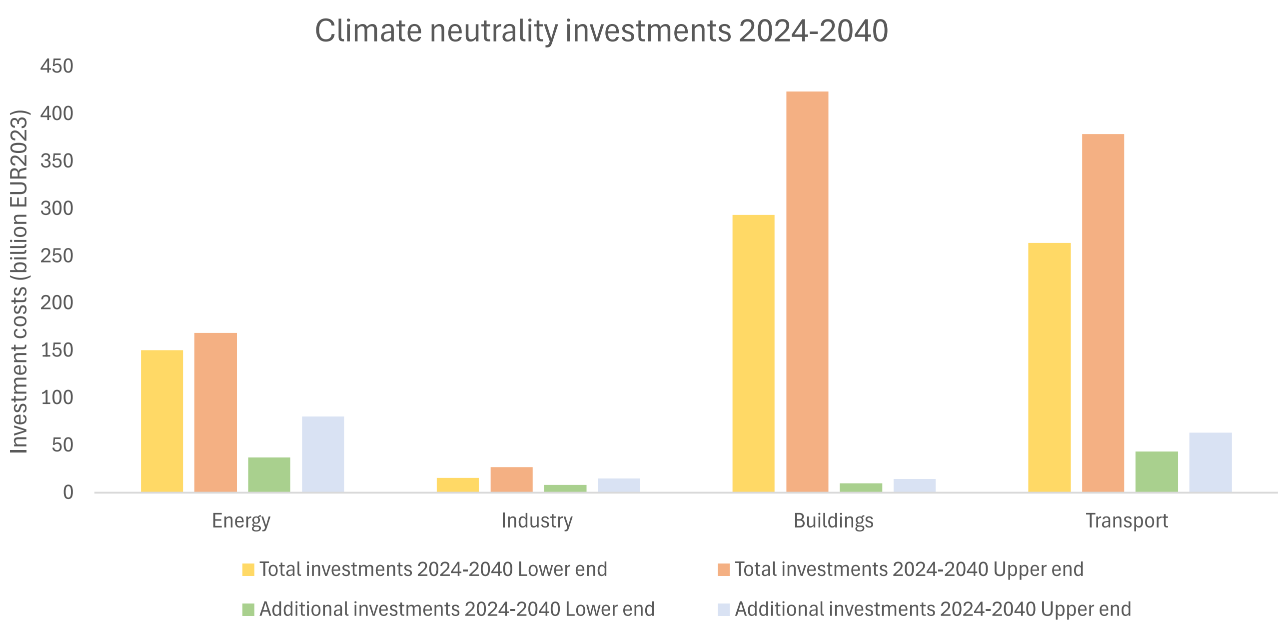



**Figure 6.1** Expected investment costs for climate neutrality 2040 per sector (Source: Umweltbundesamt, 2023, in Weyerstraß et al., 2024).

A substantial share of additional investments will be made by the governments at different levels, or by public enterprises. Bröthaler et al. (2023) find that, until 2030, the Austrian government can make direct green investments between approximately $EUR_{2023}$ 80 billion (conversion scenario) and $EUR_{2023}$ 138 billion (expansion scenario – in line with the Transition 2040 scenario, especially for the energy sector) through specific decarbonization of the public capital stock and thus directly contribute to achieving climate neutrality in Austria. Compared to a baseline scenario, the government, including public enterprises, could directly make additional annual investments of between $EUR_{2023}$ 5.4 billion (1 % of GDP) and approximately $EUR_{2023}$ 12.6 billion (2.4 % of GDP) to contribute to a carbon-neutral Austrian economy and infrastructure.

A recent study by Schützenhofer et al. (2024) finds that the transformation of Austrian industries (iron and steel, mining, quarrying and glass, chemical and petrochemical products, paper and printing, wood products, food products, construction, vehicle construction) to meet Austria's climate targets in 2040 requires a total investment between $EUR_{2023}$ 17.4 and 24.4 billion for the period 2025–2040. Investment volumes depend on the assumed scenarios. A focus on circular economy and thus secondary production requires the lowest investment volumes, while a focus on innovation, e.g., best-available and break-through technologies, requires the highest investment volumes.

Investments for climate adaptation will also be required to minimize damages from future climate change impacts that we are already committed to. For example, infrastructure will need to be made more resilient to extreme weather events (e.g., adjusting flood level protection levels) and suitable technologies implemented or developed to cope with ongoing climatic change (e.g., irrigation systems to better deal with drought spells, sowing of crop varieties and trees that are better suited to future climatic conditions). Finally, divesting from stranded assets (e.g., crude and refined oil or natural gas production) is a challenging but necessary requirement for achieving climate mitigations goals.

The macroeconomic effects of green investment are also of interest (see the emerging literature on green multipliers; for an overview see Köppl and Schratzenstaller (2022)).

### 6.7.2. Cost of (in)action

Climate inaction entails costs and future financial risks for private actors and public budgets as well as for the economy as a whole. The total costs of climate inaction already incurred today as well as future (budgetary) risks cannot be precisely and comprehensively quantified for Austria due to missing data (particularly for the subnational levels), uncertainties regarding future international developments (e.g., regarding climate-induced international migration; see Section 6.8.2) and the further progress of global warming, and because of measurement and valuation issues, particularly related to non-economic aspects (e.g., with regard to the recreational value of forests, biodiversity, or quality of life) (Parrado et al., 2021; Schiman-Vukan, 2022; Zenios, 2022; Klusak et al., 2023). Although data and estimates are incomplete and sparse, available analyses suggest that costs of climate inaction for Austria are already substantial today and are expected to increase in the coming decades (Steininger et al., 2020; Köppl and Schratzenstaller, 2024a) (*limited evidence, high agreement*). Obviously, only a part of these costs and future (budgetary) risks can be mitigated through policy measures by the Austrian government.

Climate change related damages, caused by extreme weather events and climate conditions as well as negative consequences of climate change for energy supply and public health, are estimated at currently $EUR_{2019}$ 2 billion on average per year and are expected to increase to at least $EUR_{2019}$ 2.5–5.2 billion/yr by 2030 and to $EUR_{2019}$ 4.3–10.8 billion/yr by 2050 (Steininger et al., 2020). The European Environment Agency (EEA) estimates cumulative damages through extreme climate and weather conditions in Austria for the period 1980–2021 at $EUR_{2019}$ 12.4 billion/yr. As of today, property insurance risks through weather hazards are estimated at 0.25 % of GDP by the Swiss Re Institute (Bannerjee et al., 2024). According to simulations by Bachner and Bednar-Friedl (2019), under a medium scenario of 2°C global warming by 2100, Austrian GDP will be reduced by 0.2 % annually until 2050. Gugele et al. (2022) and Schiman-Vukan (2022) estimate that climate change will reduce productivity by 0.05 % annually until 2050. Austria's overall – i.e., public and private – contributions to international climate finance reached EUR 398 million on average for 2021 and 2022 (BMK, 2022). Another cost factor for the overall economy are net imports of fossil energy, which amounted to a yearly average of EUR 9 billion in the period 2010–2021 and jumped to EUR 10.7 billion in 2023, illustrating the vulnerability of the Austrian economy due to its high dependency on fossil fuel imports. Moreover, privately as well as publicly owned fossil firms are exposed to substantial financial risks through stranded assets, for which no estimations exist.

Existing estimates point at considerable direct and indirect climate-related costs and future risks for public budgets

(Köppl and Schratzenstaller, 2024a) (*medium evidence, high agreement*). Bachner and Bednar-Friedl (2019) estimate annual climate adaptation expenditures by the federal government of EUR 1.1 billion for 2014–2020, which in a medium scenario of global warming will grow to a EUR 1.68 billion/yr from 2021–2030 and to EUR 2.338 billion from 2031–2050. Of the cumulative damages related to extreme climate and weather events estimated by the EEA for 1980–2021, EUR 9.4 billion (75.8 %) were not insured, so that it can be assumed that at least part of them would have had to be compensated by the government. In this context, it is highly relevant that the Austrian public sector focuses on ex-post compensation payments for private actors or subnational jurisdictions affected by damages through extreme weather events, instead of providing incentives for more formalized insurance arrangements, which could lead to lower and more predictable ex-post compensation payments for the public purse (Sinabell and Url, 2006; Unterberger et al., 2019). Bachner and Bednar-Friedl (2019) estimate an increase of public disaster management expenditures by 184 % ($EUR_{2019}$ 547 million) until 2050. Based on the projection of GHG emissions by Gugele et al. (2022), Austrian emissions will be reduced by 30 % compared to 2005. On the new burden-sharing reduction goal of 48 %, Schiman-Vukan (2022) estimates overall expenditures for emission certificates of $EUR_{2022}$ 4.7 billion for the period 2021–2030 and an annual average of 0.2 % of GDP after 2031. Average public contributions to international climate finance reached $EUR_{2022}$ 327 million on average for 2021 and 2022 (BMK, 2022). Assuming the average yearly growth rate of these contributions between 2013 and 2020, which amounted to 10.2 %, Austria's public contributions will increase to $EUR_{2023}$ 658 million by 2030 (Köppl and Schratzenstaller, 2024b). Climate counterproductive permanent public subsidies are substantial (*limited evidence, high agreement*). Kletzan-Slamanig et al. (2022) estimate climate counterproductive public subsidies at $EUR_{2019}$ 4.1 to 5.7 billion annually on average during the past few years. Klusak et al. (2023) estimate that deficits in climate resilience and vulnerability to climate change will decrease the rating of the Republic of Austria by 1.16 notches by 2100, which would increase interest rates and therefore spending related to public debt by $EUR_{2023}$ 204 to 296 million/yr in a medium scenario limiting global warming to 2°C. The estimated climate change induced decrease of GDP by 0.2 %/yr until 2050 entails a yearly reduction of tax revenues by 0.3 % and an increase of unemployment payments by $EUR_{2018}$ 618 million (10.6 %) according to simulations by Bachner and Bednar-Friedl (2019). Not least, migration into Austria induced by climate change will put additional strain on public budgets; however, estimates for the potential additional public spending are not available (ACA, 2021).

Part of these (future) costs of climate inaction and climate change can be influenced by Austrian policy. The expansion of renewables reduces the dependence on and the cost of fossil fuel imports. By reaching the Austrian climate goals, public expenditures for emission certificates can be avoided; many climate-counterproductive subsidies can be influenced by the Austrian government; and by making the Austrian economy more climate resilient, an increase of interest rates for public loans can be avoided.

### 6.7.3. Greening public finances in Austria

The public sector plays an important role in advancing the green transformation (see Figure 6.2) (*high confidence*). In Austria, a federalist country, the relevant governmental actors are the federal government, the federal provinces, and the municipalities.

At the federal level, various implementation and monitoring mechanisms supporting the greening of public finances have been adopted recently. In 2021, the Action Plan Sustainable Public Procurement of 2010 was updated and reinforced to reorient public procurement, which accounts for about 18 % of GDP in Austria on average in the period 2015–2020 (Klien et al., 2023) and for about 19 million tons (5.6 million tons) of GHG emissions worldwide (in Austria), towards the SDGs. The Action Plan complements and reinforces the Federal Public Procurement Law, which anchors the best bidder principle and thus allows for the explicit application of sustainability-oriented selection criteria. A comprehensive evaluation of the effectiveness of the Action Plan is lacking. For public procurement at the federal level in six crucial areas, Klien and Berger (2023) estimate that the Action Plan will reduce GHG emissions by 2030 by more than 100,000 $tCO_2eq$ in the first years and 43,000 $tCO_2eq$ in 2030.

Starting in 2022, following the recommendations of international organizations and the examples of other OECD and EU countries, respectively (Bova, 2021; OECD, 2021b), the BMF launched several initiatives related to green budgeting (BMF, 2023). As one element, green spending reviews, which are part of the reforms included in the National Recovery and Resilience Plan, have been conducted. Federal expenditures with a positive climate impact are identified and quantified within yearly federal budgetary plans, whereby this green spending review focuses on mitigation spending, thus neglecting expenditures for adaptation. Green as well as environmentally harmful tax expenditures are identified, however, without quantifying their budgetary and environmental impacts. At the subnational levels, green budgeting initiatives play a very limited role. An exception is the City of Vienna, which is currently setting up a climate budget. Moreover, the new Fiscal Equalization Agreement 2024–2028 foresees the implementation of green budgeting pilot projects in two federal provinces. An alignment of green budgeting with performance budgeting at the federal level and existing priority budgeting approaches (gender budgeting in particular) are lacking so far. Other priority budgeting approaches and in particular SDG budgeting do not play any role yet. Moreover, medium- and long-term budget planning and projections, which are generally underused in Austria, largely ignore climate-related aspects.

Environmental taxes (as defined by the OECD/Eurostat) have been increasing over time in Austria, although they remain considerably below the EU average (Köppl et al., 2023a). While tax increases in this area were initially motivated primarily by revenue considerations, environmental objectives have increasingly come to the fore in the last decades. With the recent steps to green the tax system, and particularly the introduction of a $CO_2$ price in 2022 (Baumgartner et al., 2021), Austria is joining the growing group of countries that have implemented a $CO_2$ price as an instrument of climate protection, albeit at a very moderate level and based on a rather unambitious trajectory (the $CO_2$ price is set to increase from EUR 30 in 2022 to EUR 55 in 2025) (Köppl et al., 2021). Recent initiatives to green the Austrian tax system through the implementation of new or the extension of existing green taxes and tax expenditures have focused almost exclusively on climate objectives, while further environmental objectives, in particular reducing resource use (including soil), protecting biodiversity, and supporting the circular economy, play only a minor role. Moreover, the potential of green levies at the subnational levels is not fully utilized (Kletzan-Slamanig and Schratzenstaller, 2022), particularly as instruments to contain land use (Arnold et al., 2023; Bröthaler et al., 2024) (*limited evidence, high agreement*).

Another revenue category that has recently gained importance is public green securities. The Republic of Austria's Green Framework, adopted in 2021, aims to raise green funds to finance green expenditures in eight categories: (i) Clean transportation, (ii) renewable energy, (iii) energy efficiency, (iv) pollution prevention and control, (v) environmentally sustainable management of living natural resources and land use, (vi) terrestrial and aquatic biodiversity, (vii) sustainable water and wastewater management, (viii) climate change adaptation (OeBFA, 2022). In 2022, Austria issued EUR 5.1 billion in green securities, followed by EUR 5.5 billion in 2023. According to the associated performance and impact assessment, the projects and infrastructure financed through green securities issued in 2023 lead to an annual GHG emissions reduction or avoidance of 4.4 million t (OeBFA, 2024).

A comprehensive greening of intragovernmental fiscal relations is still lacking (Kletzan-Slamanig et al., 2023), and the new Fiscal Equalization Act 2024–2028 implies only limited progress in this respect (Bittschi et al., 2024; Mitterer, 2024) (*limited evidence, high agreement*). Ecological fiscal transfers, which can be found in a growing number of countries worldwide (Busch et al., 2021), are used unsystematically in selected areas only. Additionally, there is a lack of a comprehensive multi-level climate governance framework aimed at coordinating particularly environmentally friendly subsidies and the reform of climate-counterproductive subsidies, green public investments, commitments to meet Austria's climate targets, and implementation and monitoring mechanisms across all levels of government.

Regarding European/international commitments and initiatives, three areas are of particular relevance. First, 59 % of the measures included in the Austrian Resilience and Recovery Plan (RRF), based on which funds from the European Resilience and Recovery Facility are granted, are dedicated to climate objectives, which by far exceeds the minimum share of 37 % and the share of 40 % for the RRF. Second, against the background of the current international discussions and negotiations on the contributions of industrialized countries to international climate finance, Austria's respective contribution is of interest. In 2015 Austria committed itself to make at least EUR 0.5 billion available by 2020 in contributions to international climate finance; with a total of EUR 1.365 billion, the promised amount was exceeded by far (BMF, 2023). Third, the national $CO_2$ pricing system is to be integrated into the EU ETS, which will be revised and extended by 2027 through a second EU ETS for transport and buildings (see Chapter Box 6.1).

In general, some progress has been made in greening of public budgets, however, substantial gaps remain (*limited evidence, high agreement*). Significant data gaps on the current status of the greening of public finances exist for all governmental levels, with the largest gaps at the subnational levels (Köppl et al., 2023a). Recently, some important steps and initiatives have been taken in several relevant areas, in par-

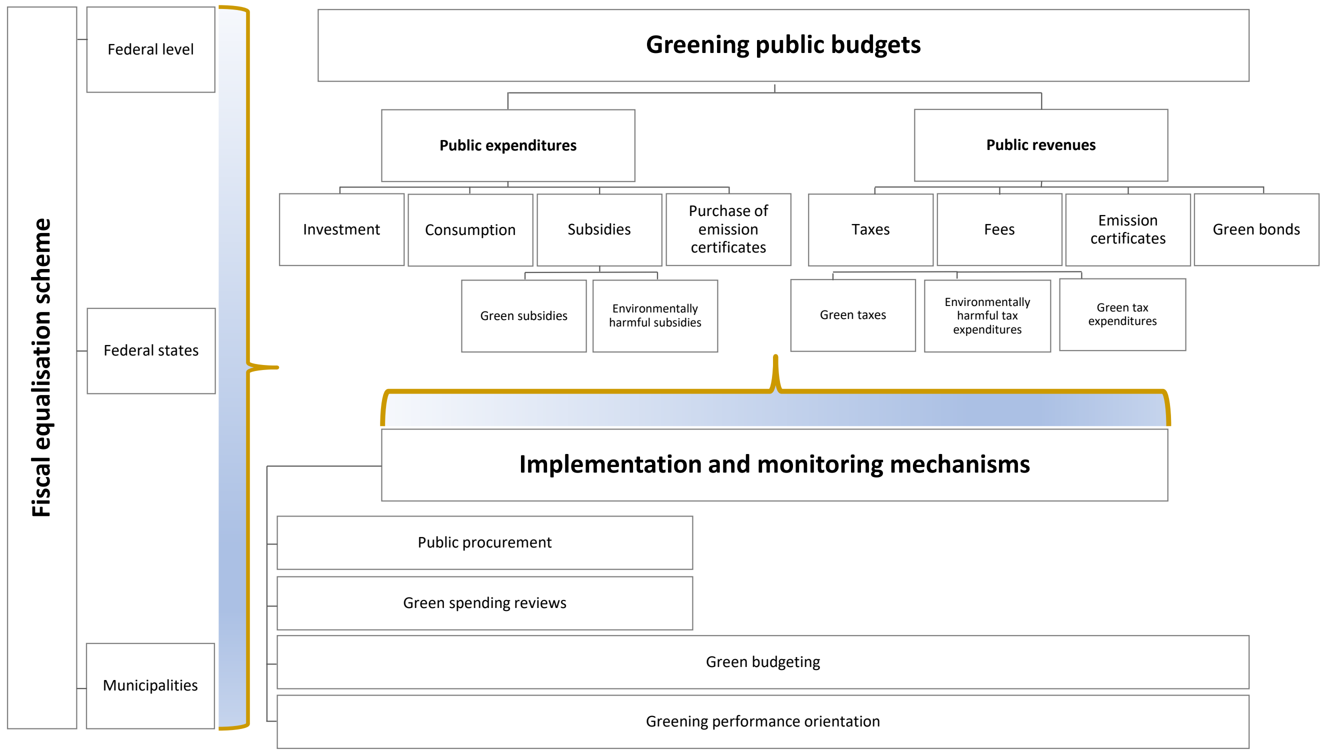



Figure 6.2 Areas and mechanisms relevant for greening public finances (Source: Modified from Köppl et al., 2023b).

ticular regarding climate expenditure, implementation and monitoring mechanisms, as well as the greening of public procurement, the tax system, the fiscal equalization system and public debt. Progress has been strongest at the federal level, with subnational levels lagging behind. There has been little progress in reforming the considerable volume of environmentally harmful subsidies, which have been significantly increased by temporary support measures to alleviate the social and economic consequences of the recent energy price crisis (Kettner et al., 2023; Kletzan-Slamanig et al., 2023). As Egger et al. (2024) show for the various areas of the welfare state, there is considerable potential for making social infrastructure and provisions more climate-friendly. Moreover, the current perspective on the greening of public finances is still largely input-oriented, while a systematic monitoring and evaluation of budgetary climate mitigation and adaptation measures is missing and existing mechanisms – in particular the performance-informed budgeting at the federal level – are underused (Köppl et al., 2023a). The negative consequences of climate change are already placing a substantial burden on public budgets (see Section 6.7.2). Future budgetary risks resulting from climate change are largely neglected in budgetary projections and medium-term budget planning, although they are estimated to be significant.

## 6.8. Societal aspects

### 6.8.1. Just transition

The just transition concept was first proposed in the 1970s by trade union movements to address tensions between social and environmental justice caused by the impacts of a shift to cleaner forms of production on the labor market (Henry et al., 2020; Stevis and Felli, 2020; Bainton et al., 2021). While maintaining the focus on labor markets and paid work as the central arena for securing livelihoods and welfare, the concept has greatly expanded, with NGOs, local authorities, corporations, governments and also scholars promoting multiple and contested interpretations (McCauley and Heffron, 2018; Roberts et al., 2018; Atteridge and Strambo, 2020; Wang and Lo, 2021; Newell et al., 2022; Kyriazi and Miró, 2023) (*high confidence*). These interpretations range from narrower visions of a socio-technical transition to efforts aimed at building a comprehensive social-ecological framework for justice. Key questions include who deserves justice, the balance between social and ecological justice, the role of the state, and the links between the Global North and South (White, 2019;

Tomassetti, 2020; Kalt, 2021; Pichler et al., 2021b), see also Cross-Chapter Box 7.

This rich foundation is reflected in the IPCC's (Pathak et al., 2022) expansive definition in its recent report, which describes just transition as "a set of principles, processes and practices aimed at ensuring that no people, workers, places, sectors, countries or regions are left behind in the move from a high-carbon to a low-carbon economy". The flexible use of the just transition concept is also visible in Austria, where stakeholders use the term differently, to promote socio-technical investments in SMEs in high-emission regions (ÖROK, 2022), and as a general call for basic public services, for co-determination and for the democratization of work (Initiative Wege aus der Krise, 2019; ÖGB, 2021).

The importance of a just transition is recognized for securing public acceptance, support for climate policy, and overcoming resistance to rapid decarbonization (Meckling et al., 2015; Evensen et al., 2018; Atteridge and Strambo, 2020; Groh and v. Möllendorff, 2020; Bolet et al., 2023) (*high confidence*). Conversely, high levels of existing inequality also hinder support for green policies (Vona, 2023). Besides their impact on fossil-intensive economic sectors and jobs, policies aimed at reducing $CO_2$ emissions can have direct and indirect negative impacts on vulnerable groups of people or households; they can also exacerbate existing inequalities or hinder social policy objectives (Gough et al., 2008; Markkanen and Anger-Kraavi, 2019; Lamb et al., 2020b) (*high confidence*). With such policies potentially having more pronounced and multi-dimensional regressive effects than previously thought, targeted place-based just transition policies for particularly vulnerable communities can be most impactful, especially when sensitive to political acceptability concerns (Vona, 2023; Weller et al., 2024). Just transition policies must consider structural differences (such as varying needs) and vulnerabilities such as low household income, old age and other obstacles to social inclusion (Atteridge and Strambo, 2020; Lamb et al., 2020b; Tikkakoski et al., 2024).

Little peer-reviewed research exists on labor market impacts of just transitions in Austria. Reports and gray literature use the term mainly to quantify sectoral-regional impacts of sustainability transitions. Decarbonization impacts extend beyond the immediate sectors and the overall employment effects are uncertain, with projections of employment impacts in Austria ranging from slightly positive to very negative outcomes. The studies agree on the most affected sectors but reach different conclusions due to methodologies and positions on the socio-technical transition potential. There is a high degree of agreement that the automotive and metal industries, mineral and chemical processing, pharmaceuticals, and the glass and ceramics industries will be strongly affected (Gabelberger et al., 2020; Großmann et al., 2020; Hoffmann and Spash, 2021; Keil, 2021; Meinhart et al., 2022) (*limited evidence, high agreement*). Research also highlights various federal provinces, such as Lower Austria, Carinthia, Upper Austria, and especially Styria, as significant areas with high GHG emissions and a substantial industrial workforce, with a potential regional mismatch of jobs (Gabelberger et al., 2020; Großmann et al., 2020; Hoffmann and Spash, 2021; Keil, 2021; Meinhart et al., 2022).

There is disagreement on the recovery potential of certain sectors (e.g., pulp and paper processing) and on overall labor market effects (Gabelberger et al., 2020; Großmann et al., 2020; Meinhart et al., 2022). The Austrian government's 'Just Transition' report (ÖROK, 2022) emphasizes that medium-term projections and forecasts have largely not considered the significantly increased adjustment pressure on different industries to meet the new target requirements of the Paris Agreement, with low-skilled workers being severely affected, especially support staff in highly affected sectors. Skills mismatches are therefore likely to worsen. Regardless of the overall expected level of employment, there is consensus on the need for retraining, upskilling, and addressing regional disparities (Gabelberger et al., 2020; Großmann et al., 2020; Hoffmann and Spash, 2021; Keil, 2021; Meinhart et al., 2022). Just transition potentially entails broader changes, including restructuring work and production, and providing basic services beyond paid labor (Kalt, 2021; Abram et al., 2022).

Regarding the just transition requirements on the labor market, Austria has prepared a national action plan on training and re-qualification (*Just Transition – Aktionsplan Aus- und Weiterbildung*). This action plan focuses on skill requirements for employees, job entrants and job seekers, defining education and training measures in the energy and heating sector. An Austrian Labor Market Service policy review (Neier et al., 2024) for the Austrian Chamber of Labor underscores Austria's just transition-relevant labor market policies, such as short-term work assistance, (re)training allowance, partial retirement, and educational leave. However, it reveals challenges, including undefined 'green jobs' and skills, insufficient information on environmentally friendly occupations, and lack of tailored programs to promote sustainable occupations, hampering a broader just transition.

A study commissioned by the Ministry of Social Affairs (Seebauer et al., 2021), which screened 300 climate change mitigation measures at the federal and regional level in Austria, highlights important categories of measures that have been implemented so far, comprising levies on energy, $CO_2$ pricing, the introduction of energy efficiency standards, increased investment in public transport, energy consultancy and a broad range of subsidies and incentives (for, among others, energy efficiency retrofits, the thermal renovation of buildings, solar PV installations, greening of buildings, e-cars and e-mobility).[15]

There is limited empirical evidence on the social impacts of other Austrian climate policies, particularly from ex-post evaluations (Schneider, 2023). More generally it has been noted that "sophisticated empirical studies are lacking as scholars seem more interested in creating various just transition analytical frameworks than in applying these frameworks to empirical investigations" (Wang and Lo, 2021). An Austrian pilot project suggests that personalized consultation can assist households, especially those with low incomes, in managing rising energy expenses (Seebauer et al., 2021). Subsidies and incentives for energy efficiency retrofits, thermal building renovation, solar energy, and similar measures, can make important contributions to reduce GHG emissions (*high confidence*). Because they require initial investments, however, they tend to benefit wealthier households disproportionally, exacerbating pre-existing inequalities (Lamb et al., 2020b; Seebauer et al., 2021). In cases where thermal insulation and refurbishments lead to higher rents, vulnerable households might be affected negatively. An Austrian case study focusing on low-income, energy-poor households shows that refurbishing rented dwellings can lead to rent increases surpassing energy cost savings, forcing low-income and energy-poor households to leave due to unaffordable rent increases (Berger and Höltl, 2019). Existing inequalities and social exclusion may limit the effectiveness of emissions reduction measures, by curbing adoption rates (Schneider, 2023). International examples show possibilities for designing measures to target low-income households, for example with interest-free loans and progressive subsidies (Lamb et al., 2020b).

At the European level, the European Green Deal includes funding for just transition policies through the Just Transition Fund (JTF) and the Social Climate Fund (SCF). The JTF aids employment, regions and industries during the green transition, supporting fossil-fuel dependent areas. The SCF compensates vulnerable households affected by higher fuel prices from ETS 2 (Kyriazi and Miró, 2023). The JTF allocates EUR 17.5 billion from 2021–2027, with Austria receiving EUR 136 million for Upper Austria, Carinthia, Lower Austria, and Styria, based on the Territorial Just Transition Plan (TJTP) (C/2021/4872; ÖROK, 2022). SCF should provide up to EUR 65 billion (2026–2032) for income support, energy efficient renovations and sustainable transport, with a maximum of EUR 643.5 million going to Austria (C/2021/4872; Wilson et al., 2023). These European schemes can contribute to a just transition. However, scholars have raised concerns about the governance and general setup of the JTF, which might lead to implementation problems, risk the propagation of already present injustice, and create lock-in effects, which reduce incentives for transformation, for example through allowing financing of gas projects (Moesker and Pesch, 2022; Kyriazi and Miró, 2023). The Austrian Chamber of Labor has acknowledged the contribution of the TJTP in Austria's transformation policy, while criticizing its limited scope and governance problems (Soder and Templ, 2022). Details on the measures associated with the SCF are still to be defined, as Member States are required to submit national Social Climate Plans, in which climate action and social compensation measures are set out.

## 6.8.2. Migration

### Climate change and migration linkages

Environmental factors influence migration in complex and often non-linear ways. The strength and direction of the relationship is shaped by economic, socio-political, and demographic conditions which moderate the extent to which households are exposed and vulnerable to climate change impacts (Bardsley and Hugo, 2010; McLeman, 2018) (*high confidence*).

Climate change affects migration through multiple channels, including through its impacts on agricultural productivity (Feng et al., 2010; Cai et al., 2016), food and water security, threats to (traditional) livelihoods and opportunities for income generation (Kaczan and Orgill-Meyer, 2020), socio-political stability and conflict (Schleussner et al., 2016; Abel et al., 2019), and health (Hunter and Simon, 2019; Schwerdtle et al., 2020). These channels are often closely interlinked, challenging the identification and forecasting of migration impacts (Hoffmann et al., 2020) (*medium confidence*).

15 For evidence on the social impact of carbon pricing, see Section 6.5.1, particularly the subsection on compensation instruments.

In contexts where environmental factors influence migration, they typically have a stronger impact on internal as opposed to international migration (*medium evidence, high agreement*). In many cases, migrants move towards urban centers, contributing to rapid urbanization processes in some regions (Barrios et al., 2006; Henderson et al., 2017; Adger et al., 2020) (*medium confidence*).

Recent literature provides evidence that impacts of climate change together with non-climatic drivers can increase mobility constraints, potentially trapping populations in hazardous places (Black et al., 2013; Nawrotzki and DeWaard, 2018; Zickgraf, 2019). This may result in a vicious cycle of increased exposure, vulnerability, and limited possibilities to escape from the hazards (*medium evidence, high agreement*).

Migration can represent a suitable means for migrants and their communities to adapt to climate change impacts (Black et al., 2011, 2013) (*medium evidence, high agreement*), but it also comes with significant challenges and risks for migrants and their communities. Migration can be maladaptive if it does not lead to long-term benefits and improved conditions (Gemenne and Blocher, 2017; Jacobson et al., 2019; Vinke et al., 2020) (*medium evidence, high agreement*).

### Climate impacts on migration to and within Europe

There is mixed evidence that environmental factors influence migration to Europe (Mulligan et al., 2014; Hoffmann et al., 2020; Beine and Jeusette, 2021; Šedová et al., 2021) (*limited evidence, medium agreement*). Studies show that temperature fluctuations and increases can lead to increased asylum applications in the European Union (Missirian and Schlenker, 2017) and raise migration to OECD countries (Cai et al., 2016). At the same time, droughts in Africa were found to decrease irregular migration to the European Union, especially from agrarian countries, suggesting more complex relationships (Cottier and Salehyan, 2021).

Limited evidence exists on the role of environmental factors for migration within Europe, which has been considered primarily as a destination region for climate migrants (Obokata et al., 2014; Piguet et al., 2018). Only recently, European Union institutions have started to engage more closely with the topic (Noonan and Rusu, 2022). The lack of empirical evidence on climate-induced migration within Europe constitutes a major gap in the scientific literature with implications for policy and planning processes (*limited evidence, high agreement*).

### Climate impacts on migration to and within Austria

There is no evidence about the impacts of climate change on migration flows within Austria. Instead, Austria is primarily considered as potential migration destination. A recent study examined the immigration acceptance among students in an Austrian university, showing a similarly high acceptance level for migrants who move because of climate change compared to those who move because of conflict (Henning et al., 2022) (*limited evidence, high agreement*).

There is evidence that environmental degradation and impacts of disasters in countries of origin are being taken into consideration by Austrian courts when making decisions about the granting of subsidiary protection. Country-of-origin information about environmental degradation and disaster impacts provided to courts varies in quantity and quality depending on geographical region (Mayrhofer and Ammer, 2022) (*limited evidence, high agreement*).

Planned relocation (otherwise also referred to as 'managed retreat'), has been undertaken in Austria as a flood management policy, however this is seldom joined up to the migration literature. In this context, planned relocation has been defined as "a directed measure that is initiated, overseen and financed by public authorities at different political level, in which a community of private households moves from a risk to a non-risk location where they resettle permanently" (Thaler et al., 2020, p. 2). In planned relocation that has taken place along the Danube in Upper and Lower Austria, deficiencies have been found in knowledge transfer between national, regional, and local authorities as well as citizen engagement (Thaler et al., 2020), and programs have been organized in a top-down manner. Whether households choose to take part in relocation programs depends on several factors: Rational economic calculations, fear of future flood events, place identity, belief in efficiency of future flood preparedness, and status as a long-term resident. Decisions on whether to relocate are taken from an intergenerational perspective, with children's opportunities being crucial (Seebauer and Winkler, 2020a). However, keeping relocation programs open for a long time has been shown to increase uptake (Thaler et al., 2020). Furthermore, the planned relocations failed to address social inequalities and did not focus enough on vulnerable populations (Thaler, 2021). Households who choose not to participate in relocation problems face a different set of challenges of living in now de-populated areas (Seebauer and Winkler, 2020b) (*limited evidence, high agreement*).

### Political discourses on climate change and migration in Austria

A great deal of literature points to the dangers of the securitization of the discourse on climate change and migration, which is not likely to lead to increased efforts for climate mitigation as often intended (Bettini et al., 2017) (*medium evidence, high agreement*). Within Austria, the links between climate change and migration are often dismissed as irrelevant until such a point where international migration towards Austria becomes visible. This is partly due to the restrictiveness of Austria's migration politics in general, making civil society actors reluctant to engage in the area of work (Nash, 2023) (*limited evidence, high agreement*). Among parliamentarians at the nation state-level, differing discourses on climate change and migration can be traced back to differing understandings of responsibility and conceptions of national interests (Nash, 2023).

## 6.8.3. Climate Change Education

Researchers worldwide emphasize and confirm the great potential of Climate Change Education (CCE) in actively promoting a just transition, covering mitigation, adaptation, and transformation education (Anderson, 2012; Lutz et al., 2014; Lee et al., 2015; Otto et al., 2020; Reid et al., 2021; Reimers, 2021). The immense importance of education has also been universally acknowledged by highlighting the special role of SDG 4 'Quality Education' as a key instrument for achieving all SDGs, which is particularly true for Climate Change Education and SDG 13, 'Climate Action'. By identifying CCE as a 'social tipping element', Otto et al. (2020) highlight the prominent role of education, as it opens up the possibility to help activate social-tipping dynamics that can lead to a sufficiently fast reduction in GHG emissions. Not only can education in its various forms (formal, non-formal, livelong, etc.) and facets (e.g., political literacy) (Kranz et al., 2022) support and amplify norms and values, but also inspire behavior change among individuals and lead to social tipping processes, especially when the new generation enters the job market and public decision-making bodies (Otto et al., 2020; Schrot et al., 2021). Hence, by educating key actors in education such as university teachers, teacher educators, in-service teachers, pre-service teachers, environmental educators, and university and school students, they can act as multipliers for climate change knowledge, awareness, and action. As a consequence, they help raise societal acceptance of climate policy measures (e.g., Schelly et al., 2012; Tobler et al., 2012; Andersen, 2018; Stevenson et al., 2018; Brennan, 2019; Kuthe et al., 2019; Thaller and Brudermann, 2020). Beyond that, in order to push climate action right now, it is as important to educate adult multipliers in all societal sectors such as work councils (Arbeiterkammer Wien, 2022), farmers (HBLFA Raumberg-Gumpenstein, 2023), administrative personnel (AdaptBehaviour, 2017), and the general public through lifelong learning approaches (Schrot et al., 2019, 2021).

School and university students and their respective teachers are seen as key 'change agents', defined as strategic multipliers towards climate-friendly competence and action (Skamp et al., 2013; Stevenson et al., 2017; Andersen, 2018; Kuthe et al., 2019; Möller et al., 2021; Winter et al., 2022). Studies show that young people can influence the energy-saving behaviors or climate change awareness of their families and friends in positive ways (Hiramatsu et al., 2014; Andersen, 2018; Brennan, 2019; Parth et al., 2020, 2024; Keller et al., 2022). On the larger scale, the recent FFF movement demonstrates that school students did not only shape the visibility of the topic but also influenced political decisions. It is estimated that within just half a year the movement grew to 1.5 million students in 125 countries, including Austria (Wahlström et al., 2019; Nash and Steurer, 2021). The effects of educational campaigns can be strengthened by participation in FFF (Deisenrieder et al., 2020), but also by a supportive family and community context as well as by media campaigns (Suranovic, 2013; Kubisch et al., 2020). For Austrian students, this was shown to be especially relevant for action-related components of climate change awareness or an enhanced feeling of self-efficacy that might be triggered by perceived collective efficacy (Deisenrieder et al., 2020).

However, CCE, in the framework of Education for Sustainable Development (ESD), is a complex socio-scientific issue that requires the acquisition of 'Climate Literacy', a framework whose key component is an understanding of how humans influence the climate and vice versa (Wise, 2010; Leve et al., 2023). There is growing evidence that teaching and learning CCE in order to reach climate literacy, climate change awareness and climate action, is highly demanding as it has specific challenges: (i) A highly complex and interdisciplinary science with multi-layered interrelationships of effects that complicate understanding, (ii) ethical, political, psychological, and social dimensions, (iii) the constant updating of scientific findings, the still open development of consequences and solutions, and (iv) the resulting public debate, which is controversial and polarized, and can lead to a misinformation about underlying scientific facts (Dawson, 2015; Cook et al., 2018; Rahmstorf and Schellnhuber, 2018; Horn and Bergthaller, 2019; Möller et al., 2021; Winter et al., 2022; Schubatzky and Haagen-Schützenhöfer, 2023). As achieving CCE goals is an extremely complex challenge, close consideration of research results about CCE is vital. These suggest that inter- and transdisciplinary education (and research) settings in combination with moderate constructivist learning settings, like in the Austria-wide CCE research and education program 'makingAchange', promise high learning effects (Rieckmann and Bormann, 2020; Kohl et al., 2022; Bohunovsky and Keller, 2023; Liebhaber et al., 2023; Parth et al., 2024; Rauch et al., 2024; Schickl et al., 2024).

Taking into account the above-mentioned demands and challenges, there is growing evidence that the formal Austrian education system at school and at higher education levels (e.g., university), with its current objectives and structures, does not contribute to a sustainable future and climate-friendly living to the extent necessary, and limits the promotion of action-oriented and participatory CCE (Winter et al., 2022; Bohunovsky and Keller, 2023). In order to achieve a fundamental paradigm shift in Austrian education structures (e.g., whole-institution approaches) and systems towards fostering competences for climate-friendly living and sustainable development, there is high agreement that a transdisciplinary development and implementation of comprehensive CCE concepts at all levels of formal and non-formal (e.g., communities/municipalities, museums, libraries, etc.) education must be promoted and that the contribution of all actors and stakeholders to CCE needs to be fundamentally transformed and intensified strongly and promptly (Martens et al., 2010; Leiringer and Cardellino, 2011; Ryan, 2011; Saltmarsh and Hartley, 2011; Rauch and Steiner, 2013; Sachs et al., 2019; Hübner et al., 2020; Winter et al., 2022; Bohunovsky and Keller, 2023). As a first step, the structural anchoring of climate change contents (physical science, mitigation, adaptation, societal transformation) and CCE concepts in the curricula of all school and university subjects is key, especially in those subjects whose graduates will have a high impact on education (teachers) or public decision-making bodies (legal practitioners, business people) in the future (Otto et al., 2020; Bohunovsky and Keller, 2023). In addition, CCE should be established in the curricula of vocational education and in-service training, especially for teachers (Keller and Rauch, 2021; Bohunovsky and Keller, 2023). Vocational education for sustainable development in Germany (Michaelis and Berding, 2021; Kaiser and Schwarz, 2022; Bohunovsky and Keller, 2023), successful CCE in-service teacher training (Kubisch et al., 2020; Möller et al., 2021) as well as ESD certificate programs for university teachers (Hübner et al., 2020) in Austria can serve as a blueprint.

Systematic research for Austrian school and university curricula is lacking, but in the USA the probability that a student takes at least one climate change class via the core curriculum at the top 100 universities and liberal-arts colleges is estimated at 0.17 % (Hess and Collins, 2018; Hess and Maki, 2019). In a representative study, the vast majority of German in-service teachers indicate that ESD has 'never' (69 %) or 'seldomly' (22 %) been the topic in their teacher training (Grund and Brock, 2018), assuming the same or worse for CCE. Hence it is not surprising that the majority of pre-service teachers as well as in-service teachers lack foundational content knowledge in the field of CCE, often have the same rudimentary or scientifically incorrect understandings of key climate change concepts as their students, and fail to accurately present the scientific consensus on climate change in their lessons (e.g., Papadimitriou, 2004; Boon, 2010; Shepardson et al., 2011; Lambert and Bleicher, 2013; Niebert and Gropengiesser, 2013; Plutzer et al., 2016; Namdar, 2018; Competente, 2019). School textbooks, also in Austria, not only rarely take these misconceptions into account, but often contain scientifically incorrect or outdated content on climate change themselves (e.g., Choi et al., 2010; Kuthe et al., 2019), which can further reinforce erroneous conceptions. Even though some current Austrian school and university curricula suggest taking CCE into account, for example through cross-curricular approaches or in specific subjects such as Biology, Geography or Physics (BGBl. II Nr. 185/2012; BMBF, 2014; Universität Wien, 2016), and even though Austrian teachers report that CCE is very important and that they are willing to teach it, they often do not feel sufficiently supported by their university and in-service education to actualize their transformative potential as change agents (for details, see Winter et al., 2022). They also believe that they will not have enough resources or teaching time to conduct CCE in the future (Winter et al., 2023). In general, it remains unclear whether teacher training programs include not only the promotion of scientific content knowledge about climate change, but also topic-specific pedagogical content knowledge (i.e., didactic knowledge) to address climate change as a socio-scientific issue (Dawson, 2015; Clausen, 2018; Li et al., 2021; Möller et al., 2021). Also, research shows that teachers' political beliefs and values are the greatest predictor of rejection of climate science knowledge, and relevant for the willingness to teach CCE (e.g., Plutzer et al., 2016; Stevenson et al., 2016; Nation and Feldman, 2021). In terms of CCE teacher professionalization, emphasis should therefore also be placed on affective aspects such as attitudes and values in students and teachers alike (Oberauer et al., 2023).

Currently, inter- and transdisciplinary cooperations, which are pivotal for ESD and especially CCE, are disadvantaged by the Austrian school and university system, which is dominated by discipline-centered structures (Engartner, 2019; Winter et al., 2022). There is evidence that the creation of specific structures for inter- and transdisciplinarity in education is necessary, such as the establishment of appropriate institutes, research centers, professorships ('Brückenprofessuren'), study programs, textbooks, journals, societies, research networks (for an overview, see Bohunovsky and Keller, 2023). To achieve climate-friendly and sustainable living, research literature suggests that CCE should generate system knowledge, target knowledge, and transformation knowledge (Schneidewind and Singer-Brodowski, 2014) and be open to the production of new types of knowledge and competencies (Norström et al., 2020; Chambers et al., 2021).

If the scientific evidence base on the effects of (novel) CCE approaches in the Austrian education system is to be increased, there is high agreement that accompanying research about CCE and evaluation of CCE programs is pivotal, not only in the relevant subjects but also in an inter- and transdisciplinary way (*high confidence*).

## 6.8.4. Media representation of climate change in Austria

In principle, the climate crisis, as a long-term, global, highly complex process can be only partially directly perceived by individual senses. As a result, most people's knowledge of climate change, and the environmental and weather changes it triggers, comes from (news) media (Lörcher, 2019).[16] Media also informs about causes and effects of climate change (e.g., Bolsen and Shapiro, 2018). However, it is also socially constitutive in the sense that communicative negotiation processes discursively construct and frame which social, political and economic adaptation measures are necessary and feasible to prevent or mitigate climate change, as well as which social groups and institutions are responsible (Nisbet, 2009; Reisigl, 2021). In addition, media is a central platform for various actors to present, interpret and shape debates around climate change and its governance (Tindall et al., 2018).[17] There is only very little research on the media representation of climate change in Austria (Rhomberg, 2016; Theine and Regen, 2023), however, studies from other (German-speaking) countries and comparative cross-country evidence exists.

In Austria, media attention to climate change increased since the mid-2000s both in terms of content (Kathrein, 2015; Narodoslawsky, 2020) and organizationally, as some media outlets have established special beats, pages or special editions on climate topics (Theine and Regen, 2023) (*medium confidence*). At the same time, long-term analyses show that media attention – despite the increase – is still at a low to medium level (Theine and Regen, 2023, based on; Boykoff et al., 2023, 2022) (*limited evidence, high agreement*). In addition, the basic trend of increasing media attention is highly dependent on geographic, social and media-specific conditions (Boykoff, 2013; Schmidt et al., 2013). Regarding the media-specific conditions, media representation of climate change is shaped by different media systems, structural determinants of media organizations as well as wider cultural and political factors (Eskjær, 2013; Theine and Regen, 2023). A country's exposure to the impacts of the climate crisis seems to be only a weakly positive determinant of increasing media coverage (Barkemeyer et al., 2017). Media attention is driven by shorter-term extreme weather phenomena, high stakes political events like the annual World Climate Conferences, protests (particularly by FFF) and less so by long-term climatic changes (Pianta and Sisco, 2020; von Zabern and Tulloch, 2021) (*limited evidence, high agreement*).

Increasing media coverage does not necessarily entail scientifically accurate coverage of the climate crisis and transformative discourses. Internationally, several media-specific processes and structural features have been identified that promote misinformation and false balance. Such processes and structural features are: (i) The ideological stance of the media, (ii) the proximity to far-right political milieus and think tanks (McKnight, 2010b, 2010a; Forchtner et al., 2018), (iii) the unique access of fossil fuel, automotive and other high-emitting industries to influence mainstream media representations via advertisements and source power

[16] The subchapter excludes research on social media and climate change for the following reasons: There is very little research on the Austrian case, existing reviews of international literature (e.g., Pearce et al., 2019) are somewhat applicable to Austria due to shared global dynamics in social media use.

[17] Media and journalism are in a complex relationship with societal actors and state and governance institutions. Ideally, they fulfill a watchdog-role vis-a-vis other power actors, but they clearly have some impact on forming public knowledge and public opinion, and are typically located outside of official state governance (at least in most democratic countries).

(Bacon and Nash, 2012; Beattie, 2020; Schäfer and Painter, 2021), as well as (iv) the impact of the media crisis through reduced resources for (investigative and specialized) reporting (Gibson, 2016; Schäfer and Painter, 2021).

For Austria, the high degree of tabloidization and the affiliation of some media outlets with the ÖVP, the FPÖ and far-right movements likely favors climate change-skeptical positions and climate delay (Magin and Stark, 2015; Forchtner, 2019) (*limited evidence, high agreement*). On the other hand, evidence from Germany, where high trust in public service broadcasting parallels high expectations regarding broad and serious coverage of the climate crisis and of extreme weather events, might also hold true for the Austrian context (Neverlaa and Hoppe, 2023; Reif et al., 2024). One discourse analysis of the public broadcaster's ORF2 program 'konkret' suggests that its coverage engages with climate change in the appropriate manner but also suggests that the focus of the reporting is strongly driven by economic and consumer-oriented logics (Sedlaczek, 2017) (*limited evidence, high agreement*).

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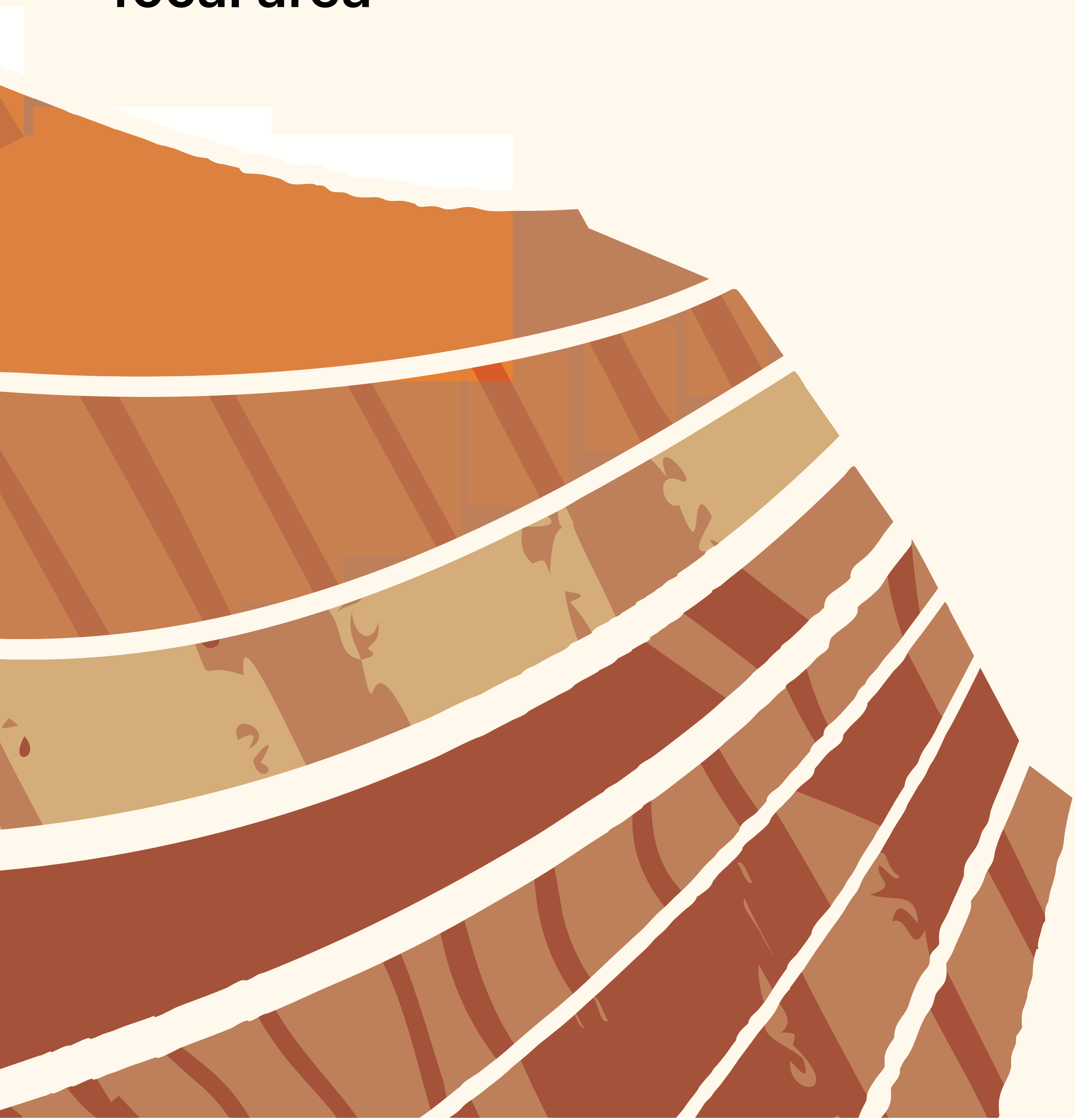
## Chapter 7

# The Austrian Alps as multi-dimensional focal area



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## EXECUTIVE SUMMARY

**By 2024, the temperature in the Austrian Alps had increased by 3.1°C compared to pre-industrial times (*high confidence*).** It is projected to keep increasing in the future, conditional on future emissions (*high confidence*). While past and future temperature increases within the Austrian Alps are spatially relatively homogeneous, changes in precipitation vary from region to region (strongest increase of 10 % for median precipitation in the north in winter and almost no change in summer for GWL 4.0°C) (*medium confidence*). {7.3.1, 7.3.2}

**In the past (instrumental period), warming in the Austrian Alps was almost identical to the rest of Austria (*high confidence*)**; for the future, model simulations show a slight elevation dependent warming (*medium confidence*). In an Austria-wide comparison, the role of the Alps as sentinels of climate change is thus hardly evident in their specific warming trend, but rather in the change in specific impacts such as the strong decline of the cryosphere in response to warming. The following changes in the cryosphere characteristics of the Alpine landscape are directly related to climate change: (i) Decreasing snowfall and snow on the ground (about 3 cm/decade decrease in mean snow depth); (ii) About 7 days/decade decrease in snow-cover days since 1961 and further decline by 10–15 snow-cover days under GWL 2.0°C/60–80 snow-cover days under GWL 4.0°C) (*robust evidence, medium agreement*); (iii) Glacier retreat (40 % of glacier area in Austria were lost between 1969 and 2015 and glaciers will completely disappear under GWL 4.0°C) (*high confidence*); (iv) Increase in permafrost temperature (e.g., +0.1°C/year at 3 m depth since 2016) and widespread permafrost degradation (*low confidence*). These changes will further exacerbate alpine and downstream droughts, challenge tourism and alter the ecosystem services of the Alps. {7.3.1, 7.3.2, 7.4.1, 7.4.2}

**The role of the Alps as a water tower for Austria and even more for Central Europe is evident from the climatic water balance (which is positive by average of 466 mm for the period 1981–2010) (*high confidence*)** and from the comparison of the runoff contribution to the area-related mountain share of individual river catchment areas. Such a comparison shows that the runoff contribution clearly exceeds the area share (33 % to 17 % for the entire Danube catchment, 38 % to 21 % for the entire Rhine catchment) (*high confidence*). As a result of future climate change, a positive shift in the climatic water balance in Austria is anticipated (+107±56 mm) under GWL 2.0°C. The role as a water tower will increase on average, but the increasing risk of droughts will lead to a stronger negative climatic water balance for subperiods within a year (*medium confidence*). {7.4.1}

**In recent decades and in the future, the hydrological cycle in the Austrian Alps has been and will be characterized by changes in snow depth, earlier and increased snowmelt (*high confidence*) and an increase in extreme precipitation events on the time scale of hours (thunderstorms) in summer (*robust evidence, medium agreement*).** As a result, summer floods in small catchments in the Alps have increased and will continue to do so in the future, while floods caused by heavy spring snowmelt are increasingly shifting to winter (*high confidence*). Increasing glacier loss exacerbates low flow conditions in glacierized catchment areas in the Alps in summer, however, with a decreasing contribution in the future due to the disappearing glaciers (*high confidence*). {7.4.1}

**There is evidence that some natural hazards in the Alpine region will become more frequent and more intense in the future, such as wildfire and fluvial flooding (*high confidence*), torrential flooding (*medium confidence*) and pluvial flooding (*low confidence*).** For fluvial floods, the trend is more pronounced in smaller catchments than in larger ones. A clear seasonal shift from winter and spring fluvial floods to summer floods is detectable (*high confidence*). Expected changes in the components of the hydrological cycle as the main driver of slope failure will facilitate the occurrence of landslides. This will affect alpine communities by causing major economic losses, specifically as the built environment and land use expand. Furthermore, it will affect the transport infrastructure and services, and thus the mobility of the population and the accessibility of mountain communities, and it may interrupt pan-European transport routes. {7.4.1, 7.4.3}

**There is evidence of an upward shift of plant and animal species due to warmer conditions (*high confidence*).** Therefore, cold environments above the tree line will shrink, leading to a loss of biodiversity. Large-ranged, warm-demanding species will replace short-ranged, cold-adapted species, some of which are endemic and restricted to the Austrian Alps (*medium evidence, high agreement*). There is an increasing risk of mismatching of interactions between groups of organisms, e.g., plants and pollinators, and of physiological stress of high-elevation species due to warming (*medium confidence*). {7.4.1}

**Climate change has a negative impact on the condition and availability of transportation infrastructure in Alpine regions (*high confidence*).** An increasing frequency of high temperatures can cause physical deterioration of traffic infrastructure, including railway tracks and road tarmac. This phenomenon is particularly prevalent in mountainous regions especially in tight bends, leading to (thermal) overload of the infrastructure. This is exacerbated by the increase in heavy goods traffic, growth of tourism and local travel. Congestion increases due to the limited availability of alternative routes in mountainous areas and emissions increase significantly as a result. Adaptation can be achieved by shifting transit and holiday traffic to rail by, e.g., robust accompanying planning and policy measures for the Brenner Base Tunnel, making public transport more attractive, improving services for carless travel, and reducing traffic-related pollutant emissions through alternative drive systems. {7.4.3}

**Winter tourism based on snow and ice sports will be severely affected by shortened ski-seasons and deteriorating snow-making conditions (*high confidence*).** Without adaptation and transition to snow-independent tourism, this could lead to significant economic losses and unemployment in regions with high climate-related risks (*medium evidence, high agreement*). Job losses in regions dependent on winter tourism could increase commuting and out-migration. {7.4.2}

**Summer tourism may benefit from more pleasant temperatures compared to the lowlands and urban areas, but risks and costs from natural hazards for hikers and the hiking infrastructure are likely to increase (*medium evidence, high agreement*).** The maintenance of hiking and climbing infrastructure is currently mainly provided by alpine NGOs. If increasing costs for maintenance cannot be handled by NGOs anymore, other stakeholders such as destination management organizations or regional governments are required to step in to prevent a decline of summer tourism's high quality and reliability. {7.4.2}

**Rising air temperatures and more frequent and severe drought periods will lead to shifts in tree species distribution and forest composition, which may have negative consequences for the protective function of forests at elevations <1,000 m a.s.l. This will happen in parallel with other natural forest disturbances caused by wind, fire, pests and insects (e.g., bark beetle) leading to a decrease in the protective function of forests at higher elevations (*high confidence*).** Tangible and intangible losses to infrastructure, buildings and human lives may result because of increasing hazard potential downslope of a degenerated protection forest. Furthermore, secondary hazards may develop in affected areas (such as snow avalanches and debris flows), and soil loss and increasing surface runoff may be observed. Post-disturbance management decisions can have an important impact on the protective effect of forests. If left in the stand, deadwood could maintain the protective function of forests after windthrow and bark beetle disturbances, especially during the first 15 years. To better adapt to these threats, uneven and multi-layered stands with trees of all sizes and age classes, and a minimum canopy cover of about 40 %, only small openings and a sufficient presence of natural regeneration should be considered. {7.4.2}

## 7.1. Chapter introduction

The European Alps are the largest mountain range in Europe, covering more than 190,000 km² and are home to 14 million people, more than 30,000 animal species and 13,000 plant species (Permanent Secretariat of the Alpine Convention, 2019). Eight countries share the Alpine area and according to the Alpine Convention, Austria is the country with the largest share of the Alpine area (28.7 %) (Salto, 2024). The European Alps are often referred to as the 'water towers' of Europe as they supply four large European river basins (Danube, Rhine, Rhone and Po) with water (Permanent Secretariat of the Alpine Convention, 2009). Consequently, the European water balance is dependent on the Alpine water storage volume. Moreover, the European Alps contain unique landscapes, diverse cultural heritage, ecosystem services, they are an important tourist destination, and a source of livelihoods. Since a significant number of studies suggest that the European Alps are disproportionately affected by climate change, the challenge is to strike a balance between promoting economic development and, at the same time, preserving environmental quality (Alpine Convention, 2015).

Chapter 7 focuses on the Austrian Alps (hereafter 'the Alps') and the impacts of climate change on them, as this region not only offers special lifestyle opportunities for its inhabitants but is also of great importance for Austria as a whole. Thus, the Alps are examined on three levels: As a natural or near-natural environment, as a provider of services, goods and livelihoods, and as a home to communities. The following two hypotheses form the backbone of the assessment in Chapter 7 and are explored throughout.

- Climate change in the Alps shows a different intensity compared to the foreland, as suggested by various processes (e.g., albedo feedback, water vapor effect, cloud formation). These processes will continue to have an impact in the future, making the Alps particularly sensitive to climate change.
- Due to their special socioeconomic features, their dependence on certain sectors, and the national and European significance of the region, the Alps have special vulnerabilities but also capacities to adapt to and mitigate these changes compared to the rest of the country.

This chapter aims to describe the manifestations of climate change in the Alps and its impacts on natural hazards, biodiversity, demography, settlements, mobility, and ecosystem services, and services and goods (forestry, agriculture, tourism, energy). Existing mitigation and adaptation options are presented and the needs for further adaptation and mitigation are outlined. First, the area of interest of Chapter 7

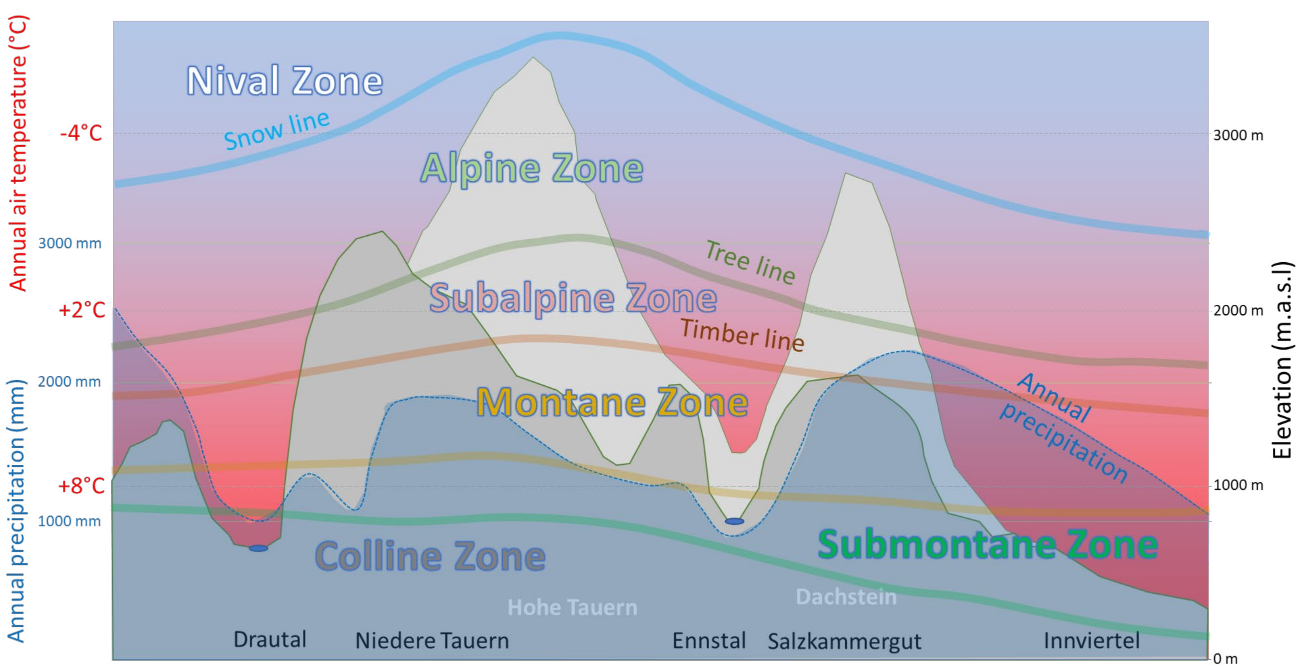


Figure 7.1 Schematic and simplified North-South cross-section through the Austrian Alps at approximately Salzburg with information on altitudinal vegetation belts, annual mean air temperature and mean annual precipitation. The climatic snowline and tree line are higher in the Inner Alps, because of lower precipitation and higher solar insolation.

(7.2.1) together with the demographic and spatial setting (7.2.2) are presented. The manifestation of climate change in the Alps is then shown (7.3). The Alps are then addressed as a natural environment (7.4.1), as a provider of services and goods (7.4.2), and as a home to communities (7.4.3). Based on these insights, adaptation and mitigation needs are identified and discussed in Section 7.5.

## 7.2. Delineation and differentiation of the Austrian Alps

This subchapter defines the area of interest (presents the criteria for such a definition) and describes its special characteristics in the context of climate change.

### 7.2.1. Natural boundaries

Austria has the largest share of the European Alps, as defined by the Alpine Convention, covering more than 65 % of the country. Regional subdivisions of the Austrian Alps, such as North, Central and South Alps further subdivide the Alps, but more important in the context of climate change is the vertical vegetation zonation such as the montane, alpine, subnival and nival zones as well as the tree line ecotone, and the expected changes due to the effects of climate change (Figure 7.1).

Natural boundaries can be used to delineate the Austrian Alps from the rest of the country. Delineation can be done using natural boundaries such as vegetation or climate boundaries, gradient thresholds, features, characteristics, topography, etc., but none of these seem to be universally applicable (and climate alone will not be sufficient to delineate the Austrian Alps). For an in-depth discussion see, for example, studies by Kapos et al. (2000), Elsen and Tingley (2015), Körner et al. (2021) and Price et al. (2022). Mountain topography has a high degree of complexity that affects climatic conditions. This includes elevation, slope steepness and slope direction, resulting in (steep) gradients of climate variables in both vertical and horizontal directions. Gradients can be observed in terms of, e.g., temperature, precipitation and solar radiation. Additional effects of mountain

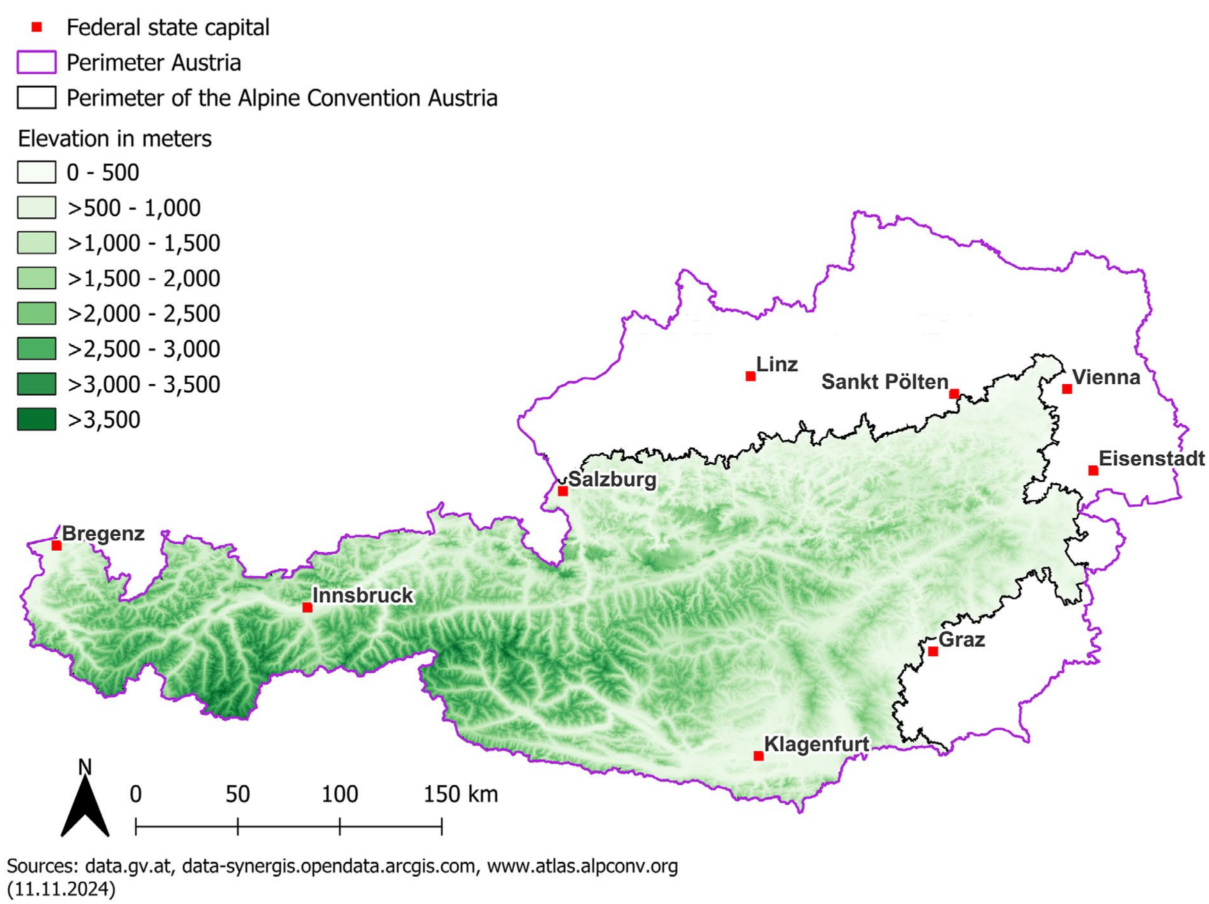


Figure 7.2 Delineation of the Austrian Alps according to usage in Chapter 7.

topography such as shading, clouds, surface material (bedrock, bare rock, vegetation of various types), local wind, and snow drift add to the observed variability. The lower human influence, compared to the Central European lowlands, together with the compression of thermal life zones along the elevation gradient, the diversity of microclimates and geology make the Alps an outstanding biodiversity hotspot (Smyčka et al., 2017). With about 4,500 species of vascular plants, they host about 40 % of the continent's native flora, 750–800 of which are alpine, including 270 endemic species (Ozenda and Borel, 2003).

In this chapter, the widely used delimitation according to the Alpine Convention is used (Figure 7.2).

### 7.2.2. Socioeconomic settings

Although the Alps cover 65 % of the country, only 39 % of the population lives in the region. However, it needs to be considered that in most Alpine municipalities the potentially suitable area for settlements, traffic infrastructure and agriculture is less than 25 % of the total area (Permanent Settlement Area, DSR – *Dauersiedlungsraum*) (Wonka, 2008). This limitation has a significant impact on the development of settlements in Alpine areas. The DSR is significantly lower in Alpine federal provinces and municipalities than in non-alpine areas. In Tyrol, the DSR amounts to 12 % of the total state area of the federal province resulting in a concentration of settlement activities, major transportation routes and agriculture in a very limited space (Österreichische Raumordnungskonferenz, 2023a). Related to the DSR, population density in many municipalities in the main valley areas exceeds 250 inhabitants/km² (Österreichische Raumordnungskonferenz, 2020). According to the urban-rural typology of the European Union, a population density of more than 300 inhabitants/km² is considered urban (European Union, 2010). Thus, agglomeration effects are not limited to alpine cities but also occur in ribbon-like settlements in the main valley areas. Given the significant demand for housing and commercial space, the limited amount of land available for development also affects housing density, the proportion of building land and subsequently the amount of land take and soil sealing (Österreichische Raumordnungskonferenz, 2023b). However, both the amount of building land per capita and the amount of sealed area per capita, are significantly lower in Alpine federal provinces and districts (Österreichische Raumordnungskonferenz, 2016; Umweltbundesamt, 2023a), indicating a more efficient use of building land there (Österreichische Raumordnungskonferenz, 2021). This is attributed to the comparably higher building land prices in many Alpine regions, which show significant peaks in urban centers and distinct tourist areas (Statistik Austria, 2023a). In addition to the influence of limited development space, high land prices in Alpine valleys can also be regarded as the result of increasing land competition there.

The Austrian Alps are characterized by different settlement structures. While most of them can also be found outside the Alps, ribbon-like settlement structures with high population densities in the main valley areas (e.g., Rhine valley, Innsbruck urban region) (Schindelegger et al., 2022), scattered settlements on slopes and hillsides (permanent and recreational) as well as tourist resorts with urban characteristics, can be regarded specific to Alpine regions. Major differences compared to settlement development outside the Alps are caused by specific framework conditions including the limited area suitable for development, topographic barriers to infrastructure provision, the potential exposure to various natural hazards (Fuchs et al., 2015b; Meyer and Job, 2022) and of local significance high development pressure from tourism. These conditions also have a significant impact on the transport systems and, thus, the mobility patterns in the Alpine areas compared to the rest of Austria (Tomschy et al., 2016).

Demographic changes, including changes in population and households, reflect existing structural and economic disparities among Alpine regions. Furthermore, demographic changes are a major driver of settlement and infrastructure development. Available data on population development for the period 2011–2021 (Österreichische Raumordnungskonferenz, 2023c), indicate a divide in the Austrian Alps with a population increase in the western part (i.e., Vorarlberg, Tyrol except for East Tyrol, Salzburg except for Lungau) and population decline in the eastern and southern part. Population data at the municipal level for 2011–2021 indicate population growth in all urban regions and, for the western part of the Austrian Alps, also in the main valleys. In the western part of the Austrian Alps, municipalities in side valleys and peripheral locations show a smaller increase and in some cases a decrease in population. In the eastern part of the Austrian Alps, population growth is mainly limited to urban and regional centers. These regional migration trends from side valleys to main valleys and from rural regions to urban and regional centers have also been observed in previous decades (Österreichische Raumordnungskonferenz, 2023c).

Population growth in Alpine regions affects the growth in all settlement types, with a greater impact on the expansion of building land in ribbon-like structures. A decrease in population results in vacant buildings rather than a reduction in built-up areas.

Urban influences outside of cities and ribbon-like settlement structures can be found in distinct tourism locations where urbanization processes occur selectively, on a small scale and far from existing urban areas (e.g., Sölden, St. Anton am Arlberg), a phenomenon referred to as micro-urbanization (Chai and Seto, 2019).

These demographic and spatial characteristics of alpine areas together with natural features suggest that climate change may have different impacts that require alpine-specific adaptation and that the potential for mitigation may also differ from non-mountainous areas in Austria. These aspects are analyzed and discussed in the following sections.

An economic activity of above-average importance in the Austrian Alps compared to the rest of Austria is tourism. As landscape attractiveness and perceived naturalness are important resources for tourism (Romeo et al., 2021), the Austrian Alps offer good natural conditions for this economic activity. Abundant natural resources combined with limited economic alternatives in rural areas have led to the importance of tourism in the Austrian Alps. In Tyrol, the most tourism-intensive federal province of Austria, the contribution of tourism to the gross regional domestic product is 14.9 % if only direct effects are considered, or 19.7 % if indirect effects are also included (Fritz et al., 2021). Due to the importance of climate-sensitive natural resources, climate change is considered a major challenge for mountain tourism (Steiger et al., 2022) (*high confidence*).

The labor market in the Alps differs when it comes to employment opportunities in tourism. The alpine tourism labor market is characterized by high seasonality and many part-time jobs. Therefore, finding and keeping qualified workers is an evident problem in the hospitality industry in the Alpine region (Heimerl et al., 2020). While the demand is increasing, the seasonal labor force, which is needed for winter tourism, is decreasing (Humer and Spiegelfeld, 2020). Unattractive working conditions, difficulty in finding housing in ski resorts, labor law issues and climate change, leading to uncertainty and a possible shorter season are mentioned as the main reason for this development (ORF, 2023). Furthermore, the dismissal of seasonal workers at the beginning of the pandemic may have damaged the image of workplaces in tourism (Mayer et al., 2021). To counteract the shortage of staff, improving the working atmosphere, the attractiveness of the job and the payment were found to increase occupational commitment in response to staff shortages (Schwaiger and Zehrer, 2022).

## 7.3. Manifestation of climate change in the Austrian Alps

The manifestation of climate change in the Austrian Alps is presented in the following sections starting with a description of past climate change, followed by a subchapter focusing on the future climate change in the area.

### 7.3.1. Past climate change in the Austrian Alps

Past climate in the Austrian Alps has been described by observations since about 1770 (see Section 1.2.1), but observation networks at higher alpine sites are less dense and have been established more recently (e.g., Hochobir, 2,140 m a.s.l., in 1851). As a result of the ZAMG HISTALP-initiative (GeoSphere Austria, 2017) and later projects, the description of past climate in the Austrian Alps is based on an outstanding database and related analyses.

The **air temperature** in the Alpine region has increased relatively homogeneously in space by 2°C since pre-industrial times (3.1°C for year 2024, see Section 1.2.1), which is about twice as much as on the global scale (Auer et al., 2014; Olefs et al., 2021). Individual months have shown weak signals of an altitude dependence of the warming in the Alps, which, however, averaged out when analyzed on an annual basis (Auer et al., 2014; Tudoroiu et al., 2016).

In contrast to temperature change, **precipitation** change varied both seasonally and spatially in the Alpine region (also within Austria) (Auer et al., 2014; Olefs et al., 2021). A dichotomy (e.g., increase of precipitation in the north, decrease in the south in winter) (Auer et al., 2007) reflects the effect of the Alps as a barrier on atmospheric circulation and thus on precipitation. The accuracy of precipitation measurements decreases significantly with increasing altitude. A high-resolution climate model experiment (Ménégoz et al., 2020) forced by ERA-20C for the period 1903–2010, confirmed the precipitation increase in the northern Alps in winter and suggested accelerated increase at higher elevations, whereas drying in summer was decreased or even not significant at higher elevations. Overall precipitation trends in Austria vary seasonally and spatially, with a general wetting trend in the north in winter and only a weak trend or a general decreasing trend in the north and south in summer (*robust evidence*). Moreover, the wetting intensity increases with altitude in the north in winter and decreases with altitude in summer (*low confidence*). Generally, the confidence in spatio-temporal trends of precipitation decreases significantly with altitude.

The increase in **air temperature** has led to a vertical shift of the **zero degree** line (temporal trends transferred from Switzerland, north: 133±40 m/decade, south: 118±37 m/decade, for the period 1984–2018) (Scherrer et al., 2021), as well as the **snow line** by 42±26 m/decade in the north and 88±44 m/decade in the south (Hu et al., 2020). In an earlier work, Hantel et al. (2012) estimated a temperature sensitivity of the median snowline of 166 m/°C for 1961–2010. This has significantly reduced the proportion of snow precipitation at high elevations in the Alps, especially in the summer. The associated effects on the energy balance at the Earth's surface (**albedo** lowering) have led to a significant increase in the snow and ice melt (snow cover, glaciers, permafrost) in the Austrian Alps (Olefs et al., 2021; Schöner et al., 2019) (for glaciers and permafrost, see also Section 7.4.1). However, the dependence of the winter snow cover was also strongly influenced by weather conditions and precipitation amounts. This means that the change in mean snow depth in Austria varied spatially. A significant decrease in the south (-12 cm/decade) contrasted with only a slight decrease in the northeast resulting in an overall trend for Austria of -3 cm/decade for 1961–2020. Mean snow depth trends at low elevations have been driven by changes in air temperature, while those at the highest elevation sites of the Austrian Alps have been driven by precipitation changes (Schöner et al., 2019).

In summary, regarding the snow in the Alps, temperature increase has led to an increase of zero-degree line altitude by about 130 m/decade in the northern part of the Alps and by about 120 m/decade in the southern part of the Alps (derived for 1984–2018) (*medium evidence, low agreement*). Compared to the zero-degree line elevation the increasing trend of the snowline was much weaker for 1984–2018, with about 40 m/decade in the north and 90 m/decade in the south (*medium evidence, low agreement*). Snow depth has generally decreased in the Austrian Alps over the last 50 years but with clear spatial patterns (strongest decreasing trend in the south and non-significant trend in the northeast (*robust evidence, medium agreement*).

High-quality measurements of radiation in Austria have only been available since 2012 (ARAD Measurement Network) (Olefs et al., 2016). Measurements of sunshine duration (as a proxy for global radiation dating back to the 1880s in Austria) showed a clear increase since about 1980, especially in summer (see Section 1.2.1). Altitude-dependent effects are difficult to interpret due to data uncertainty and small differences in measurements. A recent study by Correa et al. (2022) detected a west-east trend in surface solar radiation in the Austrian-Swiss Alps. The trend was positive/negative in the east/west for the period 1980–1995, but negative/positive for the east/west for the more recent period of 1996–2015 (see also Section 1.2.1). According to Correa et al. (2022), trends of surface solar radiation at low elevations were likely driven by clear sky forcing, while at high-elevation sites cloud optical properties and surface albedo seemed to be the main drivers of the trends.

### 7.3.2. Future climate change in the Austrian Alps

Given the rugged terrain and correspondingly steep horizontal gradients, even the 'high-resolution' CORDEX simulations (see below) are too coarse to adequately resolve the relevant atmospheric processes over mountainous terrain like the Alps (Rotach et al., 2022). Climate simulations are therefore more challenging and have potentially greater uncertainties than those over flat terrain (Rotach et al., 2022).

The most comprehensive information on the possible development of climate variables comes from so-called ensemble simulations. For the Alpine region they stem from EURO-CORDEX (Jacob et al., 2020), an initiative under the umbrella of the World Climate Research Program of the WMO, in which coordinated numerical experiments are carried out. The coordination concerns the emission scenarios, the grid spacing, the time span, etc. so that the results are comparable. The latest EURO-CORDEX results are available for 3 scenarios (RCP2.6/4.5/8.5) and for medium resolution (about 50 km grid spacing) and high resolution (about 12.5 km grid spacing). For the Alpine region, an update and extension of the earlier work of Gobiet et al. (2014) and Smiatek et al. (2016) is presented by Kotlarski et al. (2023), with a special focus on characteristic areas (ALPS NW, ALPS NE, ALPS S – and all three considered together as ALPS). The Austrian Alps are best represented by ALPS NE, so the numbers given below refer to the results for this region, where available. In this study, 24 RCM simulations of high resolution for scenarios RCP2.6/4.5/8.5 are used and evaluated for the 'climate period 2070–2099' (as 'end of the 21st century'). Temperature, precipitation and snow cover (i.e., snow water equivalent, SWE) are considered. The results of these studies are translated to Global Warming Levels (GWLs) below.

Within the CORDEX framework, a Flagship Pilot Study (CORDEX-FPS) with convection-permitting (resolving/allowing) or 'kilometer-scale' dynamical downscaling experiments (from about 12.5 km to a few km grid spacing) has been established (Coppola et al., 2020), which also has the 'greater Alpine region' as a focus. Due to the immense requirements of computing power, the resulting ensemble simulations typically consist of fewer members and are performed as 'time-slices' for the reference period ('current climate' 1996–2005), mid-century (2041–2050) and end-of-century (2090–2099) 10-year periods. Initial analyses focus on the validation (Ban et al., 2020, 2021, for precipitation; Soares et al., 2024, for temperature) of the current climate. Pichelli et al. (2021) is the first available study using the CORDEX-FPS to assess future climate change signals for precipitation in the Alpine region.

Single-model future climate simulations for the Alpine region at the km scale are furthermore available and typically focus on specific variables (Ban et al., 2015, 2020 – precipitation; Lüthi et al., 2019 – snow cover; Vergara-Temprado et al., 2021 – sub-hourly precipitation; Peleg et al., 2022 – spatial storm structure).

In summary, the general characteristics of the future climate in the Austrian Alps are as follows:

Regarding the **temperature**, a consistent increase is expected in all regions, in all seasons (all models) (*high confidence*) (Figure 7.3). The magnitude strongly depends on the scenario. Temperature changes are elevation dependent: Simulation studies consistently find a stronger heating signal at higher elevations – but the details (seasonal behavior) depend on model choice and resolution (Lüthi et al., 2019) (*medium evidence, low agreement*).

Concerning **precipitation**, the mean annual precipitation amount does not show a clear signal because it is the result of a seasonal redistribution (Figure 7.4): A decrease in summer precipitation and an increase in winter precipitation (*medium evidence, high agreement*). The magnitude of the (seasonal) changes is strongly dependent on the forcing (strongest for RCP8.5, which corresponds to a GWL of 3.8°C for the shown period 2070–90, shown in Figure 7.4) and strong signals are only emerging in the second half of the century

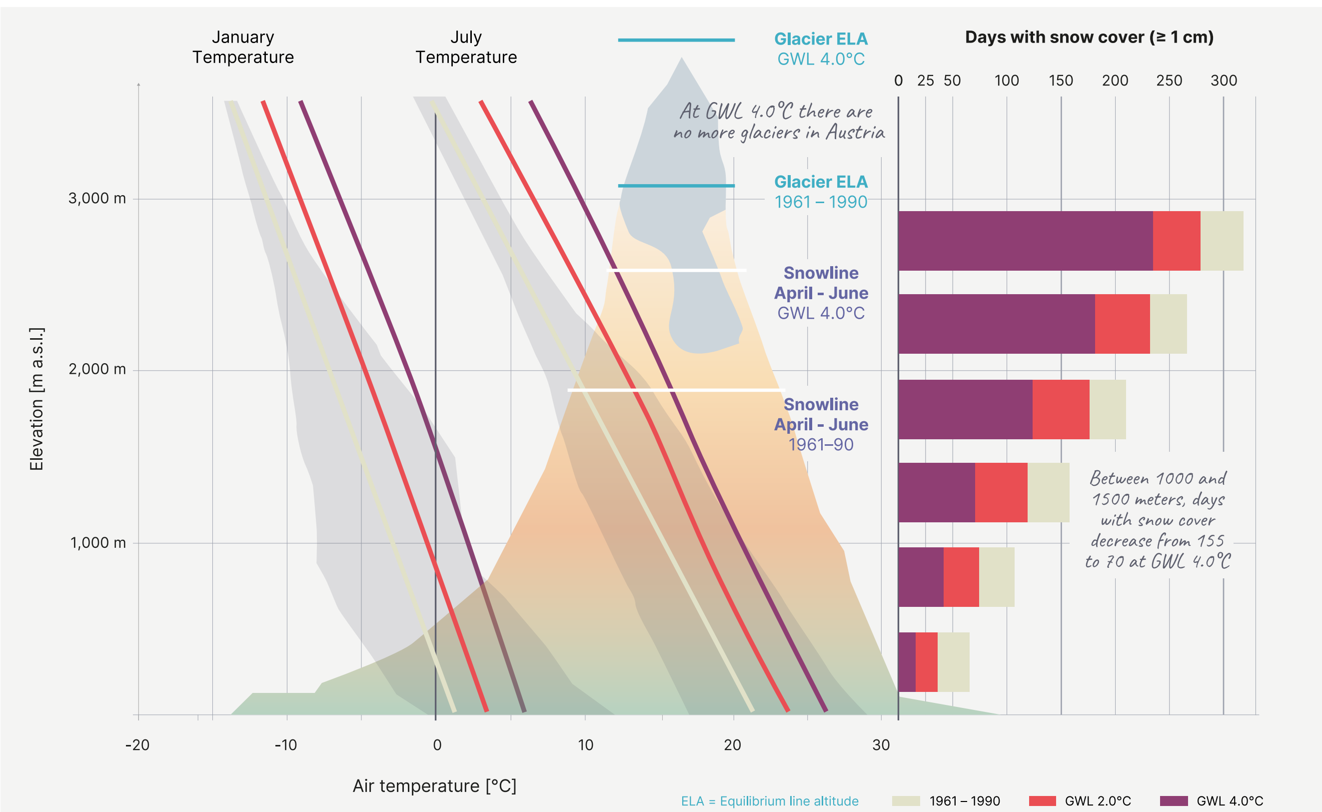


**Figure 7.3** Synthesis for key variables of altitude-dependent climate change in the Austrian Alps for the future compared to the 1961–1990 reference (1984–2018 for the snow line). The altitude dependence of the air temperature for January and July is taken from Hiebl et al. (2009), with the variation within the Alps shown by the shaded areas in light gray. The median temperature increases for GWL 2.0°C and GWL 4.0°C were derived from Kotlarski et al. (2023), based on the EURO-CORDEX cmIP5 ensemble for the Alps. Days with snow cover (>1 cm) for 1961–1990 and for GWL 4.0°C are taken from Chapter Box 1.1 of this report (derived from the FUSE-AT project). The snow line estimates (period April to June) are satellite data analyzed by Hu et al. (2020), using the values for the Salzach catchment and the temperature sensitivity of the snow line from Hantel et al. (2012) to project the snow line for GWL 4.0°C. The equilibrium line altitude (ELA) of glaciers in the Alps for 1961–1990 and for GWL 4.0°C is based on the study by Žebre et al. (2021).

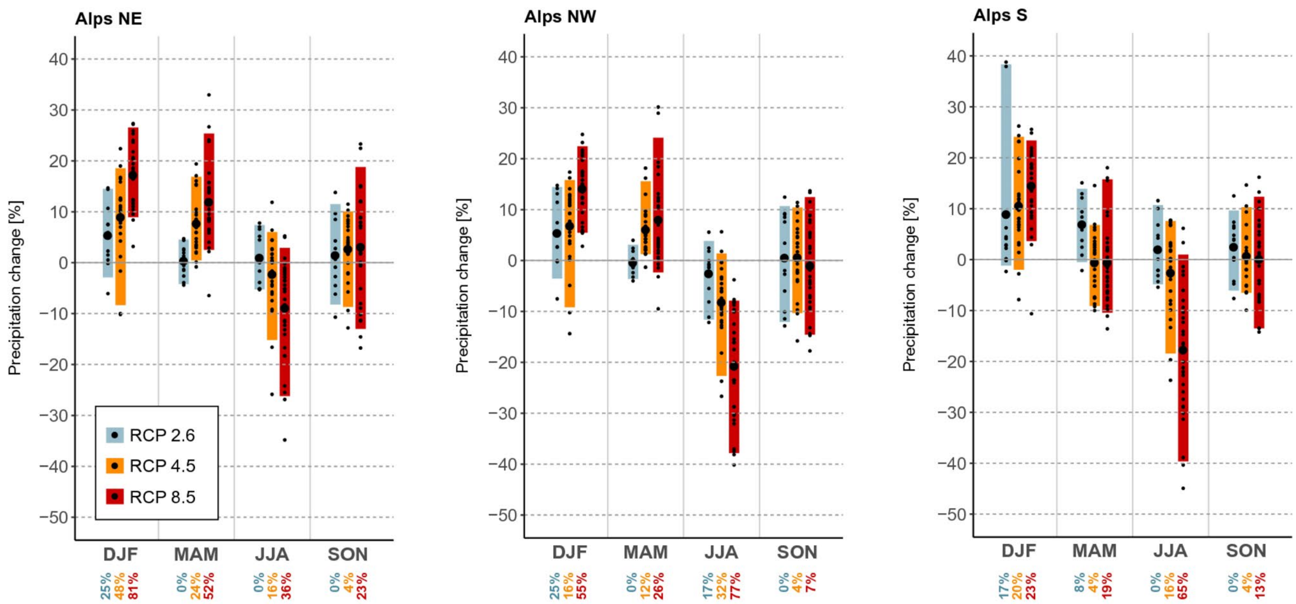


**Figure 7.4** Future precipitation changes in the Alps. The figure shows change of seasonal mean precipitation [%] between 1981–2010 and 2070–2099 in the three sub-domains and for the three emission scenarios RCP 2.6, 4.5 and 8.5. RCP 4.5 is equivalent to a GWL 2.2°C, RCP 8.5 to a GWL 3.8°C. Small dots refer to the individual simulations of the full model ensemble (EUR-11 and EUR-44, based on the EURO-CORDEX cmIP5 ensemble), bold dots to the multi-model ensemble mean. Colored bars indicate the ensemble uncertainty range as given by the lower (p5) and upper estimate (p95). The numbers below the panels refer to the percentage of simulations (rounded to full numbers) in the respective ensemble that shows a statistically significant change of seasonal mean precipitation (two-sided unpaired t test, p value of 0.05) (figure from Kotlarski et al., 2023).

(*medium confidence*). The winter increase is accompanied by a shift from solid to liquid, thus resulting in a reduction of 20–40 % in seasonal (Sept.-May) snow amount (Frei et al., 2018) (*limited evidence, medium agreement*). Summer precipitation is characterized by a decrease in the precipitation frequency and number of precipitation 'events', while the intensity of extreme events increases (Ban et al., 2020, 2021) (*medium confidence*).

Regarding the **snow cover** (measured as snow depth), there is an overall consistent decrease in seasonal snow cover, that is strongly scenario-dependent (strongest in RCP 8.5 of course) (*high confidence*). Future changes in snow cover are expected to be strongly elevation-dependent (*high confidence*). Changes for the Austrian Alps are assessed by the Fuse-AT project (Gobiet, 2021). Snow cover days (SCD) in Austria will continue to decrease by 10–15 days under GWL 2.0°C and by 60 to 80 days under GWL 4.0°C. A case study for Obergurgl (Ötztal) by Kotlarski et al. (2023), shows that in the scenario with the highest emissions, the reduction in the number of snow days at 1,920 m a.s.l. (Obergurgl) leads to a reduction in season length: -40 % by 2050, -80 % by 2100; in the ski area (i.e., at 2,500 m a.s.l.), the changes are -10 % by 2050, -35 % by 2100 (not including artificial snow production).

## 7.4. Impacts of climate change on the Austrian Alps

### 7.4.1. The Alps as natural environment

#### The hydrosphere and cryosphere

A detailed assessment of the impacts of climate change on the hydrosphere, including runoff generation processes, magnitude, seasonality, and frequency of fluxes in streams, is presented in detail for Austria in Section 1.4. The most important impacts are briefly summarized here, where possible with a special focus on the Alpine region.

The role of the Alps as a water tower for downstream areas, even far away from the Alps, has been discussed for a long time, but it is only in the last decades that it has been thoroughly documented by quantitative studies (Viviroli et al., 2007; Rounce et al., 2023). For Austria and even more for Central Europe, the influence of the Alps on the water cycle is evident from the climatic water balance, which is positive with an average of 466 mm for the period 1981–2010 (Haslinger et al., 2023) (*high confidence*), and from the comparison of the runoff contribution to the area-related mountain share of individual river basins. Such a comparison shows that the runoff contribution exceeds the area share (33 to 17 % for the entire Danube catchment, 38 to 21 % for the entire Rhine catchment) (Messerli et al., 2004) (*high confidence*).

Hydrological regimes of mountain regions are expected to be strongly affected by climate change by 2050 and further altered by the end of the 21st century, as also shown by several studies for the Austrian Alps (Eitzinger et al., 2014; Nachtnebel et al., 2014; Laaha et al., 2016; Blöschl et al., 2018; Pistotnik et al., 2020; Schöner and Haslinger, 2020; Hanus et al., 2021). Generally, future surface water availability is characterized by both a more positive water balance and an increase in temporary droughts. Changes in precipitation and snowmelt are the main drivers of this future water balance alteration in Austria (Haslinger et al., 2022). Increasing air temperature leads to an increase in evaporation, exacerbating the summer low-flow situation. A more rapid decline in runoff is expected in the spring, resulting in an earlier start of the summer low-flow period. The winter months are characterized by an upward shift of the snow line elevation and a weakening of frost processes (*high confidence*), resulting in a higher low-flow discharge. Snowmelt is shifted towards winter, changing the annual runoff pattern (Blöschl et al., 2011a). Trend projections of runoff under different climate scenarios consistently show increasing low flows (Q95-values) of about 10–30 % by 2021–2050 (Blöschl et al., 2011a; Eitzinger et al., 2014; Nachtnebel et al., 2014; Laaha et al., 2016; Pistotnik et al., 2020; Schöner and Haslinger, 2020) (*high confidence*) and a decrease of the mean summer runoff of up to about 10 % by 2050 (Blöschl et al., 2011a, 2011b, 2018) (*limited evidence, high agreement*). These changes are expected to intensify by the end of the 21st century (Blöschl et al., 2011a, 2011b, 2018) (*medium evidence, high agreement*). Glaciers can significantly dampen the low-flow discharges during summer in the Alpine basins of rivers such as the Salzach, Inn or Ill (Koboltschnig et al., 2008; Koboltschnig and Schöner, 2011; Stahl et al., 2022) but with a decreasing meltwater contribution in the future, as many glaciers in the Austrian Alps have already passed their peak (Wimberly et al., 2024).

Recent updates of mean flow conditions for Austria, which represent the average water availability in the catchment as the difference between precipitation and evapotranspiration, have been provided by Duethmann et al. (2020). They found an increase in annual precipitation totals of approximately 120 mm over the last 35 years. This increase offsets a rise in evapotranspiration of approximately 110 mm over the same period, resulting in nearly unchanged mean runoff conditions. In particular, an increasing trend in mean flow conditions has been observed in the Alps. Regarding future conditions, Blöschl et al. (2017) and Haslinger et al. (2023) reaffirm the water balance assessment of the previous AAR14 report as largely valid. They anticipate an increase in winter runoff in the Alps due to a shift in snowmelt to winter and a higher proportion of liquid precipitation.

Flood events, triggered by significant and/or intense precipitation, combined with antecedent snow and wet conditions, as well as complex runoff generation processes, have increased significantly in 21 % of Austrian catchments for the period 1978–2020, especially in small catchments north of the Alpine ridge (Blöschl et al., 2017; Laaha et al., 2025). The trend averages +11.8 % in 43 years (+2.7 %/decade), with more pronounced values in the winter period (5.2 %/decade; see Section 1.4.1).

Given the physical reasons for a 7 % increase in the intensity of heavy precipitation events per degree Celsius, the current positive trends in hourly precipitation totals or extreme precipitation (98th percentile) are likely to persist (see Section 1.2.1). While some of the heavy precipitation-related weather patterns are expected to become less frequent in the coming decades, they may produce heavier amounts when they do occur (Blöschl et al., 2017). However, all projections of heavy precipitation are highly uncertain due to limitations in the model representation of convective processes. Blöschl et al. (2017) summarize the projections of climate change on future floods as follows: (i) Seasonal changes in precipitation will hardly impact HQ100 except in areas with increasing intensity of convective summer events; (ii) An increase in intense convective events may potentially increase floods throughout Austria; (iii) There will be a minimal effect on floods from a rise in the snow line; (iv) Earlier snowmelt and the resulting lower summer runoff coefficient, as well as higher evapotranspiration, will slightly reduce flooding; however, (v) floods (HQ100) along the northern rim of the Alps show hardly any change. Systematic investigations of pluvial floods over Austria or the Alpine region are currently limited and certainly deserve further attention.

Low flow generation is primarily attributed to freezing and temporary snow storage during the winter months, contrasting with summer precipitation deficits in the lowlands below 900 m a.s.l. (Laaha and Blöschl, 2006). During summer heatwaves, the water sectors can suffer significant impacts, while potential threats to ecosystems exist, e.g., due to high water temperatures during low flow conditions (see Section 1.4.1).

In recent years, low flow trends have become more pronounced, particularly in Alpine catchments. Drying trends, characterized by decreasing Q95-values (the 5th percentile of daily runoff), have been observed in the lowlands. Conversely, in alpine catchments above 900 m a.s.l., wetting trends with increasing low flow conditions prevail (Laaha et al., 2016) (Section 1.4.1). Moreover, the magnitude of mean low flows has intensified, with a decrease of 3.9 % per decade in lowland areas and an increase of 5.3 % in high-elevation catchments for the period 1977–2018 (Laaha et al., 2016; Blöschl et al., 2017). While future low flow scenarios for Austria yield different results, a significant increase of 10–15 % is projected for the Austrian Alps.

Changes in Austrian glaciers have been continuously monitored for more than a century documenting climate-induced glacier change in one of the longest records worldwide. Recent projections of future glacier change indicate a loss of 80–100 % of glaciers in the Central European Alps under warming scenarios between +1.5°C and +4°C (Rounce et al., 2023). Most of the ice loss will occur by 2050 and ice melt will increase significantly at elevations below 3,200 m a.s.l. (Zekollari et al., 2019; Sommer et al., 2020; Cook et al., 2023) (*high confidence*). Glaciers in Austria are located at lower elevations compared to the Western Alps (Switzerland, France) (Fischer et al., 2015; Sommer et al., 2020) indicating that their disappearance is expected to occur earlier than in the Western Alps (*high confidence*). Debris cover on glaciers can significantly delay the ice melt at individual glaciers and impact local changes in glacier runoff. Currently, debris cover on glaciers in Austria is increasing (Fleischer et al., 2021) (see Section 1.3.2).

The melting and disappearance of glaciers affect mountains in a variety of ways ranging from landscape changes, river runoff, slope stability, and biodiversity to tourism. Effects will occur at different temporal and spatial scales, and some impacts will show a transition towards new conditions once the glacier has melted. On-site impacts of glacier retreat locally modify previously ice-covered ground at high elevations. These impacts include the reworking of proglacial sediments and an increased sediment supply into rivers (Lane et al., 2017), the establishment of biodiversity through the colonization of ice-free ground, and the formation of new glacier lakes. The number of glacier lakes above 1,700 m a.s.l. has increased over the past century with formation rates increasing over the past 20 years (Buckel et al., 2018). This trend is expected to continue with lakes forming at higher elevations (Otto et al., 2022) (*medium evidence, low agreement*).

Glacierized catchments in Austria are considered to have passed the point of peak water beyond which runoff decreases due to decreasing glacier volume. For the major rivers draining the Alps (Danube, Rhine, Rhone, Po), peak water was reached in 2006 and glacier melt contribution to runoff has decreased since then (Huss and Hock, 2018). Ongoing glacier melt will lead to a seasonal shift of the glacier runoff peak from late summer to early summer towards the middle of the 21st century (Hanus et al., 2021). For example, the runoff contribution from glaciers in the Danube catchment is estimated to decrease by up to 60 % in August, September and October in 2090 (Huss and Hock, 2018).

Steep bedrock slopes and cirque headwalls may experience an increase in slope instabilities, such as rockfalls, as a result from the debuttressing of slopes and changing temperature conditions following glacier melt, as has been reported in a case study at Kitzsteinhorn (Hartmeyer et al., 2020). These slope instabilities may affect high alpine infrastructure and are likely to increase as glaciers continue to melt (*medium evidence, low agreement*) (Cross-Chapter Box 1).

Locally, rockfall events associated with glacier melt are interfering with changes in permafrost conditions. The distribution and temperature conditions of permafrost in Austria are largely unknown and limited to restricted areas (Schrott et al., 2012; Kellerer-Pirklbauer, 2019; Rode et al., 2020). Due to the diverse landscape patterns of the Austrian Alps, permafrost occurrence is highly fragmented and not exclusively limited to the upper altitudinal zones of the mountains. In the Hohe Tauern Range, permafrost occurs at elevations above 2,500–3,000 m a.s.l. on the northern and southern slopes (Schrott et al., 2012). Isolated patches of permafrost are reported from extreme locations at altitudes around 1,000 m a.s.l. (Stiegler et al., 2014). Borehole temperatures at permafrost sites throughout the European Alps show an increase in permafrost temperatures even at depths of 20 m (Biskaborn et al., 2019; Haberkorn et al., 2021). Existing borehole data from Austria report permafrost temperatures around -2 to -1°C at about 10 m depth (Schöner et al., 2012; Hartmeyer et al., 2020; Greilinger et al., 2023; Hartmeyer, 2023) and a near-surface increase of 0.1°C/yr (Hansche et al., 2023; Hartmeyer and Otto, 2024). Considering the ongoing rise of air temperatures, the permafrost area is likely to decline significantly (Chadburn et al., 2017; Magnin et al., 2017). Bedrock temperatures in Austria are likely to increase towards zero degrees in the coming decades (*medium evidence, high agreement*). In unfavorable locations, bedrock temperatures close to zero degrees may lead to reduced slope stability, which favors increased frequency of rockfall processes and increased hazard potential at higher elevations (Haeberli et al., 2017) (*medium evidence, high agreement*). As glaciers continue to melt, water storage and discharge from permafrost landforms such as rock glaciers will become increasingly important. Rock glaciers in Austria are assumed to contain up to 2 $km^3$ of freshwater and are capable of storing additional resources for several months (Wagner et al., 2021). Rock glaciers are assumed to be less affected by warming due to the protective effect of the rock above the ice content (see Section 1.3.3 and Cross-Chapter Box 1).

## The (terrestrial) biosphere

Within the Austrian Alps, two main zones can be distinguished with regard to the predominant vegetation types and human land use: (i) The valley bottom and the adjacent cultivated grassland and forest area upslope to the climatic forest line, comprising the montane belt and the lower part of the subalpine belt (addressed in Section 2.2); (ii) The high mountain area from the tree line ecotone to the highest elevations, comprising the upper part of the subalpine, the alpine, subnival and nival zones (see below). For consistency reasons, only the area above the timberline is considered in this section, whereas forests and agricultural areas are dealt with in Section 7.4.2.

Due to their difficult accessibility and low temperatures, the Alps remain the only large more or less contiguous area of Austria, where ecosystems have not been completely or predominantly transformed into landscapes of intensive agricultural production, forest plantations, settlements, transport, commercial and industrial infrastructure. As the Alps cover more than 65 % of Austria, the country contains larger proportions of forested areas, mountain valleys, interspersed traditional cultural landscapes and naturally treeless alpine ecosystems than anywhere else in central Europe.

### *Effects of climate change above the tree line (high mountain area)*

The area above the tree line comprises the majority of unmanaged land in Austria, where settlements and traditional land use practices cease and give way to naturally treeless alpine landscapes. However, the area above the tree line in the Austrian Alps is only partly unmanaged and partly used for tourism and low-intensity livestock grazing, mainly in the lower alpine zone, but occasionally extending to above 3,000 m a.s.l. (Grabherr and Ringler, 2018). For the Alps as a whole, 29 % of its mountainous area lies above the elevation of 2,000 m and 10 % above 2,500 m a.s.l. (Körner, 2007). A similar proportion can be assumed for the Austrian Alps. On the European level, alpine ecosystems cover only 3 % of the continent, however, they are exceptionally rich in biodiversity. About 20 % of the continent's native vascular plant species have been reported to have their center of distribution in this area (Väre et al., 2003). In contrast to the Scandinavian mountains, which contain the largest proportion of alpine land, the Alps and the European mountains further south, host the largest proportion of endemic mountain species (Pauli et al., 2012). Austria, therefore, bears a great responsibility for the preservation of biodiversity in Europe's high mountain biome. Even if the immediate urgency of nature conservation measures in the high Alps is currently less pressing than in the small, fragmented and highly endangered remnant areas of the lowlands, the issue of nature conservation is a priority in alpine areas – particularly in the context of climate change. This is because climate change effects are pervasive and affect the most remote parts of the Alps. In addition, mountain areas such as the Austrian Alps will rapidly gain in importance as refugia for natural biota and in attractiveness for humans, who are increasingly suffering from a hotter and probably drier environment in the surrounding lowlands (Beniston et al., 2018). The low temperature regime, including a short growing season, is the strongest ecological factor determining ecosystems in the Alps and is the main ecological filter preventing the growth of woody plants (shrubs, trees) in the alpine zone (Körner, 2021). In addition, the amount of precipitation, especially the duration of snow cover, influences the position of the tree line. In the outer ranges, such as the northern, northeastern and southern Limestone Alps, the tree line is several hundred meters lower than in the central Alps due to higher rainfall and snow loads as well as fewer hours of sunshine (Figure 7.1 and Cross-Chapter Box 1). Climate change leads to changes in the distribution patterns of species, of their interactions and community compositions. Differences in species' abilities to cope with rapid climate change, such as different rates of movement, and capabilities to newly establish and compete with new neighbors, are expected to result in substantial biodiversity losses (Alexander et al., 2015; Lenoir and Svenning, 2015) (see also Cross-Chapter Box 1). Climate warming affects all parts of the Austrian Alps, regardless of their remoteness, by shifting the low temperature filter uphill and from southern to northern slopes. This has several implications for biota living in, and in many cases confined to, mountains:

(i) An upward shift of vascular plant species leads to increased species numbers, but also to competitive displacement of dwarf-growing light-demanding alpine plants by taller plants from lower elevations. Accelerating rates of plant species colonization at summit habitats at high elevations have been found to be highly synchronized with rising temperatures. This pattern was consistent across temperate to northern Europe, including the Alps and the Arctic (Steinbauer et al., 2018) (*high confidence*). The warmer slopes (i.e., the southern and eastern sides of the mountains) showed the highest number of vascular plant colonizations (Winkler et al., 2016) (*medium evidence, high agreement*) and in the Eastern Alps movement rates of 17–40 m of upward shift per decade have been reported (Vitasse et al., 2021). Besides the previously observed upslope shifts of upper range margins of species (Pauli et al., 2012), a more recent study showed that the lower range margins of vascular plants and the optimal ranges of plant species have been moving upslope, at least as fast as the upper range margins in the Eastern Alps (Rumpf et al., 2018) (*medium confidence*). Species of other organism groups have also been found to shift upward (*limited evidence, high agreement*) such as butterflies, albeit with concurrent declines in abundance (Kerner et al., 2023), and fruiting bodies of fungi (Diez et al., 2020). See Section 1.6.4 for further references on the upward shift of different taxonomic groups in Austria.

(ii) Changes in species abundances are generally a faster response than actual range shifts, however, detailed historical data for comparison are scarce. An increasing abundance of alpine vegetation has been detected by remote sensing techniques, showing a greening (i.e., productivity gain) in 77 % of the European Alps above the tree line, while <1 % showed a browning (productivity loss) (Rumpf et al., 2022). Increasing greening can be caused by the promotion of more warmth-demanding and more vigorously growing plants at the expense of the cold-adapted species. This process, first described for alpine areas as thermophilization by Gottfried et al. (2012), has been repeatedly confirmed in the Austrian Alps (Lamprecht et al., 2018) (*high confidence*). Plant species adapted to very cold conditions (cryophytes) continued to decline in abundance (Lamprecht et al., 2018) (*medium evidence, high agreement*). This dieback may have been caused by overly warm conditions, leading to direct physiological disadvantages for the cryophytes due to their inability to down-regulate dark respiration under warmer conditions, leading to a rapid loss of carbohydrates (Larigauderie and Körner, 1995; Steinbauer et al., 2020) (*limited evidence, medium agreement*).

(iii) Further, a shift to longer growing seasons will change the duration of phenological development stages (Beniston et al., 2018). Leafing and flowering have occurred an average of 2.4–2.8 days/decade earlier over the past four decades (Vitasse et al., 2021), which can lead to both exposure to late frost events and mismatches in plant-pollinators interactions (*medium evidence, high agreement*). Earlier snowmelt is expected to have a strong influence on soil microbial life, because snowmelt triggers an abrupt transition in the composition of soil microbial communities, as has been confirmed by experimental snow cover manipulations in the Tyrolean Alps (Broadbent et al., 2021). This is closely linked to shifts in soil microbial functioning and biogeochemical pools and fluxes. Further, earlier snowmelt due to climate change could disrupt the synchronized seasonal dynamics of nutrient exchange between plant and soil microbiota, i.e., microbial organisms depend on carbon supply, plants on labile forms of nitrogen, which show strong seasonal variations (Bardgett et al., 2005; Bardgett and van der Putten, 2014) (*limited evidence, high agreement*). Some vertebrate species, such as the mountain hare (*Lepus timidus*) and the rock ptarmigan (*Lagopus muta*), undergo seasonal color change from brown to white for reasons of camouflage, which is mainly controlled by the photoperiod. Earlier snowmelt can, therefore, be detrimental for these species, as they become easily detectable prey (Zimova et al., 2018).

There is some debate regarding the extent and immediacy of the threat to high mountain species from climate change. Some authors argue that a rugged topography and the resulting variation in microclimate provide a buffer against the threatening effects of climate change, as plant and animal species may be able to find suitably cold refugia in nearby upslope or less sun-exposed locations (Körner and Hiltbrunner, 2021). Others point out that the high topographic variation and elevation differences in mountains have favored orographic isolation and thus the generation of many small-ranged endemic species (Dirnböck et al., 2011). In the Austrian Alps, endemic plant and animal species are concentrated in the subalpine to alpine zone of marginal mountain ranges, such as the northeastern Alps, which remained unglaciated during the Pleistocene, but where potential refugia are very limited due to lower elevations compared to the Central Alps (Semenchuk et al., 2021). Increasing warming-induced fragmentation and shrinkage of alpine areas and the associated competitive displacement of alpine plants by taller and more vigorous plants from lower elevations, are therefore expected to accelerate extinction processes (Wessely et al., 2017). The generally slow-growing, but often long-lived, alpine plant species may persist in their increasingly climatically unsuitable habitats, but with declining populations until they reach their lifespan (Cotto et al., 2017), i.e., when their extinction debt is paid off (Dullinger et al., 2012; Alexander et al., 2018). In the case of the high central part of the Alps, from the Hohe Tauern westward, cold-enough refugia will be more abundant, however only in scattered patches where soil substrates are available (Kulonen et al., 2018). Moreover, even if such refugia did exist in nearby locations, the pronounced topographically determined variation in meso- and microclimates could form abrupt climatic barriers to the colonization of new habitats, e.g., toward a nearby north-exposed slope (Dobrowski and Parks, 2016). In this context, a recent study from the Stubai Alps suggests that the mesoscale topography and the overall elevation gradient are stronger determinants of plant distribution than the microscale (Chytrý et al., 2024), which does not support the hypothesis of climate change buffering effects through topographic variation. The role of the Alps as a biodiversity refugium and/or as a trap is an understudied topic (*medium evidence, low agreement*).

There is *medium evidence* but *high agreement* that shrub and forest vegetation will advance to currently treeless zones and thus outcompete dwarf-growing alpine species (Lenoir and Svenning, 2015). Yet, in the Alps, only a small percentage of forest advance could be attributed to responses to climate warming, rather than to land abandonment because actual tree lines are positioned well below their climatic limits (Gehrig-Fasel et al., 2007). Similarly, the recent expansion of shrubs in subalpine areas, mostly of green alder (*Alnus alnobetula*), was mainly explained as a consequence of land abandonment (Caviezel et al., 2017; Hohensinner et al., 2021).

The situation is different in the alpine zone. Repeatedly confirmed warming-related species enrichments and upward shifts of alpine plants (Matteodo et al., 2013; Winkler et al., 2016; Steinbauer et al., 2020; Nicklas et al., 2021; Vitasse et al., 2021) (*high confidence*) are of immediate relevance for nature conservation. Especially the alpine areas at the margins of the Alps, where many endemic species live, are of great concern because their fragmented alpine areas are already very limited in space. Due to the conical shape of mountains, shifts of the lower range margins of plant species to higher elevations, as detected in data from across the Eastern Alps (Rumpf et al., 2018) and confirmed for several other organisms (Rumpf et al., 2019), can lead to rapid declines and species extirpation (*medium confidence*).

Two other ecological factors may amplify the vulnerability of alpine biota to climate change. First, rising temperatures may lead to drier conditions even with unchanged precipitation, due to increased evapotranspiration. This would expose alpine plants that grow, for example, on the humid northeastern margin of the Alps, to a climate to which they are not adapted. Experimental studies in the Alps have shown that alpine plants are more affected by drought than their relatives at lower elevations (De Boeck et al., 2016; Rosbakh et al., 2017) (*medium confidence*). The second factor is the increasing availability of soluble nitrogen, which may favor colonization by more warmth-demanding plants from lower elevations, resulting in a competitive displacement of alpine species. An increase in widespread nitrophilous plants and a concurrent loss of small-ranged species has been observed in protected areas in lowland meadows, forest understorey vegetation as well as on alpine summits (Staude et al., 2022). While soluble nitrogen deposition from industrial agriculture is expected to be the primary cause at lower elevations, a combination of warming, leading to increased nitrogen availability and nitrogen deposition may explain the situation in alpine areas. Many parts of the Alps currently receive many times the pre-industrial rates of soluble nitrogen deposition, even in areas above the tree line (Körner et al., 2021), and alpine habitats are typically oligotrophic and, thus, sensitive to nutrient additions (*medium confidence*).

*Effects of climate change on conservation areas*

The Austrian Alps host several protected areas including three national parks, three UNESCO biosphere reserves, two UNESCO geoparks and several nature parks, nature reserves (ALPARC, 2019a) and Natura 2000 areas. They are in a rather difficult situation, especially the smaller ones with limited vertical extent, in the face of the effects of anthropogenic warming and nutrient deposition. Refugial areas on the margins of the Alps are already very small, and regions where receding glaciers are opening up land for new colonization (Fischer et al., 2019) are usually far away from the areas of endemic species. Besides, the future area of glacier forelands will be too small (see Sections 1.3.2 and 1.3.3), with their lower parts located in alpine climates, and will therefore be rapidly colonized (Fickert and Grüninger, 2018). Progressive succession will lead to closed vegetation

(Fickert, 2020), leaving no space for cold-adapted species (*medium evidence, high agreement*).

Nevertheless, the role of mountain protected areas will multiply in importance, especially if they are extended over large elevation gradients and connected to corridor areas (Elsen et al., 2018). In this way, the potential of the Austrian Alps as a top priority biodiversity refugium can be significantly enhanced. An intact biosphere in the Alps will be decisive for the sustainable functioning of its ecosystems, such as water supply, slope stabilization, biodiversity refugium, and recreation. As warming and drought influence human activities such as tourist infrastructure, hydroelectric, wind, and solar power development, careful consideration of their impacts in the context of the biodiversity crisis is essential. Traditional grazing with low livestock numbers is important for the conservation of species-rich pastures in the montane zone and may slow down uphill migration of tall and competitive plants in the lower alpine zone, but additional inputs of manure or other fertilizers can rapidly lead to species impoverishment (Grabherr and Ringler, 2018). Under changing climatic conditions, protected areas in the Alps need to be more flexible, adapted to the local situation including the local population, and large enough to effectively protect biodiversity (ALPARC, 2019b; Job et al., 2022). Maintaining or rewilding alpine ecosystems and restoring parts of the forest belt (Pereira and Navarro, 2015) will become particularly important in the course of an amplifying climate crisis.

## Natural hazards

The natural hazards described below are in line with Table 1.A.3 and Section 1.8. According to this table, rockfall and rock avalanches are particularly affected by climate change in high alpine regions. Furthermore, according to this table, all the hazards described below show an upward trend, except for snow avalanches, which show a diverse trend depending on the elevation.

### *River and torrential flooding*

In the coming decades, climate change-induced changes in river flooding in Austria are expected to be relatively small compared to the observed natural variability (Blöschl et al., 2018; Blöschl, 2020) (*high confidence*) (Section 1.4.1). Large-scale (stratiform) precipitation events (especially due to Vb cyclones) (van Bebber, 1891; Messmer et al., 2015), which lead to large-scale flooding events, are not expected to increase in frequency (Hofstätter et al., 2015; Blöschl et al., 2018; Blöschl, 2020), while there are indications that summer convective precipitation is expected to increase over the Alps (Giorgi et al., 2016). The intensity of short heavy precipitation events is expected to increase in summer (Ban et al., 2015; Chimani et al., 2015; Hofstätter et al., 2015; Formayer and Fritz, 2016; Blöschl et al., 2018; Blöschl, 2020; Hanus et al., 2021) (*medium confidence*). The existing trend towards increasing magnitudes of small to moderate floods outside the summer season (especially of winter floods; Section 1.4.1) as well as the lengthening of the season of summer low-pressure systems with particularly high precipitation, is expected to increase in the Austrian mountain regions in the future (*medium confidence*), as it is expected in the Swiss mountain regions and on a European scale (Beniston, 2006; Blöschl et al., 2011a, 2011b; Hall et al., 2014; Nachtnebel et al., 2014; Beniston et al., 2018; Brönnimann et al., 2018; Pistotnik et al., 2020; Hanus et al., 2021; Schlögl et al., 2021; Laaha et al., 2025). Equally, extreme floods (return periods >10 years) are expected to occur in the summer and increase in intensity (Brönnimann et al., 2018) (*low confidence*).

Concerning torrential floods, studies on the Austrian Alps and comparable Swiss studies (Stoffel et al., 2014; Heiser et al., 2019; Prenner et al., 2019; Schlögl et al., 2021), do not show a clear trend for damage-causing processes despite increasing exposure of elements at risk (Fuchs et al., 2015b), partly due to a compensatory effect of an increasing number of technical protection measures. At medium elevations, rain-on-snow events may become more frequent by the end of the 21st century (Stoffel et al., 2014; Stoffel and Corona, 2018; Prenner et al., 2019), extending the debris flow and flood season into the March-December period (Stoffel et al., 2014; Prenner et al., 2019; Hanus et al., 2021). The likelihood of critical triggering conditions for debris flows may vary regionally and seasonally, extending to earlier in the year (Stoffel et al., 2014; Hirschberg et al., 2021; Kaitna, 2022) (*limited evidence, medium agreement*). Early season debris flows are expected to remain small, given the current climate and sediment potential, and to increase in size as rain-on-snow events become increasingly relevant. Late summer season events are expected to become more critical due to the increasing sediment potential (Stoffel et al., 2014) (*low confidence*).

From a local to regional perspective, the sediment potential is expected to increase at high altitudes where (i) glacier retreat, (ii) permafrost degradation and (iii) increased physical weathering occur. At medium elevations, sediment potential may decrease due to weaker physical weathering, potentially causing decreased debris flow activity in sediment-limited catchments. The decrease in summer precipitation may increase sediment accumulation, potentially increasing the magnitude of debris flows (Lugon and Stoffel, 2010; Blöschl et al., 2011a; Sattler et al., 2011; Stoffel et al., 2011; Eitzinger et al., 2014; Gems et al., 2020; Kaitna et al., 2020; Hanus et al., 2021; Hirschberg et al., 2021; Kaitna, 2022; Maraun and Jury, 2022) (*high confidence*). In larger catchments, the expected change in sediment potential is within the natural variation (Blöschl et al., 2011a) (*medium evidence, low agreement*).

Historical and future human-induced land use changes in mountain catchments are expected to have a major impact on flood generation processes. With the knowledge from currently available studies, a robust assessment of the contributions of land use and climate change to the alteration of the flood generation processes is not possible (Habersack et al., 2011) (*low confidence*).

*Landslides*

Evidence of the impact of climate change on landslide activity in Austria is mainly site-dependent, especially with respect to the altitude. Due to changes in permafrost conditions, increased glacier melt and destabilization of rock glaciers, local accelerations of slope movements are being recorded (Schoeneich et al., 2015; Hartmeyer et al., 2020; Hartl et al., 2023) (*high confidence*) (see also Section 1.7). In the lower regions, especially those not affected by permafrost and glacier retreat, there is no evidence yet of an increase in either the frequency or the magnitude of slide and fall events (Sass and Oberlechner, 2012) (*limited evidence, medium agreement*). Rock, earth and debris slide and fall occurrence, and velocities are, however, strongly dependent on groundwater flow, which has been numerically demonstrated (Zieher et al., 2017a; Schneider-Muntau, 2020; Schneider-Muntau et al., 2022) (*high confidence*). A direct correlation between precipitation and slide or fall occurrence has been often postulated (Walter et al., 2011; Zieher et al., 2017b, 2023; Stumvoll et al., 2020), although this correlation is difficult to assess and is only based on case studies due to the different duration of precipitation to groundwater flow (Gassner et al., 2015; Zieher et al., 2023) and the still unclear influence of long-term precipitation events versus short-term but extreme events (Offenthaler et al., 2020) (*medium confidence*) (see also Section 1.7). Recent research indicates that there may also be a significant difference between the influence of precipitation and snowmelt, with snowmelt appearing to have greater effect on creep velocity (Holzmann and Perzlmaier, 2022). However, a robust correlation between snowmelt, precipitation, and groundwater levels, which would fill the current gap in understanding the effects of climate change on slide and fall occurrence, has not yet been found.

*Snow avalanches*

The relationship between avalanche activity and climate change can be direct (effect of changes in snow and meteorological drivers on avalanche release and propagation on short timescales), or indirect, as a consequence of changes in land cover due to climate change. For example, the warming-induced rise of the tree line affects avalanche release (Eckert et al., 2024). With ongoing climate change, the types of avalanches as well as their frequency may change. There is *high agreement* with *medium evidence* that temperature increase will cause changes in the frequency, intensity, and types of snowfall (Hock et al., 2019). Depending on elevation, this will affect the quantity and quality of snow cover, leading to changes in the magnitude and frequency of avalanches. While it seems clear how climate change will affect mountain snow cover at lower elevations, changes above the tree line (1,800–2,200 m a.s.l. in the European Alps) are less well studied (Strapazzon et al., 2021) (*limited evidence, high agreement*). The effects of climate change on snow avalanches, therefore, remain vague, especially since most avalanche release zones in the Austrian Alps are located above the tree line. A common view, expressed with *medium confidence* in a recent IPCC special report (Hock et al., 2019), is that the number of avalanches and runout distances will decrease at lower elevations. Due to warmer temperatures, the snow volume may respond with a reduction of 90–50 % at mid-elevation sites (1,000–2,000 m a.s.l.) and 35 % at high-elevation sites over the next few decades (Keiler et al., 2010). Future snow avalanche hazards will depend on interactions between increasing air temperatures and, possibly, increasing precipitation intensities (Reuter et al., 2020). An increase in air temperature will raise the snowfall line, leading to more liquid precipitation and less solid precipitation (Blöschl et al., 2018) (*medium evidence, high agreement*). Furthermore, the duration of snow cover will be greatly reduced, mainly due to earlier spring snowmelt.

The number of studies focusing on the effect of future environmental change on the frequency and magnitude of snow avalanches is limited (Fuchs et al., 2015a). However, a few papers provide insights into the climatic control of snow avalanches (Eckert et al., 2010). For the period between 1950 and 2017, Eckert et al. (2024) reported a 19 % decrease in the number of avalanches in the French Alps, with a significant correlation with increases in mean winter temperature (R= -0.42, p=0.002) and decreases in snow depth at 2,400 m a.s.l. There is no doubt, that changes in temperature, precipitation (amount and solid/liquid share) and wind characteristics influence the structure and stratigraphy of the snowpack and, consequently, the release and properties of snow avalanches. On the one hand, this leads to a decrease in snow cover duration at lower altitudes (*high confidence*), and on the other hand, more precipitation – due to warming – is expected to negatively influence snow cover stability (*medium evidence, high agreement*) (see also Glade et al., 2014). The study by Eckert et al. (2010) focused on changing annual avalanche runouts in the French Alps and correlated them to climate variability using an advanced statistical framework. The results indicate no change in the mean avalanche runout altitude during the last 60 years, despite an increase in temperature. In contrast, it is reported that the release zones of avalanches migrated upslope during the period of 1850–1920, together with a more than sevenfold reduction in the annual number of avalanches, a severe shrinkage of avalanche size, and shorter avalanche seasons as well as a reduction in the extent of avalanche-prone terrain (Giacona et al., 2021). Corresponding to the high variability of snow depth and snow cover in mountain areas, possible effects on snow avalanche activity will cover a wide range from a decrease or an increase in occurrence to a shift from dry to wet snow avalanches (*limited evidence, high agreement*). Results from downscaled climate models under climate change scenarios coupled with snow models, calculated that spontaneous avalanche activity in the French Alps will decrease by 20 % and 30 % by the mid and late twenty-first century, respectively, relative to a 1960–1990 baseline. However, high winter avalanche activity is expected to increase in the mid and late twenty-first century relative to the same baseline, due to an earlier transition from dry to wet snow conditions (Castebrunet et al., 2014). This is consistent with studies by Zgheib et al. (2022) who reported a general increase in the annual avalanche frequency from 1946 to 2009 in the French Alps, and by Pielmeier et al. (2013) and Mayer et al. (2024a) for the Swiss Alps.

For the French Alps, it has been reported that despite the anticipated stability of precipitation sums, the interaction between temperature increase and topography will constrain the evolution of snow-related variables on all considered spatio-temporal scales. This will result in a decrease of the dry snowpack and an increase of the wet snowpack. Wet snow conditions are projected to occur at high elevations earlier in the season (Castebrunet et al., 2014). In AAR14 it was reported that a decrease in avalanche activity was expected, however, this decrease was not supported by data or other evidence (APCC, 2014). Following Castebrunet et al. (2014), a general decrease in mean (20–30 %) and interannual variability of avalanche activity is projected. These changes are relatively strong compared to changes in snow and meteorological variables. The decrease is amplified in spring and at lower elevations. In contrast, an increase in avalanche activity is expected at high altitudes in winter due to conditions favorable for wet snow avalanches early in the season (Castebrunet et al., 2014) (*limited evidence, high agreement*).

*Glacial Lake Outburst Floods (GLOFs)*

The release of previously covered bedrock after glacier retreat leads to a debuttressing of slopes and the establishment of different thermal conditions in the rock. An increase in rockfall processes is reported for deglaciated bedrock slopes in an Austrian case study (Kitzsteinhorn) (Hartmeyer et al., 2020). Glacier retreat may also cause the formation of glacial lakes and landslides, in some cases with the potential for glacial lake outburst floods (GLOFs). GLOFs result from dam bursts or overtopping due to rockfall into the lakes. The most recent documented catastrophic GLOFs in the Austrian Alps occurred in the 17th–19th centuries with a maximum in the 1860s, when the surging Vernagtferner glacier repeatedly dammed lakes in the Ötz Valley in Tyrol (Hoinkes, 1969; Braun, 1995), producing several destructive GLOFs (Aulitzky et al., 1994; Embleton-Hamann, 2007). Even though the number of glacial lakes increased during the 20th century, none of the existing lakes are currently considered hazardous (Mergili et al., 2012; Buckel et al., 2018; Fuchs et al., 2022) (*medium confidence*). According to modeling studies, the number of lakes in Austria is expected to increase and changes in the hazard potential are possible, especially if future lakes form at higher elevations closer to steep bedrock slopes (Otto et al., 2022) (*medium evidence, low agreement*). Further studies on GLOF hazards in the Austrian Alps are currently lacking. Historical outlines of GLOFs are reported in Nicolussi (2013) and Richter (1889, 1892).

*Wildfires*

In the European context, wildfires are considered an emerging risk (see Cross-Chapter Box 1). The burnt area in Europe in 2021 is about 2.5 times higher than the area burnt between 2008 and 2020 (IFRC, 2021). It is particularly alarming that significant wildfires have recently occurred not only in countries of the European South but also in countries with a short record of wildfire events (e.g., Sweden, Austria). Wildfires in Austria are mainly human-induced (85 %) and related to tourism and recreational activities (Müller et al., 2020). Consequently, the wildfire risk in Austria is expected to change partly due to the expected increase of fire weather days (Müller et al., 2020) and partly due to the continuous development of the wildland-urban interface (Papathoma-Köhle et al., 2025) (see also Cross-Chapter Box 1, Sections 1.6.2 and 2.2.2). In more detail, fire weather is the combination of certain conditions of surface temperature, humidity and wind (Clarke et al., 2022). Based on these characteristics, fire indices are developed and used to predict wildfire danger. According to Arpaci et al. (2013), the Canadian Fire Weather Index (FWI) is the best performing FWI In Austria. Models developed during the FIRIA (Fire Risk and Vulnerability of Austrian Forests under the Impact of Climate Change) project (2011–2014), showed that not only the number of fire weather days in Tyrol will increase by more than 40 days by 2100 (2014–2100), but also that areas that have not experienced wildfires in the past will be at increased risk of wildfires in the future. Moreover, the fire seasons are expected to expand and shift throughout the year (Müller et al., 2020). Relatively recent wildfire events in Austria (e.g., Absam 2014, Lurnfeld 2015, Rax 2022), have shown that crown fires in combination with strong winds can challenge suppression efforts and can be highly dangerous to people, infrastructure and property, in addition to affecting the forests themselves. The term ‘forest fire’ which refers to wildfires affecting forests excluding grassland fires or other types of wildfires, is used elsewhere in this report (see Sections 1.6.2 and 2.2.2) since this is a very common type of wildfire in Austria. There is no study addressing wildfire risk only for the Austrian Alps, but it can be assumed that since the topography is one of the factors that influence the initiation and extent of a wildfire in mountainous areas (Airey-Lauvaux et al., 2022), and that the number of fire weather days are going to increase, the wildfire hazard will also increase, threatening settlements in the wildland-urban interface and ecosystems. On the other hand, significant changes are expected in the exposure of people and ecosystems. In more detail, the wildland-urban interface and intermix (WUI) in Austria, where people live very close to or within the forest, occupies 13.6 % of the country (Bar-Massada et al., 2023). Additionally, the number of people living in the WUI in Europe is expected to increase according to different climate change scenarios. For the 3°C global warming scenario (GWL 3°C), an increase of 24 % of the population living in the WUI and exposed to high to extreme fire danger at least 10 days per year is expected. This percentage is reduced to 7.9 % for 1.5°C global warming (GWL 1.5°C) (Feyen et al., 2020). According to Feyen et al. (2020), the vulnerability of the ecosystems in the WUI is also expected to increase due to the northward shift of European ecological areas.

*Multi-hazards (compound events, hazard cascades)*

Many hazards occur, coincidentally or not, simultaneously or sequentially (see also Section 1.8). In general, preparedness and adaptation to multi hazard events are a prerequisite for a resilient society (UNDRR, 2015). Risk assessment for single hazards should be extended to include secondary effects (floods, landslides) or processes occurring simultaneously (wildfires, heatwaves, droughts) (Terzi et al., 2019). There are a few studies focusing exclusively on the influence of climate change on multi-hazards (occurrence, frequency, magnitude) for the Austrian Alps, although multi-hazard events have occurred frequently in the region in the past (Hübl et al., 2005; Eder et al., 2006; Pfurtscheller, 2014). Stoffel and Corona (2018), focusing on the wider Alpine space, argue that future winters will be characterized by multiple events triggered by changes in precipitation and temperature. However, the interactions between different hazardous processes in the Austrian Alps have often been the topic of research studies. For example, Sass et al. (2012) investigated the effects of wildfires on other geomorphological processes in Tyrol, and Kaitna et al. (2023) investigated the influence of hydrometeorological triggers on the occurrence of debris flows in the Austrian Alps. Some studies focused on specific elements at risk, such as the road network (Oberndorfer et al., 2020), while others focused on multi-hazard exposure mapping in Austria (Fuchs et al., 2015b; Nachappa et al., 2020), or in the Alps, including part of the Austrian Alps (Pittore et al., 2023). Terzi et al. (2019) have developed a framework for climate change and related multi-hazard for mountain areas. Nevertheless, it is not clear from the literature whether mountain areas are more susceptible to multi-hazards and if climate change will affect multi-hazards differently in mountain areas than in the rest of the country.

*Implications for vulnerability and risk*

In summary, changes in the frequency and intensity of natural hazards in the Austrian Alps must be considered in order to adapt to climate change. The risk to natural hazards is subject to change not only due to changes in the frequency and intensity of natural hazards in the Alps but also due to increased exposure (Fuchs et al., 2015b) and vulnerability dynamics, according to a number of publications (Papathoma-Köhle et al., 2021, 2022a, 2022b) (see also Sections 7.4.2 and 7.4.3). Specifically, around 5 % of the building stock in Austria is exposed to torrential flooding, with hotels and guest houses as well as agricultural buildings showing an above-average exposure. The total number of properties exposed to torrential flooding has risen by a factor of six, from 18,797 to 111,673 buildings, over the last century. Considering these temporal dynamics, it can be assumed that if construction activity continues in the same pattern as in the last 100 years, the exposed buildings will increase by 2 % per year (Fuchs et al., 2015b, 2017).

## 7.4.2. The Alps as a provider of services, goods and livelihoods

### Forestry and agriculture

*Effects of climate change on forests*

The Austrian Alpine area as delineated by the Alpine Convention is largely dominated by forests (Figure 7.5). Forests are divided into productive forests, recreational forests, and protective forests (BML, 2022). Timber production drives the forestry sector in Austria, which is mainly dependent on coniferous species that cover 53 % of the forested area, dominated by Norway spruce (42 %). Single-species spruce forests, established during the economic crisis following World War II, often exceeded ecological limits, resulting in 'secondary spruce forests' (BFW, 2022). Forestry is an important backbone of the regional economy in the mountain regions of Austria. It supports the local value chain of the bio-economy and provides energy in rural areas (Jandl, 2023). Due to climate change, a wide range of possible changes in forestry are expected, e.g., a change in tree species requires a change in wood processing technology (Pramreiter et al., 2023). However, recent research shows that the high proportion of

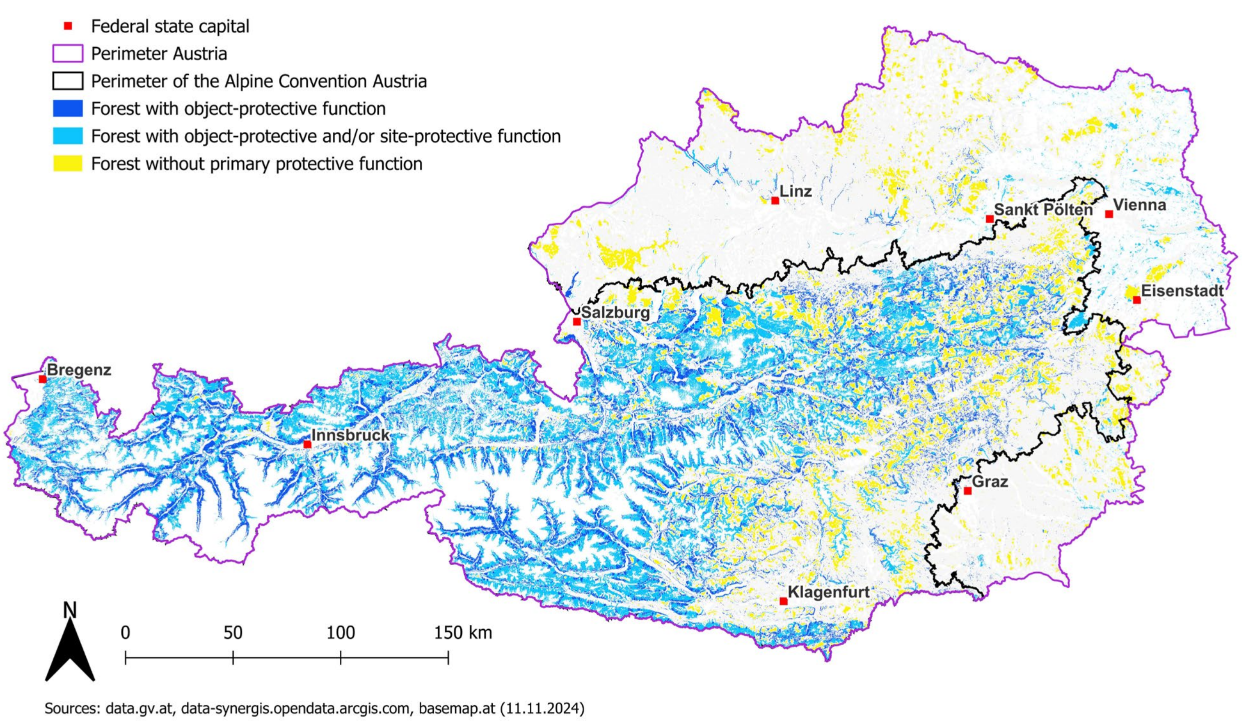


**Figure 7.5** Protective forest in Austria.

private forest owners makes it difficult to estimate the implementation of necessary adaptation measures (Mostegl et al., 2019; Pröbstl-Haider et al., 2020a) (*limited evidence, high agreement*) (see Section 1.6.2). Effects of climate change on forestry and agriculture in Austria are discussed in Section 2.2. Here, the focus is on forests and agriculture in mountain areas. With regard to forestry, the focus in mountain areas is on protective forests.

Protective forests have the primary function of protecting people or assets from the effects of natural hazards (Brang et al., 2001). They are common in mountainous areas, and less common in low elevations (Figure 7.5) (Makino and Rudolf-Miklau, 2021). Strategic management concepts are implemented to sustainably maintain a desired forest structure that provides protection against gravitational and hydrological hazards (Perzl, 2014; Perzl et al., 2021; Teich et al., 2022; Moos et al., 2023; Gaube et al., 2024). Protective forests are uneven and multi-layered stands with trees of all sizes and age classes, a minimum canopy cover of about 40 %, only small openings and a sufficient presence of natural regeneration (Frehner et al., 2005; Perzl, 2008). However, species composition and specific silvicultural objectives for protective forest management are highly dependent on the natural hazard process while the assessment of the protective effects is still subject to uncertainties (Perzl et al., 2021).

Global warming poses several challenges for mountain forests. However, at high elevations (montane and subalpine forests), the pressures from climate change are not as manifest as in valleys. Temporarily, climate change even promotes productivity and the upward shift of the tree line. Over several decades, the positive effects of warming will be outweighed by the negative effects that reduce forest productivity (Bebi et al., 2009; Lexer et al., 2015; Irauschek et al., 2017a, 2017b; Ledermann et al., 2022; Gaube et al., 2024). In addition, mountain forests will be more frequently and severely affected by natural disturbances (Seidl et al., 2017). In a warmer world, pests and pathogens will become an increasing challenge (Netherer et al., 2015; Hlásny et al., 2019; Hoch et al., 2019; Steyrer et al., 2023). For example, epidemic bark beetle outbreaks are becoming more common as bark beetle habitat shifts upward due to rising air temperatures, causing increasing problems in high-elevation forests (Jakoby et al., 2019; Hallas et al., 2024) (*high confidence*).

Rising air temperatures and more frequent and severe droughts will lead to shifts in tree species distribution and forest composition (Hanewinkel et al., 2013; Mauri et al., 2022; Amt der Steiermärkischen Landesregierung, 2023a, 2023b). The dynamics of natural forest disturbances such as wind, fire, pests and insects are accelerated by climate change such as the ongoing unprecedented bark beetle outbreak in protective forests in Austria and other countries in Central Europe, which may result in a temporary or irreversible loss of their protective effects (Seidl et al., 2017; Albrich et al., 2020; Senf and Seidl, 2020; Moos et al., 2023) (*high confidence*). However, post-disturbance management decisions have an important impact on the protection. For example, remaining deadwood after windthrow and bark beetle disturbances, can have a positive effect on rockfall and avalanche protection, especially during the first 15 years (Wohlgemuth et al., 2017; Teich et al., 2019; Caduff et al., 2022). However, a careful balance between salvage logging to reduce bark beetle infestations, and salvage logging to maintain the protective function is of paramount importance and depends heavily on the local conditions as well as the severity and the stage of the disturbance.

### *Mitigation*

The role of forests in mitigating climate change has been analyzed in the Special Report Land Use (Jandl et al., 2024), including the carbon storage in the tree biomass and in soils, and its impact on the Austrian greenhouse gas (GHG) emissions budget (Gingrich et al., 2024). Since 1990, forests have compensated between 4 and 35 % (on average 15 %) of the GHG emissions of other sectors (Umweltbundesamt, 2023b). The mitigation role of forest management has been investigated in simulation projects (Braun et al., 2016; Weiss et al., 2020; Kraxner et al., 2024). The publications cover the entire Austrian forest and not only mountain forests. The simulations suggest that the climate change mitigation effect of forests is temporary. With sustainably managed forests in a regime of moderate climate change, the carbon pools in soils, biomass, and wood products can be maintained. Unabated warming trends threaten the sink capacity of forests. The scientific discourse on the future role of forests and forest management in mitigating climate change is compromised by opinionated views on the desirable intensity of forest management (*robust evidence, medium agreement*).

### *Adaptation*

Adaptation measures for forests in non-mountainous areas in Austria are discussed in Section 2.3. Here, the focus is on adaptation for forests in the Alpine region. Some measures to adapt forests to climate change are controversial. One aspect is to reduce the population of ungulates (red deer, roe deer, chamois), as natural regeneration of various tree species is low due to browsing damage (Reimoser, 2003; Mayer et al., 2017). A decade-long dialog between foresters and hunters has not resolved the issue (BML, 2022) (*robust evidence, low agreement*). Another controversy is the choice of tree species. Foresters assert the need to establish stands of non-native tree species in locations where they are promising alternatives to native species that are struggling, or for use in locations where native tree species or provenances are not competitive in a future climate (Hanewinkel et al., 2013; Baumgarten et al., 2024; Chakraborty et al., 2024) (see also Section 4.3). The option of introducing non-native tree species is heavily debated (Bauhus et al., 2021) (*robust evidence, low agreement*). A fallback position for unstable and particularly vulnerable forests is to reduce the rotation cycle to avoid premature stand collapse. Common ground is reached when mixed-species stands are to replace single-species stands. From an adaptation perspective, this strategy simply distributes the externally applied risk agents (fire, storm, bark beetle, endemic pathogens) among tree species with different traits. The expectation is that a disturbance event will not destroy the entire forest stand, but only some elements that are particularly vulnerable with respect to the relevant disturbance agent (Pluess et al., 2016; Pretzsch et al., 2017; Yousefpour and Gray, 2022) (*high confidence*).

Recommendations for the management of protective forests to cope with the impacts of climate change on their protective effects are site-specific. Studies examining different management interventions such as thinning and regeneration cuts in combination with different climate scenarios show contrasting impacts on the protective effects of forests against natural hazards, also suggesting strong local context dependencies (Moos et al., 2023).

*Vulnerability*

Disturbance-induced tree mortality and regeneration failure may seriously compromise the provision of protective services against avalanches, rockfall and landslides (Temperli et al., 2017). The exposure of communities, the built environment and infrastructure to natural hazards will eventually increase. Although protection forests may not be more vulnerable to climate change than other forests in Austria, alpine communities that depend on the protection of these forests are, therefore, more vulnerable than other communities in the country that are not protected by nature-based solutions that may be affected by climate change.

*Effects of climate change on agriculture*

Overall, the agricultural sector is characterized by a rather extensive production compared to the lowlands. The dominant form of agriculture in mountain areas is grassland. In Austria the grassland area has decreased from 1,812,380 ha (1990) to 1,611,521 ha (2022). During these 32 years, 85,927 ha were converted to forest, 54,972 ha to cropland, and 27,995 ha to settlements (Umweltbundesamt, 2024) (see also Section 2.2.1). As far as grassland and alpine/mountain pastures are concerned, climate change would allow a shift towards cropland. Economically, such a change in land-use reduces the importance of dairy production. Ecologically, a decline in soil carbon stocks and in plant diversity is expected (Bohner et al., 2017; Bohner, 2023). The boldest changes in agriculture are shifts in production areas for climatic reasons. The current main agricultural production area is located in the northeast of Austria. This area is expected to be subject to more frequent and intense drought events (Haslinger et al., 2019, 2022). Accordingly, the main agricultural area is expected to shift westward and upward where climatic conditions are more conducive to crop production (Haslmayr et al., 2018). However, future site conditions are highly uncertain. Longer and more frequent droughts will reduce the yield of grasslands and the quality of fodder (Bohner, 2022, 2023). There is greater certainty about future pest and pathogen pressure and the adverse effects of extreme climate events.

*Mitigation*

Climate change mitigation in agriculture has some peculiarities. Carbon capture in the biomass will be of little relevance. A prominent role is given to consumer demands, or social transformation (APCC, 2023) (see also Sections 2.3.2, 2.3.4 and 2.A.9). Currently, a meat-producing farm uses more than 5 ha for corn production to supply feed. Additional feed can be purchased from other countries at an ecological cost (soy imports). The ecological footprint is therefore significant.

Grassland soils have higher soil carbon stocks than cropland soils (Baumgarten et al., 2024; Umweltbundesamt, 2024). Many realistic mitigation strategies aim to maintain rather than increase current soil carbon stocks (Zosso et al., 2023). Further mitigation strategies include the integration of landscape elements that increase the plant species diversity and the implementation of agroforestry. However, the increase in soil carbon stocks after the reforestation of extensively used grassland is low (Hiltbrunner et al., 2013; De Stefano and Jacobson, 2017).

### *Adaptation*

Climate change will require agriculture to adapt. In some areas, technological adaptation will be required, such as irrigation of crops, in others different crop varieties and the introduction of non-traditional crops may be the solution. Soil protection and sustainable forms of soil management are well studied. The carbon sequestration potential of soils is not well understood. Soil processes leading to an increase in soil carbon stocks are usually slow. Many strategies have already been implemented in Austria. Further increases in soil carbon stocks are expected to be small (Tiefenbacher et al., 2021; Wenzel et al., 2022) (*medium evidence, high agreement*).

In Austria, permanent grassland soils are important for organic carbon (C) storage due to their high soil organic matter (SOM) stocks and large areas. Especially, subsoils have a high potential for long-term soil carbon storage (SCS). In permanent grassland, soil organic carbon stocks are controlled by climate, soil properties (particularly soil moisture status and soil thickness), vegetation type (root biomass) and management intensity. Plant roots, microbial necromass and C-rich organic fertilizers (cattle manure, composted cattle manure) are most important for soil organic matter accumulation, which is generally a slow process. In Austrian permanent grassland, soil organic carbon storage is highest at an intermediate management intensity (2–4 mowings per year, annual application of cattle manure or composted cattle manure). Management practices that increase annual soil organic matter turnover are more important than those that increase the soil organic matter stocks.

In permanent grassland, the following measures and strategies are important to maintain or increase soil organic carbon stocks (Bohner, 2023; Meyer et al., 2024):

- No conservation of permanent grassland to cropland;
- Conversion of temporary grassland to permanent grassland (no plowing of grassland);
- Maintaining moderate management intensity (2–4 cuts per year), avoiding further intensification in currently intensively managed grasslands;
- Moderate grazing intensity (no long-term overgrazing);
- Increasing root growth, root biomass and rooting depth in soils by reducing management intensity in intensively managed grasslands (particularly intensively managed pastures);
- Annual application of farmyard manure (cattle manure or composted cattle manure);
- Favoring plant species with large and deep root systems;
- Maintaining or increasing the groundwater table in grassland soils affected by groundwater (particularly clay and peat soils).

### *Vulnerability*

The vulnerability of individual crops depends mainly on their water requirements. On the one hand, in drought-prone karst landscapes, crops with high water requirements are particularly vulnerable. On the other hand, sites with high water tables are less susceptible to drought and therefore more suitable for crops with higher water requirements. Providing water through irrigation is not realistic due to high investment costs and conflicting water interests of different groups. There are two additional issues related to the vulnerability of agriculture. First, the water supply for livestock in mountain areas, which may also be reduced in the future due to climate change, makes them particularly vulnerable compared to livestock in other parts of Austria. Second, the dependence of mountain farms on forests, which are also affected by climate change, makes mountain farming more vulnerable than in other areas of the country where this dependence does not exist. Conversion of land from agricultural use to alpine tourism to mitigate losses has been proposed as a solution but has been rejected by farmers (Wanner et al., 2021).

## Energy

This section describes the specific role of the Alps in the energy system. For more information on the overall energy system and its transformation, see Section 4.5. The Alpine region plays an important role in Austria's energy supply, mainly through electricity generation from hydropower reservoirs and pumped storage, run-of-river hydropower and wind power plants in exposed locations.

Solar power is currently less developed at higher altitudes, although there are potential benefits for the overall energy system from increased winter solar generation in the mountains compared to lower altitudes (Kahl et al., 2019; Đukan et al., 2024) (see Section 4.5.2). Hydropower pumped storage and reservoir power plants are located exclusively in Alpine regions due to the topographic requirements of storage power plants. Run-of-river hydropower plants are scattered throughout the country. However, the Alpine regions have a cascading effect on almost all hydro run-of-river hydropower plants in Austria due to the high water inflow resulting from the topographic setting, which determines their importance for the local and downstream hydropower utilization (Fatichi et al., 2015). In 2019, about 9 % of the installed wind power capacity in Austria was located in the Austrian Alps, with two-thirds of them located above 1,400 m a.s.l. (Austrian Wind Energy Association, 2019; APG, 2024). The majority of Austrian Alpine wind power plants are located in Styria (Austrian Wind Energy Association, 2019).

The literature base on renewable energy potentials for the Austrian Alps is limited. At the NUTS2 level, data availability is higher, with an approximation of the Alpine region in Austria using the states of Carinthia, Styria, Salzburg, Tyrol, and Vorarlberg. These federal provinces account for about 19–46 % of the technical wind potential (European Commission and Joint Research Centre (JRC), 2021; Kakoulaki et al., 2021), 39 % of the technical solar power potential, 40 % of the technical biomass potential (European Commission and Joint Research Centre (JRC), 2021), and 64 % of the technical hydropower potential, with the electricity demand of this area only accounting for around 37 % of Austria (2019) (Kakoulaki et al., 2021). In addition to the flat agricultural lowlands in northeastern Austria, remote locations in the Alps host the majority of Austria's wind potential (Brudermann et al., 2019). Generally, most of the wind potential in the Alpine federal provinces is located in non-alpine areas. However, if only the alpine areas in those federal provinces are considered, exposed sites offer the best wind potential (Ciolli et al., 2015). One third of Austria's theoretical Alpine wind power potential is located in protected areas, and the potential outside of protected areas is mainly at relatively low altitudes (Balest et al., 2015).

The sustainable potential for renewable energy in the Alps is limited by the consideration of conflicting interests such as nature conservation (Balest et al., 2015) and economic activities in tourism (Brudermann et al., 2019). The potential wind power plant sites in the Alps are sparsely populated or uninhabited, so conflicts with residential structures are less pronounced than in the lowlands (Brudermann et al., 2019). However, wind turbines at high altitudes mean increased visual intrusion at longer distances, which can lead to reduced acceptance (Kraxner et al., 2015) and conflicts with nature conservation management strategies and recreational activities such as hiking, skiing or cycling, for locals and tourists (Brudermann et al., 2019). A quarter of the total theoretical potential for wind and solar power generation in the Alps in general is located in Natura 2000 areas (Balest et al., 2015). The wide range of protected areas means different administrative and management regulations, with different levels of allowance for renewable energy expansion, which must fit within the management objectives of the protected areas (Kraxner et al., 2015). These facts highlight the potential conflicts that may arise from the expansion of renewable energy production in the Alpine region and that need to be considered in climate change mitigation and adaptation measures.

Electricity from the Alpine area is largely supplied to the neighboring urban areas due to the higher concentration of electricity demand (Kakoulaki et al., 2021). The energy demand in Alpine regions differs from other parts of Austria in that tourism is more important and snow management plays a significant role in the energy demand of certain regions (see Section 7.4.2). This has implications for the energy demand profile, such as seasonality or concentrated peak demand corresponding to the ski season. From a tourism perspective, there is a growing demand for energy for tourism infrastructure, especially for ski resorts and large wellness facilities, as well as for charging electric vehicles of visitors/tourists at the destination. However, the acceptance by tourists, who expect pristine tourism landscapes, is rather low, especially when alternative destinations are available (Broekel and Alfken, 2015). They would prefer small-scale solutions using existing infrastructure (Jiricka-Pürrer et al., 2019). Therefore, the trade-off for tourism destinations is rather difficult.

### *Effects of climate change*

A potential impact of climate change on energy supply from the Alpine region could occur through reduced precipitation as snow, recurrent droughts, and water scarcity (see Section 7.3). The effects of climate change are expected to lead to a change in the annual production of renewable energy and to changes in seasonality (see Section 4.6.2). The effects of climate change on biomass, which is mainly relevant for the heating sector (see Sections 3.3 and 4.5.2), are described in Section 7.4.2.

### *Mitigation*

Transforming the energy system towards a climate-neutral system is a key requirement for mitigating climate change. Due to the current potential for renewable energy production and storage in the Alps, this region can make a significant contribution to these efforts. The aim of the Alpine

Convention is to make a long-term contribution to meeting Europe's energy needs while limiting the negative effects of power plants on the environment and the landscape (European Union, 2005). Specific challenges for renewable energy expansion and operation in Alpine areas are steep slopes and a lack of connectivity to electricity and road networks (Kraxner et al., 2015).

Alpine regions can support the renewable energy transition, especially by providing flexibility to the overall electricity system through hydropower (pumped storage), which helps integrating high shares of highly volatile renewable energy sources into the energy system (see Section 4.6.2). Austria's topographical situation is an advantage in this case, as hydropower (pumped storage) can support the security of the energy supply in Austria as well as in the European interconnected electricity system.

For mutual benefits, it is important to consider the compatibility of biodiversity conservation and climate change mitigation through renewable energy use which has been demonstrated in best practice examples (Brudermann et al., 2019). It is unclear how sensitive the attractiveness of tourist destinations is to the installation of large-scale energy production facilities. Surveys show high levels of opposition, especially to wind turbines and large biomass or photovoltaic plants. Existing research suggests a trade-off between sustainable energy supply and tourism product development (Jiricka-Pürrer et al., 2019) (*limited evidence, high agreement*). Whether and under what conditions guests' attitudes toward sustainability will change in the long term is an open research question.

*Adaptation*

Climate change affects energy supply and demand and poses risks to infrastructure, making it important to consider these factors in adaptation of the alpine energy system (see Cross-Chapter Box 1). Possible hazards for Alpine energy infrastructure include glacier retreat, permafrost reduction, heavy precipitation and thunderstorms (Pröbstl-Haider et al., 2020b). In addition to the general trends of climate impacts on energy systems (see Section 4.6.2), the energy infrastructure in the Alps is confronted with rockfalls and rock and snow avalanches. Melting glaciers have a dual impact on local renewable energy production. First, the challenge of steep slopes for alpine (energy) infrastructure may be exacerbated by slope instability due to glacier melt (see Section 7.4.1). Second, local hydropower generation will be altered in terms of total production and seasonality which will then have cascading downstream effects on the entire energy system (Wagner et al., 2017; Schöniger et al., 2023; Wechsler et al., 2023). Adaptation strategies can increase the adaptive capacity of water governance and management systems (Maran et al., 2014). Hydropower plant design discharge optimization can partially compensate for climate change-related power generation losses, with greater design optimization potential in summer than in winter (Wechsler et al., 2023). However, the overall adaptive capacity of alpine hydropower systems to climate change is assessed as being rather low (Anghileri et al., 2018; Soomro et al., 2024), especially in catchments dominated by ice melt (Anghileri et al., 2018).

*Vulnerability*

Concerning hydropower, there is *low agreement* in literature as to whether climate change impacts lead to an increase or decrease of total generation, with a strong dependence on the climate scenarios chosen and significant geographical differences (see Section 4.6.2). The majority of currently available studies project a small decrease in the national mean annual hydropower potential by the end of the 21st century (for different GWLs) (Kranzl et al., 2010; Blöschl et al., 2011a; Eitzinger et al., 2014), with more recent climate models and scenarios showing a slight increase (Formayer et al., 2023) (*medium evidence, low agreement*). Wagner et al. (2017) predict a range of average annual changes in electricity generation in the Alps between +5 and -8 % for the period 2031–2050 in different scenarios/GWLs compared to no climate change impact. Wechsler et al. (2023) find a decrease of annual run-of-river generation in the Swiss Alps of about 2–7 % by the end of the century. The impact of climate change on run-of-river hydropower production depends strongly on the elevation of the hydropower plants with production increasing for higher elevated power plants (Wechsler et al., 2023) (*limited evidence, medium agreement*).

There is a *high agreement* in the literature on a seasonal shift of hydropower production from the summer to the winter season with increasing climate change (see Section 4.6.2) due to changes in precipitation/snowfall and earlier runoff due to warmer spring temperatures (see Section 1.4.1) (*medium evidence, high agreement*). This pattern is even more pronounced for the Alpine region than to Austria as a whole (see Figure 7.6). The projected seasonal shift in hydropower generation corresponds to the projected increase in mean and low winter flows in the Alps (see Section 1.4.1). The projected decrease of hydropower potential in summer and increase in winter has been shown for the entire Alpine region (Wagner et al., 2017), the Austrian Alps (Blöschl et al., 2011a; Formayer et al., 2023; Schöniger et al., 2023), and the Swiss Alps (Finger et al., 2012; Wechsler et al., 2023). A decrease in summer hydropower potential in mountain regions by about 2–22 % is expected (Blöschl et al., 2011a; Eitzinger et al., 2014; Wechsler et al., 2023) (*limited evidence, medium agreement*). For specific periods, a decrease of up to 70 % was found in the summer months of July and August for warm-dry periods by 2050 compared to 1961–1990 (Wagner et al., 2017). For Alpine winter run-of-river generation, an increase of 4–9 % by the end of the century is reported (Wechsler et al., 2023).

Figure 7.6 compares the hydropower generation from run-of river-power plants in the Austrian Alps and all of Austria for the periods 1971–2005 and the 20-year period up to GWL 3.0°C, according to the considered climate scenario (Formayer et al., 2023; Schöniger et al., 2023). The monthly mean production for the periods 1971–2005 and GWL 3.0°C is compared with the mean generation of the entire period 1971–2005. Although weaker and stronger GWLs are not shown in the figure, they do show the same trend.

(Pumped) storage power plants are expected to face these developments robustly, as their storage capacities buffer runoff fluctuations (Haas et al., 2008; Kranzl et al., 2010; Maran et al., 2014). However, the impact of glacier melt on the operations of reservoirs is still an open research question. For run-of-river hydropower power plants, climate-induced changes in hydrological regimes may require operational impairments and increased attention to structural and operational impacts of flooding (Habersack et al., 2011) (*low confidence*). Potential changes in sediment potential and transport dynamics further exacerbate the already existing challenges related to sediment management strategies at hydropower reservoirs (Habersack et al., 2011) (*low confidence*).

## Tourism

### *Effects of climate change and vulnerability*

Alpine regions account for 53 % of overnight stays in Austria during the summer season and 70 % during the winter season (Burton et al., 2024), making them the most important sub-sector of tourism in Austria. At the same time, tourism contributes a significant share to regional domestic products,

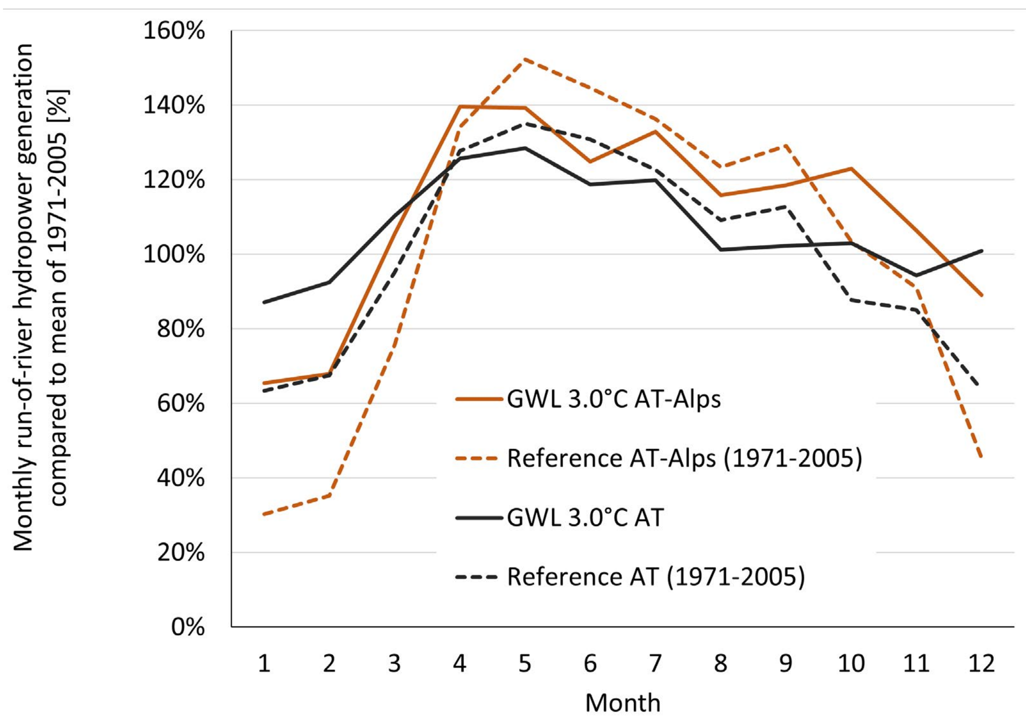


Figure 7.6 Changes in the mean run-of-river hydropower generation for the Austrian Alps and whole Austria for 1971–2005 and GWL 3.0°C (Source: Based on SECURES project runoff calculated by E-hype driven by RCP 8.5 RCM RACMO22E (KNMI, Netherlands) and GCM EC-EARTH (ICHEC, Ireland), see Formayer et al. (2023) and Schöniger et al. (2023)).

e.g., 19.7 % including indirect effects in the federal province of Tyrol (Fritz et al., 2021), and is the backbone of the regional economy in many rural Alpine municipalities (Steiger and Scott, 2020). As most tourism products in alpine tourism are dependent on natural resources (Steiger et al., 2020), climate change can have far-reaching consequences. While direct impacts refer to a change in the natural resources necessary for specific activities and tourism types (e.g., snow for skiing), indirect impacts refer to changes in landscape aesthetics (e.g., due to land use changes, shifting tree line, loss of glaciers) (Pröbstl-Haider et al., 2021). Snow- and ice-based forms of tourism are projected to face a higher risk of discontinued operation (Steiger et al., 2021a). However, the remaining regions that still provide reliable snow and ice conditions (whether due to natural or artificial snow and ice) could gain a competitive advantage as these resources become scarcer, which could even result in increasing tourism demand and pressure on tourism development (Steiger and Scott, 2020; Steiger et al., 2021a) (*high confidence*). In summer, the Alpine region is likely to benefit from the heat islands in the pre-Alpine area and urban areas, potentially stimulating summer tourism (Weber et al., 2017). In addition, summer tourism could benefit from warmer and more stable weather conditions, especially during periods of low demand such as the spring and fall months (Pröbstl-Haider et al., 2021). However, many summer tourism activities such as climbing, fishing, kayaking, hiking, and all types of aviation sports are affected by an increasing number of hot days and changes in the flow regime of alpine rivers (Pröbstl-Haider et al., 2021). Recent research reports an increasing safety risk on alpine trails due to thawing permafrost, heavy rainfall and thunderstorms (Pröbstl-Haider et al., 2020b) (*limited evidence, high agreement*). Human health problems (such as heat stress, allergies from neophytes, and deterioration of the water quality in lakes) are likely to increase in the Alps, but will occur less frequently than in the lowlands, representing a comparative advantage (Pröbstl-Haider et al., 2021).

There is a high likelihood that the costs for restoring and maintaining the extensive hiking and climbing infrastructure will increase (Pröbstl-Haider et al., 2021). The maintenance of this infrastructure is currently mainly in the hands of alpine NGOs. The demographic change on the one hand, and the increasing need for restoration and maintenance of the Austrian trail system in the mountains on the other hand, will require new adaptation strategies with significant financial support. Otherwise, the trail network which is the backbone of any kind of summer tourism will lose its current high quality and reliability. Exposure to dangerous situations could increase in the absence of professional monitoring (Pröbstl-Haider et al., 2016). For summer ski tourism, a strong decline between 2002 and 2019 was observed (-48.3 % in the summer half-year) (Mayer and Abegg, 2024). However, climate change impacts on glaciers and summer snow only explain part of this development, as societal trends (declining interest in summer skiing) also play an important role (Mayer and Abegg, 2024).

*Mitigation*

The biggest lever for reducing GHG emissions from tourism is mobility (see Section 4.3.3). Although rough estimates for tourism-related GHG emissions exist at the national level (Neger et al., 2021), there is a lack of more detailed monitoring of emissions at the subnational level that takes into account destination-specific factors such as the place of origin of tourists, the structure of the accommodation sector and the main tourist activities (high vs. low energy consumption). Opportunities to reduce GHG emissions in the tourism sector in the Alps differ from those in non-alpine areas in several ways:

Public transport to tourist destinations has been enhanced in several mountain regions in recent years, for example with night train connections from major source markets, such as Germany. While the German Railway (DB) discontinued its night train service in 2016, the Austrian Federal Railways (ÖBB) has very successfully taken over some of DB's connections and has since expanded them to other European markets; more high-speed train connections and more frequent public transport at the destination level (Gühnemann et al., 2021). However, in order to achieve a relevant shift from the car to public transport, the tourism sector depends on the tourists' willingness to consider alternatives to their usual mobility choices (for details, see Section 7.4.3). The greatest potential for reducing emissions in the lodging sector lies in improving the building structure (insulation), energy efficiency measures (room temperature, hot water use) and lighting (Energieinstitut der Wirtschaft GmbH, 2012). In Austria, the energy demand for heating buildings will decrease while energy demand for cooling buildings will increase as climate change continues (Prettenthaler et al., 2008; Dowling, 2013; Berger et al., 2014a). The net balance is estimated to be zero (Berger et al., 2014b) or even negative (i.e., decreasing energy demand) (Prettenthaler et al., 2008). Taking this into account, it can be concluded that the energy demand for the accommodation sector in Austria's mountain regions will rather decrease, since in many destinations there will be no need to cool buildings due to the higher altitude and therefore lower temperatures, and less heating of buildings will be required.

Providers of infrastructure for tourism activities can reduce GHG emissions by purchasing and/or producing green energy, increasing the share of lower emission fuels in the fleet, or promoting public transportation to/from the attraction. Ski resorts are one of the main providers of infrastructure for tourism activities in mountain regions. Ski resorts can purchase green electricity, and produce their own green electricity with wind, photovoltaics and hydropower facilities (the latter sometimes in combination with snowmaking infrastructure) (Steiger et al., 2021a). Certification (ISO, EMAS, Österreichisches Umweltzeichen), sustainability and energy concepts, support the transition in winter tourism (Pröbstl-Haider et al., 2018). A ski resort in Salzburg (Snow Space Salzburg Bergbahnen) is testing e-fuel snow groomers which have the potential to reduce emissions by up to 90 % (Umwelt Journal, 2023). The same ski resort is incentivizing public transportation by offering free transportation within the federal province when a lift ticket is purchased online (Snow Space Salzburg, 2024).

Significant potential for GHG emission reduction also lies in the composition of the countries of origin of the visitors. Although far-away source markets such as China account for only a small share of overnight stays (2.2 %), their share of tourism-related emissions is disproportionately high (18.5 %) (Neger et al., 2021). The number of overnight stays from long-haul source countries increased before the pandemic, and is expected to increase in the coming years (Lehner-Telič, 2024). Therefore, demarketing strategies for long-haul source markets could slow down demand growth and associated GHG emissions.

*Adaptation*

Snowmaking in ski resorts is commonly regarded as a climate change adaptation strategy although Steiger and Mayer (2008) showed that the underlying reasons for investing in snowmaking are multifaceted. Nevertheless, snowmaking provides an opportunity to sustain ski operations in a warming climate (Steiger et al., 2022). The amount of natural snowfall and the duration of snow cover have been decreasing in recent decades and will continue to do so in the future (see Section 1.3.1). For Austrian ski resorts, Steiger and Scott (2020) show that the season length with natural snow will decrease from 80 days in the reference period (1981–2010) to 63 days (GWL 1.8°C), 44 days (GWL 2.6°C) and 19 days (GWL 4.3°C). With snowmaking, ski seasons would be 125 days long in the reference period, 120 days (GWL 1.8°C), 111 days (GWL 2.6°C) and 84 days (GWL 4.3°C). More relevant than the average shortening of the ski season, however, is the share of ski resorts with reliable snow conditions. While in the reference period (1981–2010), 99 % of the ski resorts in Austria can be considered technically snow reliable (i.e., considering modern snowmaking systems), this share decreases to 93 % (GWL 1.8°C), 80 % (GWL 2.6°C) and 31 % (GWL 4.3°C). However, despite shortened ski seasons, a substantial increase in water for snowmaking is required: 33 % (GWL 1.8°C), 60 % (GWL 2.6°C) and 73 % (GWL 4.3°C) (Steiger and Scott, 2020). Some Austrian ski resorts will therefore have to find alternative solutions for increasingly difficult winter operations, as it may no longer be technically possible to provide sufficient snow cover in some locations.

Another adaptation measure is to consolidate the existing ski area by concentrating ski operations and related infrastructure to reduce costs and operate more efficiently. In a ski area in Lower Austria, a part of the ski area was closed, and the snowmaking infrastructure was transferred to the remaining ski area, increasing the snowmaking capacity of that part (Scherrer and Begert, 2019; Redl, 2024).

In addition, a decrease in the size of large glaciers, as well as the disappearance of Austria's small and medium-sized glaciers is expected (Helfricht et al., 2019; François et al., 2023) (see Section 1.3.2). In the short to medium term, shrinking glaciers may provide some potential for increased demand, so-called 'last-chance tourism'. However, as noted by Mayer et al. (2024b), this may not be an appropriate long-term strategy. Adaptation options for summer skiing include the cessation of summer skiing operations and shifting to excursionists and technical adaptation measures such as geotextiles to reduce snow and ice melt, and depot snowmaking to ensure the opening of the ski season in the snow-scarce fall months (Mayer and Abegg, 2024).

Broadening the winter offer to include activities that are also possible without snow, will become increasingly important. It can also be used to address leisure trends. The proportion of winter-holidaymakers whose main activity is winter hiking increased from 3 to 13 % between 2012 and 2018 (Steiger et al., 2021a). In principle, a range of summer activities can be extended to the (snow-free) winter. For example, during the extremely snow-poor Christmas holidays of 2022/23, mountain bike trails, summer toboggan runs, and motor skills parks were reopened in some Lower Austrian ski resorts (NÖN-Redaktion, 2023).

Strengthening the summer season can reduce dependence on the winter operations. Many destinations are already successful in this respect, as shown by the stronger growth in overnight stays in recent summer seasons. Escaping the heat may provide some potential for summer tourism in alpine areas (Juschten et al., 2019). However, daily spending by guests in winter (EUR 205 on average) is still significantly higher than in summer (EUR 163) (Österreich Werbung, 2023). Although the number of tourists could be increased, social and ecological impacts could be exceeded and should therefore be considered in adaptation strategies.

*Vulnerability*

Compared to urban tourism, the vulnerability of alpine tourism is significantly higher, as many destinations are still dependent on winter tourism. However, the importance of summer tourism has increased in mountainous areas reducing the dependence on snow over time (Pröbstl-Haider et al., 2021). Currently, the additional income in summer does not compensate for the losses in winter, as tourist spending is 25 % higher in winter than in summer and therefore the total value added is likely to be different as well (Burton et al., 2024). For summer tourism, increasing risks from natural hazards (e.g., by thawing permafrost and glaciers) and maintenance of the hiking infrastructure are significant challenges.

Family firms, which make up the majority of tourism businesses in the Alps, have to cope with competitive disadvantages that include poor economies of scale and scope, minimal potential for diversification and innovation and limited access to capital markets. Therefore, this structure is perceived as very fragile and less resilient due to the small company size, low growth rates, weak internationalization, relatively low market entry barriers (allowing fewer professional entrepreneurs to enter the market), limited potential for diversification, high debt-to-capital-ratios and limited qualification levels (Zehrer and Mössenlechner, 2009; Pikkemaat and Zehrer, 2016). This structural weakness could lead to significant economic impacts, if many of these family businesses were to go out of business due to climate change. Economic vulnerability is therefore higher in the Alpine region than in the lowlands of Austria. In the Alps, alternative employment opportunities outside of tourism and agriculture are limited.

### 7.4.3. The Alps as home to communities

#### Demography and settlements

*Effects of climate change*

Changes in demography and land use are mainly driven by socio-economic factors. Currently there is no evidence that climate change significantly influences demographic changes as well as allocation and distribution of settlements and infrastructure in the Austrian Alps. Conversely, it is evident that demography and existing settlement structures influence GHG emissions mainly through the associated energy and mobility demand (Stöglehner et al., 2016a; Stöglehner and Abart-Heriszt, 2022; Haberl et al., 2023) (*medium evidence, high agreement*) (see Section 3.2.2). Furthermore, demography, settlement and built infrastructure influence the potential exposure to climate-related impacts, such as heat waves (Oleson et al., 2015; GeoSphere Austria, 2022) and various natural hazards (Cammerer et al., 2013; Fuchs et al., 2015b; Löschner et al., 2017; Junger et al., 2022) (*high confidence*).

The regional divide in population development in the Austrian Alps (see Section 7.2.2) will continue to increase, as will the unbalanced intra-regional population development between the main valley areas on the one hand and the side valleys and peripheral locations on the other hand. Population forecasts at the district level until 2050 largely confirm and extend these trends for the coming decades (Österreichische Raumordnungskonferenz, 2023c). Household forecasts at the district level until 2030 indicate an increase in households in the vast majority of the Austrian Alpine districts (Österreichische Raumordnungskonferenz, 2024). The development of households is more strongly correlated with settlement development (resulting in further land take) than with population development. A decrease in average household size is projected for all Alpine districts (Österreichische Raumordnungskonferenz, 2024).

Based on these demographic trends, an increase in building, land use and infrastructure can be expected in growth areas, particularly in the already densely populated urban centers and ribbon-like settlement structures in the valleys and, depending on the development of tourism, also in tourism resorts with distinct urban characteristics. Whether the expansion of built-up land also takes place in scattered settlement areas with low densities, depends primarily on spatial planning policy (e.g., the willingness to regionally restrict settlement development to central locations), since a decline in the population and a slight increase in the number of households do not necessarily lead to a stagnation in the expansion of build-up land. There is no confirmed evidence whether and to what extent climate change is currently influencing these demographic and land use trends. Prolonged heat waves and their impacts on densely built-up urban areas (predominantly outside the Alps) could increase the attractiveness of currently sparsely populated Alpine areas as residential locations in the future, leading to an increase in population and building land uses there (Membretti et al., 2023). A substantial reduction in the intensity of winter tourism due to rising snowlines could lead to a population decline in Alpine tourist resorts (Steiger et al., 2021b).

Land competition in Alpine valleys is likely to intensify (see Section 3.2.2). This will put additional pressure on open spaces and the various ecosystem services they provide. Whether increasing settlement development in the valley areas will lead to an increase in GHG emissions, depends on how additional development is coordinated through spatial planning and the extent to which increasing mobility demands can be met by public transport. Increasing land use and population densities influence exposure to climate-related impacts (*medium evidence, high agreement*).

Comparable to the whole country, the share of older people (aged 65 and over) in the Alpine region is projected to increase (Österreichische Raumordnungskonferenz, 2023c). This development is most pronounced in Alpine regions, which are confronted with a significant population decline. It eventually leads to increased vulnerability to extreme weather events, particularly to heat waves (Hutter et al., 2007; Haas et al., 2014) (*high confidence*).

Finally, it should be noted that socio-economic development is based on complex interrelations. Related trends are therefore non-linear. Single, even minor causes may have largely unpredictable far-reaching consequences.

*Mitigation*

Density, together with the implementation of other spatial planning principles such as compactness and mix of spatial functions, urban redevelopment rather than greenfield development, and coordination of development with public mobility services (Jabareen, 2006), are crucial for energy demand, renewable energy supply (e.g., by district heating systems) and public transport systems. In contrast, low-density development and urban sprawl contribute substantially to an increase in energy consumption and motorized private transport and, thus, to an increase in GHG emissions (Stöglehner et al., 2016b; Stöglehner and Abart-Heriszt, 2022) (*high confidence*) (see Section 3.2.2).

Some spatial framework conditions in Alpine areas, particularly in densely populated urban centers and ribbon-like settlement structures in the valleys, potentially provide favorable conditions for climate change mitigation. Limited development space and higher land prices provide incentives for higher density housing and, thus, land-saving development (Österreichische Raumordnungskonferenz, 2021, 2024). Topography, limited development space and accessibility reasons (large transport infrastructure in valleys) lead to a concentration of commercial and industrial development in the valley areas. Both densification effects can be regarded as supportive of efforts to reduce GHG emissions (*limited evidence, high agreement*).

Without appropriate regional planning regulation, the development of peripheral settlements and scattered housing structures as well as decentralized tourism projects (e.g., chalets, holiday residences) carries the risk of low-density development and urban sprawl (Meyer and Job, 2022), which contributes to land take, requires substantial infrastructure efforts and increases motorized individual transport and related GHG emissions. Urban redevelopment and concentration of settlement development in local and regional development centers on the one hand, and limiting development in scattered housing areas on the other, are spatial planning strategies that support climate change mitigation (Stöglehner and Abart-Heriszt, 2022) (*high confidence*). The unbalanced population development trends in the Austrian Alps provide opportunities to concentrate development in locations that are favorable in terms of energy demand, renewable energy supply and public transportation. Related trade-offs with rural development strategies should be considered.

*Adaptation*

Aiming at higher compactness in settlement development is regarded a key issue for climate change mitigation, however, trade-offs with the provision of sufficient open spaces (including those required for climate change adaptation) and potential increased exposure to heat stress and natural hazards need to be considered (see Section 3.2.3). Population development trends in the Austrian Alps are likely to result in higher settlement densities in urban centers and ribbon-like settlement structures in the valley areas. Additionally, limited development space and high land prices put pressure on open spaces making it more difficult to implement nature-based options for adaptation to climate change (Schindelegger et al., 2022).

The need for adaptation to heat stress is likely to increase in densely built-up areas, exacerbated by an ageing population. However, urban heat islands not only depend on building density and the degree of sealing, but also on topography and climate. In particular, the supply of cold air from forests, agricultural areas, urban green spaces, and other fresh air corridors is important. In alpine areas, warm nights are less frequent than in the lowlands due to the nocturnal flow of cold air down the slopes into the valleys (Gerersdorfer et al., 2009). As Schöner and Haslinger (2020) point out, temperature extremes will play a comparatively minor role at altitudes above 800 m a.s.l. (Schöner and Haslinger, 2020). At altitudes below 800 m, temperature extremes have increased in recent decades and will continue to increase in the future. The altitude range below 800 m includes all urban centers and densely built-up ribbon-like settlement structures in the Austrian Alps (*medium evidence, high agreement*).

Whether settlement development and, especially densification, affects the need for adaptation to natural hazards depends on the location of the development and whether current and potential future hazard zones can be avoided. Due to the topography, limited development space and accessibility reasons, building and infrastructure densities and, thus, potential exposure to natural hazards are high in Alpine valley areas (Fuchs et al., 2015b). This is particularly the case for areas with a lower hazard intensity where development is not restricted by spatial planning regulations (Nachtnebel and Apperl, 2015; Löschner et al., 2017) (*high confidence*). With regard to river floods, for example, a damage potential of EUR 357 million was calculated for a 20 km stretch in the Lower Inn Valley in Tyrol in the event of a 100-year flood. In the case of a 300-year flood, the corresponding damage potential is EUR 736 million (Bundeswasserbauverwaltung Tirol, 2016; Blöschl, 2020). If flood hazards are exacerbated by the effects of climate change, this would result in further adaptation needs, particularly in urban centers and ribbon-like settlement structures. Stagnation or population decline usually do not result in a reduction in built-up areas. It is therefore likely that adaptation needs regarding natural hazards are also relevant for other Alpine settlements. In particular, the tradition of scattered housing outside the valleys has led to an extensive rural road network connecting (former) single farms to the main transport infrastructure in the valleys, which is considerably exposed to natural hazards such flash floods or landslides (*limited evidence, high agreement*).

Alpine settlements and their development, including associated infrastructure, are highly dependent on the functioning of protective forests. Climate change impacts challenge their stability, mainly by windthrow, infestation by bark beetles or wildfires (Vacik et al., 2020). These impacts are likely to influence long-term hazard exposure of settlements and infrastructure (Schindelegger et al., 2022) and may result in further adaptation needs (*limited evidence, high agreement*).

#### *Vulnerability*

There is no confirmed evidence that climate change impacts are currently influencing the number and distribution of people and building land uses in the Austrian Alps. Related changes are solely triggered by socio-economic factors. Population and household projections indicate a further increase in building land uses (settlements and infrastructure), particularly in the main valley areas of the western Austrian Alps, which will most likely lead to increased land competition and further pressure on existing open spaces. This is likely to lead to increased exposure to natural hazards and reduced scope for adaptation to climate change. These effects are less pronounced in most of the valleys of the eastern Austrian Alps as well as in areas with low settlement densities. Spatial and temporal variability leads to differentiated vulnerability patterns.

### Mobility and transport infrastructure

#### *Effects of climate change*

Mobility in the Alpine region is characterized by the overlapping of the everyday and leisure mobility of the (local) population, the arrival and departure of tourists and their on-site mobility (including day trips from neighboring (urban) regions) and tourists passing through (passenger transit). Likewise, the goods traffic of the local economy and supply overlaps with long-distance freight transit traffic. The following figures demonstrate the extent of this overlap. In Tyrol in 2022, the prominently discussed truck transit accounted for about 2.56 million trips per year (Land Tirol, 2023). In the tourism sector, there were about 11 million tourist arrivals, leading to 22 million arrivals and departures in that year (Statistik Austria, 2023b), while the local population made about 1.25 million car trips per day (Köll and Bader, 2022; Land Tirol, 2023). Due to the topographical conditions in the valley, the transport network does not offer any alternatives so that this overlapping takes place on the few main roads and leads to corresponding (temporary and seasonal) congestion and negative effects, e.g., through noise and emissions, on the population in the densely populated valleys, but also in the adjacent hillside locations (*high confidence*).

The spatial pattern of the Alpine region also leads to special characteristics of everyday and leisure mobility. Due to the high density in the central valleys, the shares of walking and cycling are comparatively high (Tomschy et al., 2016). There is also an expectation that climate change will increase the popularity of cycling, which is currently very seasonal. However, there are no reliable findings on this in the literature. On the other hand, long supply and commuting routes in peripheral valley locations are (or have to be) covered by motorized transport. This also leads to high traffic loads and congestion at the valley entrances (e.g., Zillertal Brettfall Tunnel, outer Ötztal). The valley locations have comparatively good, linear public transport connections. However, the quality of service is poor in peripheral locations, where regular service is not economically justifiable (*medium evidence, high agreement*).

Tourist mobility in the Alpine region also has special characteristics. Arrivals and departures are predominantly by car (over 80 % in winter and summer), the share of rail is relatively low at approximately 6 % (e.g., for Tyrol) (Bursa et al., 2022). Relevant winter air traffic comes from more distant source markets to regional airports (Innsbruck, Salzburg, Klagenfurt) and nearby major airports (Munich, Zurich). Although the tourism sector is of great importance for the national economy with a share of 7.6 % of the gross domestic product (in 2019 including direct and indirect effects) and even higher shares in the Alpine regions (e.g., Tyrol 16.9 %, Salzburg 13.7 %; according to Statistik Austria (2021)), it is largely unknown how much emissions the Austrian tourism sector causes. Neger et al. (2021) attribute this mainly to the fact that most products and services consumed by tourists are not exclusively related to tourism. They provide an estimate based on available data with a destination-based accounting approach that includes not only emissions within Austria but also those caused by international guests traveling abroad. They estimate the total emissions of the tourism sector in Austria at 4.31 Mt$CO_2$eq, which is a share of 4.2 % of the total emissions in Austria. Of this, 92.2 % of $CO_2$eq is attributable to travel. As they note, this high share is mainly due to air travel by international guests. In alpine tourism, however, this share is significantly lower, with more than 80 % of the guests arriving by car. Accordingly, in a case study of a Tyrolean destination (Alpbach), Unger et al. (2016) determined the share of transport in tourism emissions to be 54 %. Studies show that holidaymakers are well aware of the high $CO_2$ emissions associated with vacations but that they indicate a low willingness to change their behavior significantly in this regard (less frequent but longer vacations, closer destinations, no air travel), thus creating an awareness–behavior gap (Mailer et al., 2019).

The transport infrastructure is characterized, on the one hand, by the fact that there are only a few efficient routes or connections in the main valleys (transit areas). When the motorways become congested, traffic increasingly tries to use the less efficient parallel rural roads, causing high levels of congestion in the settlement areas. Recently, this has been countered by banning motorway exits forcing passing vehicles to stay on the motorways. Due to the topography, railways are only present in a few side valleys. On the other hand, transport infrastructures in Alpine regions are particularly exposed to natural hazards (rockfall, debris flows, snow avalanches), which require protective structures (it should be noted, that roads and railways are already more expensive to build and maintain due to the higher demand for artificial structures such as bridges and tunnels) and there is still the risk of temporary closures that restrict the accessibility of valleys. In addition, there is increased operational effort (winter service, maintenance of railway lines with narrow bends, etc.) (*high confidence*).

Population growth is leading to an increase in everyday and leisure mobility. Tourism also continues to focus on growth in the number of guests and overnight stays. Attempts to promote rail travel have not yet yielded the desired results. Shorter stays are also leading to a disproportionate increase in arrivals and departures.

While in the 1970s, guests in Austria spent on average just under 7 nights (for guests from abroad), or 6 nights (for domestic guests) in holiday accommodation, this number has now been reduced to just under 3.5 or 2.8 overnight stays (BMLRT, 2020), in line with international trends in length-of-stay (Gössling et al., 2018). Correspondingly, the number of arrivals at accommodation establishments in Austria tripled as the number of overnight stays increased by 50 % (Statistik Austria, 2019a, 2019b). This means that the intensity of travel has increased and that there is a greater overlap of arrival and departure traffic with local traffic, even on weekdays. Travelers' demands for flexibility and speed of the available means of transportation have increased significantly, in order to keep the travel time as short as possible and to spend as much time as possible at the destination. This favors the private car as the mode of transport of choice and poses major challenges for destinations that rely on climate-friendly travel (Gronau and Kagermeier, 2007).

By 2019, the number of guests from more distant growth markets had been increasing, which is also reflected in the growing number of passengers at airports near tourist destinations (e.g., Innsbruck). These markets have an above-average share of arrivals and departures by air, which also has an increasing impact on GHG emissions (Zech et al., 2013; Peters et al., 2016) (*high confidence*).

Restricting freight transit traffic is contrary to the demands of neighboring countries and the principle of free movement of goods and people in the EU. Even with great efforts (Brenner Base Tunnel), with current measures, a shift to rail seems to be limited to absorbing not much more than the increase in freight traffic. A higher shift can only be reached with additional powerful policy measures (BCP – Brenner Corridor Platform, 2021). Efforts to increase tourist traffic in the southern neighboring countries such as Italy/South Tyrol, Slovenia and Croatia will result in an increase in passenger transit (*high confidence*).

The impact of climate change on tourism has already been addressed in Section 4.3.3. This has particular implications for Alpine regions. Changing climatic conditions can alter travel and thus mobility behavior of tourists. For example, a lack of snow in some areas and a shorter winter season, can lead to higher numbers of visitors in a shorter timeframe, to tourists traveling to more snow-reliable but also more distant winter destinations in the inner Alps, or to tourists switching to other non-snow holiday destinations (e.g., the Canary Islands), which involves a switch of transport mode (from car to air) and increases travel distance. Changes in travel behavior and thus mobility behavior can also be seen in the summer season. Hot summers, in particular, drive city dwellers to the surrounding areas and nearby alpine destinations, and short summer breaks are becoming increasingly important (Cavallaro et al., 2017; Thurm et al., 2017; Juschten et al., 2019; Juschten and Hössinger, 2021) (*high confidence*).

Climate change also increases the potential for some natural hazard types to affect infrastructure (see Section 7.4.1), thus, increasing the vulnerability of transport relationships (accessibility and mobility). Increasing traffic flows and dependence on motorized (long-distance) transport will also increase this effect. In alpine regions, the expected rise in temperature is likely to have ambivalent effects on the infrastructure. On the one hand, roads will require less effort in terms of frost resistance and spring thaw. On the other hand, higher surface temperatures require higher quality materials. The same applies to railways, where the mountain routes are characterized by narrow curves, and where rising temperatures have a stressing effect and increase the risk of buckling, while less snow leads to less maintenance and operational effort and related emissions (snow removal, prevention of icing) (*medium evidence, high agreement*).

The supply of transport services can be affected by potential climate impacts. In particular, extreme weather events such as heat waves, extreme rainfall, and storms can severely restrict traffic flow and disrupt operations. But also associated hazards, triggered by events such as landslides and floods, can lead to significant damage to the transport infrastructure and disrupt traffic flows and logistics (Stahel et al., 2013; Cavallaro et al., 2017). In this context, adaptation measures are needed to strengthen the resilience of the transport systems through improved traffic management in the event of a crisis, as well as to adapt the infrastructure to ensure (not only, but in particular) the accessibility of tourist destinations (Gühnemann et al., 2021) (*high confidence*).

*Mitigation*

Avoid/shift/improve strategies and the potential of virtual mobility (see Sections 3.4.2, 3.4.3, 3.4.4) have to be considered regarding the special conditions in the Alpine region. For decarbonization, e.g., through alternative drives, there are special requirements due to the topography and the (winter) climate regarding e-mobility and the charging infrastructure due to the massive tourist travel flows and the need for on-trip charging (*medium evidence, high agreement*).

A significant reduction of travel-related GHG emissions in tourism cannot be solely achieved with technological solutions (electric vehicles) or trends (sharing); it also requires shifts in transportation patterns, such as increased use of rail and public transport over air and private road travel. Similarly, rail travel can be supported by improving on-site mobility and services along the entire travel chain (from pre-booking information to return). Due to the mentioned awareness and behavioral gap among tourists, this calls for measures that not only offer incentives (fast and direct train and bus connections, climate-friendly local transport, luggage services, attractive all-inclusive packages, etc.), but also focus on closer rather than distant home markets, encourage longer stays, and offer awareness campaigns for local stakeholders and tourists, as well as push and pull strategies (*high confidence*). Several case studies show significant effects of improving public transport services (e.g., free arrival by train) (Blättler et al., 2024) or local mobility services at the destination such as bus services and mobility hubs (BMNT, 2017; Bursa et al., 2024). The awareness created by

COVID-19 and the climate crisis can be seen as an opportunity to take appropriate measures (Gühnemann et al., 2021) even if current developments clearly indicate that there is a risk of falling back into old patterns.

*Adaptation*

There will be a need to increase resilience by upgrading and protecting transportation infrastructure against natural hazards, but also in the context of spatial planning that strengthens local supply (amenities) and thus local mobility. This is also important to ensure escape routes and supplies in the event of natural hazards. Developing emergency plans and strategies can help enhance preparedness and response efforts. When protecting the infrastructure, it is important to remember that the constructional measures themselves have a climate impact. These rebound effects can be minimized through careful selection of construction methods and materials (*medium evidence, high agreement*).

In order to keep public transport as an attractive offer both for arrivals and departures as well as for local mobility, the following measures from the adaptation strategy (BMNT, 2017) are also relevant in response to increasing heat days: (i) Ensuring thermal comfort by reducing the thermal loads in transport stations and their surroundings; (ii) Reducing possible thermal loads for passengers and staff in public transport through appropriate air conditioning (*limited evidence, high agreement*).

*Vulnerability*

In the Alpine regions, natural hazards can restrict the mobility of the population and the accessibility of places for daily needs, as there are often no alternative routes due to the limited space. The remoteness and lack of redundancy of the road network make the Alpine region particularly vulnerable. On the other hand, the expansion of protective measures for transport routes is associated with significant $CO_2$ emissions (*high confidence*).

## 7.5. Needs for resilient mountain regions in Austria

In mountain areas in general, most existing adaptation measures (structural and non-structural) are reactive rather than proactive to climate change and are often part of a post-disaster recovery strategy (McDowell et al., 2021) (*robust evidence, medium agreement*). Although many adaptation measures have been adopted in Austria, specifically for mountain regions, there are still gaps in effective adaptation. To close these gaps, transformative adaptation in different sectors is needed in mountain regions (McDowell et al., 2021) (see Section 7.5.2). However, as suggested by Salim et al. (2021), coping and incremental approaches are also needed, in addition to transformative adaptation approaches. For this reason, the section on adaptation and mitigation needs in the Austrian Alps is structured as follows: Monitoring (7.5.1), (socio-economic) transformation (7.5.2), non-structural protection measures and nature-based solutions (7.5.3), and structural measures (7.5.4). The adaptation options for mountain areas in Austria are presented in Table 7.1, according to the ASI principle (Avoid, Shift, Improve; see Cross-Chapter Box 4).

### 7.5.1. Monitoring of natural processes/hazards and provision of climate services

Continued and improved monitoring of environmental conditions and processes (e.g., climate, hydrology, glacier and permafrost changes, natural hazards) may serve as a basis for information on climate adaptation. Climate model scenarios for the Alps are still subject to high uncertainties (Section 7.3.2), especially for precipitation. Climate services of the same quality for mountain regions, as for the rest of Austria, must be advanced in regional climate modeling for the Alpine region (e.g., convection-permitting models). Monitoring of runoff and sediment dynamics of alpine rivers needs to be further improved, especially in torrent catchments that have not been monitored to date and pose a significant hazard potential and risk to the built environment (this includes also monitoring of soil properties, e.g., water storage capacity and carbon stock). Monitoring of hazardous conditions in tourist areas (e.g., hiking trails) could be used to better inform tourism stakeholders and tourists about potential risks. Moreover, monitoring and management of invasive species (Permanent Secretariat of the Alpine Convention, 2019) can support the conservation of Europe's high mountain biome. In terms of biodiversity, monitoring of species shifts, and changes in abundance and growing seasons could be beneficial. Additionally, it is important to monitor biodiversity changes of different organism groups (e.g., plants but also animal groups and soil organisms). Monitoring and mitigation of natural forest disturbances (wind, fire, pests) may also support adaptation to climate change. Monitoring of permafrost and erosion and their short- and long-term effects (Permanent Secretariat of the Alpine Convention, 2019) is also important for the assessment of changing risks to infrastructure in high alpine terrain (huts, alpine routes, ski lifts). Generally, an improved and denser monitoring network for hazard triggers and hazard processes could improve monitoring results.

According to the WMO, early warning systems (EWS) are a top priority for climate change adaptation and could be a valuable tool for disaster risk reduction in Austria's alpine region. According to Pappenberger et al. (2015), there are significant monetary benefits related to early flood warnings in Europe. Specifically, for every EUR 1 invested in early flood warning, there is a benefit of EUR 400. According to the same source, the avoided damage due to early flood warning may reach 32.85 % of the total damage. While the drivers of natural processes such as temperature and precipitation have been affected by climate change, there is still *limited evidence* that this has affected the number of natural hazards occurring in mountain areas. However, there is *high confidence* that the exposure in mountain areas has increased (Fuchs et al., 2015b, 2017). In view of the particularly strong changes in the frequency and intensity of hazard processes due to climate change, it may be beneficial to reconsider the current delimitation criteria for hazard zones (avalanches, debris flows, floods).

## 7.5.2. Transformation

Several mountain areas in Austria are characterized by climate change-related impacts (e.g., reduced snow cover), land use changes as well as other societal and structural problems, and require a significant change based on holistic analyses and awareness of the interrelated challenges. In other words, transformation is required in several sectors.

More specifically, as far as **agriculture** is concerned, adaptation measures in mountain areas may be related to transformation. Some of them are not directly related to climate change (hidden adaptation, e.g., organic farming), but to other challenges (e.g., changing agricultural policies and market conditions) (Grüneis et al., 2016). However, some hidden adaptation actions, which include measures such as long-term learning processes, self-organization, local knowledge, and adaptive governance, may be more effective. Transformation could include the cultivation of non-traditional crops, the transformation of consumer demands (consumption of local products) as well as the energy efficiency of farms (Permanent Secretariat of the Alpine Convention, 2019). In addition, shifting agricultural land upwards and improving soil properties could also contribute to adaptation (see Section 7.4.2). With regard to **forests**, the conversion of forest ecosystems to include endemic species that have been adapted to climate change (Permanent Secretariat of the Alpine Convention, 2019) as well as a shift from single tree types to multiple tree type forest could support adaptation to climate change (see Section 7.4.2). Nevertheless, the choice of tree species is often highly controversial. Regarding **tourism**, transformative adaptation measures may include alternative hiking routes and season shifting with mixed results (Adler et al., 2022) but also the promotion of activities that can be carried out without snow, the extension of summer activities in winter and the strengthening of the summer season (see Section 7.4.2). Finally, the expectation that the Alps will benefit from a shift of tourism from the Mediterranean to the Alps, due to high temperatures, is not supported by the existing literature, although the modeling of tourism demand in Europe showed that it is expected to decrease (under different climate change scenarios) for southern Europe while tourism demand for northern Europe is expected to increase (Matei et al., 2023). Further, since tourism requires energy, the transition to green fuels and investments in hydrogen drives, sustainability and energy concepts could support adaptation. Decision-making tools have been developed for other locations in the European Alps to support ski resorts in the assessment of their energy demand and provide them with information on available renewable energy resources (Polderman et al., 2020). Moreover, a transition in the accommodation sector (e.g., improving infrastructure efficiency, behavioral changes, greening energy production and carbon off-setting) would be beneficial since it is a substantial contributor (10 %) to total GHG emissions from the tourism sector. Improving infrastructure efficiency alone can reduce 15–20 % of emissions from the accommodation sector (EY Parthenon et al., 2021). However, financing can be a challenge, especially in small resorts. In addition, minimizing the carbon footprint of alpine hotels and gastronomy (regional products) should be an aim (Permanent Secretariat of the Alpine Convention, 2019). Ski areas can purchase green electricity to reduce $CO_2$ emissions from lift operation and snowmaking. For slope grooming, emissions can be effectively reduced by using alternative forms of propulsion (e-drive) or fuels (e.g., HVO) (Steiger et al. 2021a). In the energy sector, alongside efforts to improve energy efficiency and savings across all areas, there is potential for expanding renewable energy and decentralizing its production (Permanent Secretariat of the Alpine Convention, 2019). The **built environment** in the Austrian Alps also needs to be transformed to adapt to the effects of climate change, including the avoidance of new development in hazard-prone areas and the adaptation of the existing building stock. Regarding mitigation, spatial planning can be used to support the densification of existing settlement areas and guide new developments toward urban and regional centers (Section 7.4.3). In the **mobility sector**, mitigation measures could include the promotion of rail travel, on-site mobility with public transport and active transportation modes, climate-friendly local transport vehicles, a shift to short and medium distance source markets, and the provision of alternative or public transport options for tourists to and within Alpine destinations (Permanent Secretariat of the Alpine Convention, 2019). Adaptation could include a further expansion of information and early warning systems related to tourism and mobility, a functioning transport system, review/adaptation of legal standards for the construction and operation of transport infrastructure considering climate change, and ensuring thermal comfort within public transport and its surroundings (e.g., stations and stops) (Gühnemann et al., 2021).

### 7.5.3. Non-structural adaptation measures and nature-based solutions

River renaturation is crucial but there is also a need to focus on the decision-making context of nature-based solutions in the Alps, taking into account local climate projections (Dubo et al., 2022). With regard to biodiversity and ecology, more ecological connectivity projects are needed (Permanent Secretariat of the Alpine Convention, 2019). Examples of such projects already exist in Austria (e.g., project PORTAL, 'Pathways of Transformation in the Alps') (Observatoire des Sciences de l'Univers de Grenoble, 2024). Additional adaptation needs may include landscape preservation, avoidance, reduction and monitoring of soil sealing, improvement of soil quality and enhancement of the protective function of forests (Permanent Secretariat of the Alpine Convention, 2019). All of these should be supported by the appropriate legal frameworks. In protective forests, interventions such as thinning and regeneration cutting may support the coping capacity of forests (see Section 7.4.2).

To ensure effective implementation of adaptation measures, cost-benefit analyses, monitoring of adaptation plans, governance and participation as well as financing are needed, as is shown in the pilot program 'Climate Change Adaptation Model Regions for Austria – KLAR! (Klimawandel-Anpassungsmodellregionen)', which is funded by the Austrian Climate and Energy Fund. Transnational/transboundary cooperation could be emphasized, as well as communication among regions, countries, scientists, practitioners, authorities, and the public. Implementation requires giving high priority to adaptation, climate-proofing in all activities, initiating pilot actions, promoting international information exchange among mountain regions, monitoring of all actions, and enabling communication and cooperation among stakeholders (Scott et al., 2022). An example of this type of collaboration is the AlpEs ('Alpine Ecosystem Services') project, which aims to map, maintain and manage ecosystem services in several Alpine countries including Austria (Interreg Alpine Space, 2021). Finally, involving people in the adaptation decision-making process and addressing multiple rather than single risks (Terzi et al., 2019) lead to more robust adaptation strategies (Owen, 2020).

### 7.5.4. Structural adaptation measures

Although there is a trend to move from structural to non-structural measures, structural protective measures for the alpine infrastructure and settlements are still necessary. Grüneis et al. (2016) suggested that the focus is on technical adaptation measures, which may also be vulnerable to climate-related extreme events (e.g., power failure). Local structural protection mitigates hazards at low cost (Papathoma-Köhle et al., 2019) and building codes may help adapt buildings to climate change, but also improve the Build Back Better (BBB) after disaster recovery. Insurance incentives and improved risk transfer support recovery.

Climate-proofing hydropower is crucial. Future changes in flow and sediment dynamics may require a reconsideration of operational policies for existing plants, including adaptive water targets and sediment management. Cost-benefit analyses for renewals and new plants should take into account long-term effects of climate change on flow and runoff (Permanent Secretariat of the Alpine Convention, 2019).

Finally, maladaptation (adaptation measures that increase rather than reduce vulnerability) should be avoided. In this respect, cross-sectoral policies may be the solution as adaptation measures in one sector may increase the vulnerability of another sector (Alpine Convention Guidelines). For example, it is not clear whether artificial snowmaking in alpine ski resorts is a maladaptation (Roncucci, 2020), but there is potential to improve its performance, which will determine whether it can be considered a maladaptive or successful adaptation (Scott et al., 2022). According to Schinko et al. (2013), artificial snow can reduce up to 75 % of the economic impacts of climate change on winter tourism, but at the same time it increases production costs.

**Table 7.1** Adaptation options for the Austrian Alps presented considering the ASI principle (Avoid, Shift, Improve)

| Thematic area | Avoid | Shift | Improve |
|---|---|---|---|
| Climate change | Further $CO_2$ emissions through mobility and tourism in the Alps | Transitions in many sectors (e.g., mobility, tourism) to reduce further $CO_2$ emissions | Improve climate scenarios for the alpine space<br><br>Monitoring of atmospheric processes in the Alps |
| Natural hazards | Building in hazardous areas (considering variations due to climate change) | Reduce the vulnerability of the built environment and infrastructure to natural hazards by adapted design and local adaptation<br><br>River renaturation to reduce flood events | Monitoring of hazards and triggering processes<br><br>Risk transfer options (insurance) and incentives for local adaptation measures -Existing hazard mapping to include climate change<br><br>Local and regional land use planning |
| Biodiversity | Impacts of human land use (agriculture, energy production and tourism development) on biodiversity | Improvement of spatial planning | Monitoring of biodiversity changes in the Alps<br>Collaboration with nature conservation authorities to design management strategies<br><br>Public awareness about the risk of losses<br>Preservation of larger and better-connected areas to mitigate losses of alpine ecosystems |
| Forestry and agriculture | New development that could have negative effects on protective forests | Non-native species more resilient species to climate change (debatable)<br>From single species strands to mixed species strands<br><br>Introduction of non-traditional crops<br>Shift in consumer demands and preferences | Preservation and restoration of protective forest<br>Financial support for the managers of protective forests<br><br>Biological soil properties by nitrogen-fixing plants, the addition of organic material, and water conservation by a cutting height of at least 8 cm to tackle drought in the agricultural sector<br>Irrigation of crops |
| Buildings, infrastructure and mobility | New development of energy inefficient buildings and infrastructure<br>Reduce the need to travel (e.g., digitalization) | Shift from private car to public transport or non-motorized vehicles<br>Adapt building stock to withstand natural hazards | Insulation of buildings (also relevant for the thematic area 'energy')<br>Redundancy in the road network<br>Improve the energy efficiency of vehicles |
| Energy | Impact from natural hazards on energy infrastructure | More green sources of energy (also relevant for the 'tourism' thematic area) | Acceptance of renewable sources of energy from the tourism sector |
| Tourism | Old practices that encourage further $CO_2$ emissions (e.g., non-green electricity for powering ski lifts and snow making machines, diesel-powered slope preparation)<br><br>Destruction of carbon sinks for new touristic development | Find employment alternatives through the economic strengthening of regional centers<br>Identification and development of alternative tourism products<br>Promote sustainable destinations<br>Promote alternative transport modes (see transport) | Make existing infrastructure energy efficient (e.g., energy efficient hotels) |

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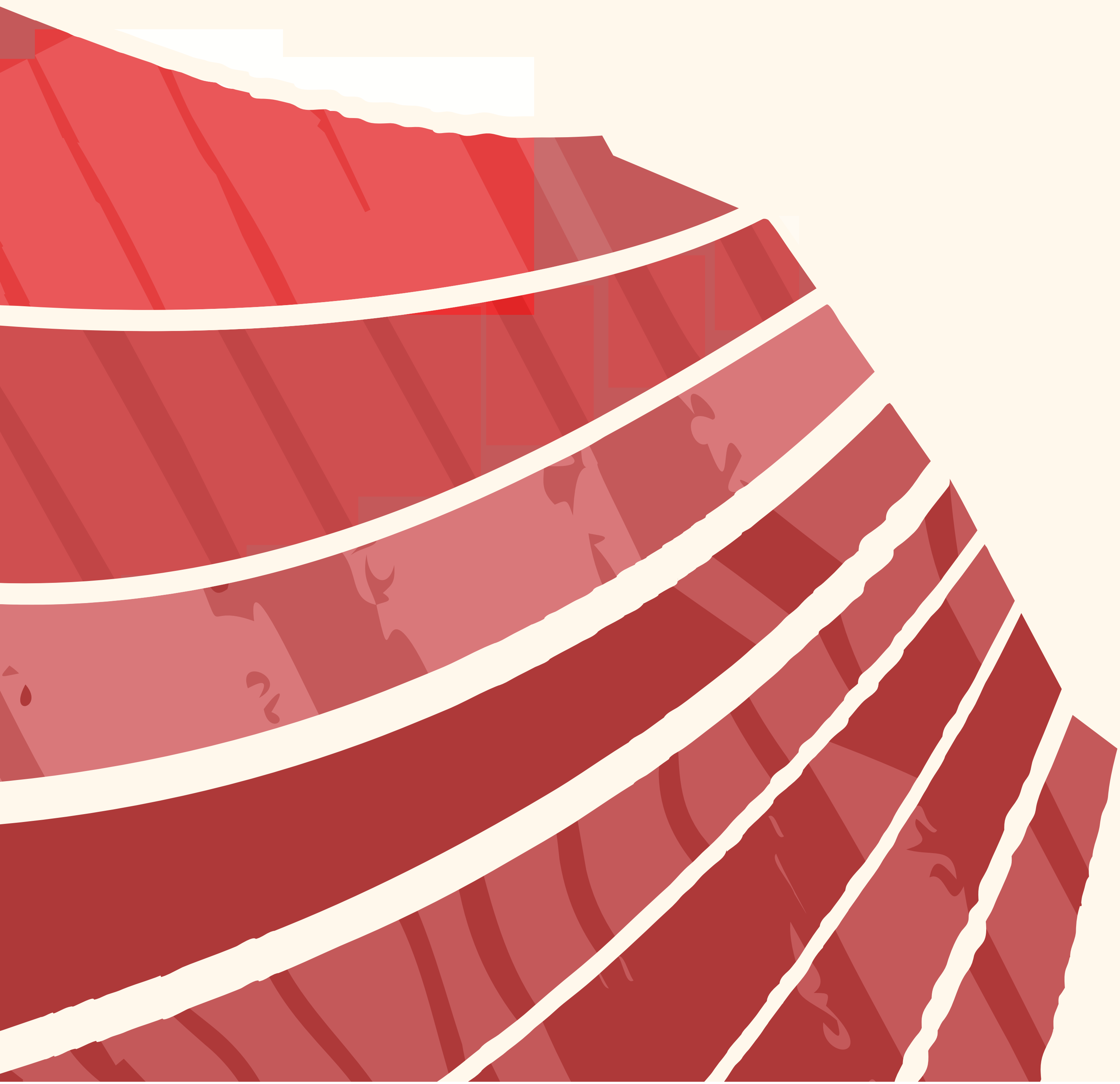
## Chapter 8

# Transformation pathways



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## Chapter 8
## Transformation pathways

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## EXECUTIVE SUMMARY

**Climate-friendly transformation pathways are trajectories for the pursuit of a good life for all within planetary boundaries and integrate mitigation and adaptation strategies as well as efficiency and sufficiency measures. These pathways draw on narratives that highlight the everyday benefits of climate action and the costs of inaction (*robust evidence, medium agreement*).** As such, climate-friendly transformation pathways integrate the reduction of both direct and indirect emissions to achieve climate neutrality, enhance resilience to climate change impacts through adaptation, and ensure decent living standards. Science-based, plan-led climate policy that underpins these pathways combines bundles of measures that merge insights from a technology-centered eco-modernist, and a sufficiency-oriented system change perspective, with their varying problem diagnoses and policy approaches. Such an integrated approach tends to be more effective than singular approaches due to mobilizing a greater range of available policy tools. Strategic autonomy as well as reduced vulnerabilities and fossil fuel import dependencies can be achieved by lowering demand through sufficiency and avoid-measures. For a long-term transition towards climate-friendly living, it is essential to limit the power and influence of incumbent interests that have diluted regulations. In the short and medium term, improving everyday living conditions by facilitating adaptation to change is crucial (e.g., living cost reducing measures like the climate bonus, repair bonus, and climate ticket). Important are initiatives with co-benefits. Examples are promoting human and planetary health, e.g., by supporting dense settlement structures that provide local access to retail, care, and leisure facilities while also reducing soil-sealing and car-dependency (*high confidence*). {8.6.1, 8.6.2, 8.6.3, 8.7, Table 8.3}

**Climate-friendly transformation pathways strike a balance between incremental and disruptive changes (*robust evidence, medium agreement*).** Relying solely on incremental measures, especially those that focus narrowly on technology and efficiency, constitutes a form of climate delay, as such measures alone are insufficient to achieve climate targets. Climate-friendly transformation pathways require policy-mixes that integrate incremental and disruptive measures and combine broadly accepted actions (e.g., green spaces and public transport expansion) with less popular approaches (e.g., dismantling soil-sealing structures like asphalt parking spaces) (*robust evidence, medium agreement*). {8.6.1, 8.6.2, 8.6.3, 8.7, Table 8.3}

**Austria's remaining carbon budget to stay within global targets of 1.5°C or 2°C is nearly (and by some estimates already) depleted, especially when responsibility for historical emissions and other fairness concerns are considered (*medium evidence, high agreement*).** Meeting international obligations to stay within such limits requires Austria to rapidly decarbonize its economy and implement all measures aligned with achieving carbon neutrality by 2040. A depleted carbon budget necessitates costly participation in international assistance and compensation schemes. {8.2.2, 8.4.5, Figure 8.18}

**Mitigating climate change can contribute towards the achievement of the Sustainable Development Goals (SDGs), though different mitigation options vary in terms of their synergy and trade-off potential. Demand-side reduction options appear more beneficial for the achievement of SDGs compared to supply-side options (*medium evidence, high agreement*).** Across all assessed mitigation scenarios, synergy potentials outweigh trade-offs. However, the extent to which synergies or trade-offs are realized, both within Austria and beyond, depends on the specific measures adopted and their implementation strategies (*high confidence*). {8.3.1, 8.4.5, Figure 8.4, Figure 8.17}

**Costs and potentials of mitigation options indicate that electrification, paired with the decarbonization of the electricity supply, as well as demand-side reduction measures are key for Austria to achieve carbon neutrality in 2040 (*medium evidence, high agreement*).** Among the assessed mitigation options, electrification of the transport, industry, and building sectors offers a significant greenhouse gas (GHG) reduction potential, provided it is accompanied by decarbonizing the electricity sector through renewable energy sources (*high confidence*). Reducing final energy demand and directly cutting GHG emissions are also necessary, though their potential has only been partially assessed for Austria (*high confidence*). {8.3.2, Figure 8.5}

**From a technological and economic standpoint, achieving climate neutrality in the Austrian energy system by 2040 is feasible if unprecedented rates of change in the evolution of the Austrian energy system are realized – along with significant transformations in the associated institutional, regulatory, and legal frameworks (*high confidence*).** Current and planned policies fail to achieve carbon neutrality by 2040. Reducing final energy demand through efficiency improvements and changes in service demand, is thus indispensable for reaching climate neutrality in Austria. The extent of the required demand reduction varies across assessed scenarios, ranging from -8 to -36 % by 2040 compared to 2021 levels. Strong differences are thereby applicable in final energy demand for transport and industry. {8.4.2, Figure 8.6, Figure 8.9, Figure 8.10}

**All assessed scenarios that achieve climate neutrality of the energy system share key technological characteristics – but show differences in the technology uptake by 2040 and beyond (*medium evidence, high agreement*).** A common feature across scenarios is increased electrification, ranging from 29 to 76 % by 2040 compared to 2021, alongside a high share of renewables in gross domestic consumption. Wind and solar PV form the backbone of the electricity supply in all scenarios for meeting the growing demand. Biomass and hydropower are additional key technology options, though their expansion potential is limited. Renewable gases, such as hydrogen, biomethane, and synthetic fuels, play a role in decarbonizing industrial processes, certain transport modes (air and ship), and, to a limited extent, the electricity sector. Their deployment by 2040 varies across assessed scenarios, ranging from 106 to 322 PJ/yr. Carbon Capture, Utilization, and Storage (CCUS) appears necessary to counterbalance residual emissions, specifically in industry, due to the absence of other viable technological mitigation options. Alternatively, sufficiency measures may also help mitigating residual emissions in other sectors like agriculture. According to the assessed scenarios, Austria's energy supply continues to rely on imports, particularly for hydrogen, ranging from 8 to 36 % of gross domestic consumption by 2040. This marks a significant decline from today's import dependency, which ranges from 52 to 75 %. {8.4.3, Figure 8.11, Figure 8.12}.

**Achieving carbon neutrality by 2040 requires additional annual investments ranging from 1.1 to 1.9 % of GDP or a total of $EUR_{2023}$ 6.2 to 10.9 billion. These investments are below the expected monetized annual costs of inaction of $EUR_{2023}$ 7.3 to 14.6 billion, especially when considering the multiple climate change impacts that have so far not been expressed in monetary terms (e.g., injuries and deaths due to extreme weather events). The required investments are furthermore expected to have positive impacts on employment, income and wealth distribution, as well as on overall economic welfare (*medium confidence*).** The limited number of estimates available on additional investment needs in energy supply, infrastructure, storage, and other sectors (buildings, transport, industry) suggest that these investments can serve as drivers of production and employment. {8.4.4, Figure 8.14, Figure 8.15, Figure 8.16, Table 8.1}

**Immediate actions are needed to overcome the inertia in key sectors and to achieve both 2030 and 2040 climate policy targets (*high confidence*).** Current and planned policies in Austria are not sufficient to achieve the 2030 climate policy targets imposed by EU regulation. The recently amended EU Effort Sharing Regulation, comprising smaller GHG emitters that are not controlled by the EU Emission Trading Scheme, requires urgent action to reduce GHG emissions specifically in the transport and building sector. The urgent implementation of far-reaching mitigation measures is also necessary for achieving Austria's long-term GHG commitments: All assessed mitigation scenarios show similar trends concerning demand reduction and the uptake of renewable energies until 2030. This helps to overcome the inertia in the energy system and other provisioning systems (mobility, housing, food, etc.). {8.4.2, 8.4.3}

**If political goals, such as increasing geopolitical security and short-term competitiveness, fail to account for climate impacts and equity concerns, Austria will not meet its national climate targets or fulfill international obligations (*high confidence*).** Integrating climate policies that transform the provisioning of mobility, housing, food, health, care and leisure within broader sustainable development policies, can help overcoming the policy silos of mitigation and adaptation. Enlarging the policy space is important to better plan transformations. Innovative, democratic, and multi-level governance models can support climate policy integration to better scale up innovations, such as renewable energy expansion, and foster exnovations, such as phasing out combustion engines (*medium confidence*). {8.5.1, 8.6.1}

**Democratic policymaking can increase the probability of meeting long-term climate targets by integrating individual measures that currently lack societal support into policy-mixes that lead to benefits for everyday life (*medium confidence*).** Such a strategy can become feasible in a democratic setting if disadvantages for actors (e.g., bureaucratic costs and inconveniences) are minimized, as societal and political acceptance of climate measures often increases after implementation – thus legitimizing ambitious climate actions ex post. Democratic policymaking can also choose to align with prevailing societal preferences and obtain political support by reducing public investments and avoiding regulations, thereby, however, implicitly accepting the likelihood of unmet climate targets. {8.6.1, 8.7}

## 8.1. Introduction

Building on the previous chapters, which primarily explored the broader physical manifestations of climate change in Austria (Chapter 1) and sector-specific impacts and mitigation potentials (Chapters 2–6), **Chapter 8** adopts a systemic and integrative approach to assess transformation pathways that align with national and European climate targets (Section 6.3). It comprehensively assesses the Austrian scenario landscape and embeds national mitigation efforts in broader biophysical, socio-economic, and socio-cultural contexts. Mitigation targets are expanded to align with the overarching goal of **climate-friendly living**, which is defined by the APCC (2023) as a good life for all within planetary boundaries. This concept encompasses both the mitigation of emissions to achieve **climate neutrality by 2040** and the adaptation to climate impacts to promote **climate resilience**. It thereby encompasses changes in the way of living, working and producing.

Section 8.2 departs from an overview of the planetary boundaries, focusing on the crises of biodiversity (Section 8.2.1) and climate change (Section 8.2.2). It provides a carbon budget analysis, examining Austria's remaining carbon budget for limiting global average temperature rise to 1.5°C and 2°C. Section 8.3 integrates, synthesizes, and assesses mitigation options in terms of their broader implications for achieving the Sustainable Development Goals (SDGs) (Section 8.3.1) as well as potentials and costs (Section 8.3.2). Section 8.4 reviews existing mitigation scenarios for Austria and assesses them based on (i) key scenario properties, such as emission trajectories, energy demand and investment needs (Sections 8.4.2, 8.4.3, 8.4.4), and (ii) the scenarios' interactions with and contributions to the SDGs, as well as their alignment with carbon budgets under different fairness criteria (Section 8.4.5). Section 8.5 focuses on the political, economic, and socio-cultural conditions that are critical for realizing climate friendly transformation pathways, as these factors can either hinder or enable effective climate action. In what follows, Section 8.6 extends the assessment by exploring the socio-cultural and politico-economic feasibility of transformation pathways, with the aim of widening the policy space for transitioning towards a climate-friendly future. It critically assesses two ideal-typical pathways, each based on different limited perspectives, and examines their potential for transitioning to a climate-friendly transformation pathway that meets both mitigation and adaptation targets. Finally, Section 8.7 links policy-relevant insights from the assessment of scenarios and transformation pathways, thereby illustrating how policymakers can use multi-perspectivity to improve their respective value- and interest-based decisions.

## 8.2. Biophysical limits and carbon budgets

The planetary boundaries framework draws upon Earth system science and identifies processes (such as $CO_2$ emissions, nitrogen and the land-use system) that are critical for maintaining the stability and resilience of the Earth system (Steffen et al., 2015). Section 8.2 therefore examines the biophysical framework of climate measures, focusing on two crucial policy fields that are at risk of trespassing planetary (systemic) boundaries. First, it undertakes an analysis of biodiversity loss in Austria. Second, it estimates the total emissions for Austria's remaining carbon budget to stay within 1.5°C and 2°C global average temperature rise. This is in line with the growing emphasis on distributing the global carbon budget among subsidiary entities, such as countries, to provide a basic benchmark. Based on this, more sophisticated analyses can be formed to specify feasible and detailed pathways. In fact, it is increasingly recognized that not the public commitment to a net zero emissions target year (e.g., 2040 for Austria) but the cumulative emissions up to that target constitute the greater challenge (CCCA, 2022). Biophysical processes are furthermore closely linked to socio-economic ones, as both affect the global opportunity structure and the biophysical boundary conditions.

### 8.2.1. Biophysical limits with respect to planetary boundaries

The concept of planetary boundaries is based on the finite nature of natural resources and sinks for wastes and emissions. Exceeding even some of these boundaries can have devastating consequences. For example, agricultural biomass production can lead to soil erosion and degradation, phosphorus and nitrogen runoff from overuse of fertilizers, and exceeding the boundaries of biogeochemical cycles and biodiversity loss. Therefore, economic structures and ways of living that enable society to live well within planetary boundaries are needed (Raworth, 2017).

Globally defined planetary boundaries can be specified at the level of individual countries and then compared with country-specific resource use footprint indicators (O'Neill et al., 2018). The analysis shows that Austrian consumption levels far exceed what is tolerable for the country's environment. The high $CO_2$ emission footprint extends far beyond the planetary boundary of climate change. Similarly, the recorded levels for phosphorus and nitrogen, which are used in large quantities in agriculture, exceed the defined pollution thresholds. **Austria's material and ecological footprint exceed the critical thresholds of the planet three- or fourfold.** In the case of land use, Austria is only slightly outside the acceptable limits, and only water use remains within the boundaries, primarily due to the large available water reserves in Austria. Translating planetary boundaries into targets that are relevant for policy and decision-making requires addressing their biophysical, socio-economic and ethical dimensions. This requires an ongoing, iterative dialogue and deeper collaboration between scientists and policy makers (Hoff et al., 2017).

One important social driver jeopardizing the feasibility of achieving climate targets and the objective of staying within planetary boundaries is consumption and the associated resource use. In Austria, consumption levels and the resulting resource utilization of production and consumption processes have an adverse impact on biogeochemical cycles and biodiversity patterns of global ecosystems (BMK, 2020). In relation to the planetary boundaries, scientific and political endeavors increasingly focus on enhancing capabilities for estimating the global impacts of national resource use

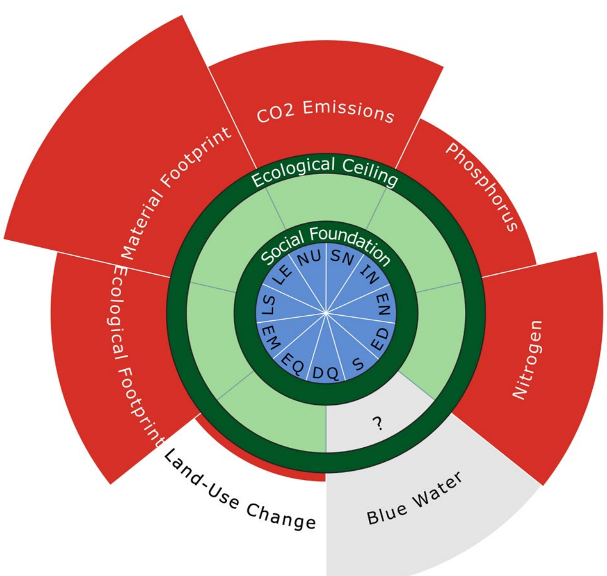



**Figure 8.1** Austria and the planetary boundaries (Fanning et al., 2022).

and to define acceptable limits at this scale (Rockström et al., 2009; Steffen et al., 2015). Fanning et al. (2022) analyze the historical dynamics of social and biophysical indicators across more than 140 countries from 1992 to 2015. Social indicators include, for example, life expectancy, nutrition, access to energy, and education. The ecological indicators downscale the three planetary boundaries of climate change, biogeochemical flows and land use change by applying different environmental footprint indicators (e.g., $CO_2$ emissions). The study demonstrates that **Austria is among the affluent countries with low social shortfall but high ecological overshoot** (Figure 8.1). In addition, it shows that the magnitude of the ecological overshoot in Austria has been increasing over the period 1992–2015, while social indicators have only hardly improved.

A plethora of measures exist to protect, sustainably manage and restore natural and modified ecosystems, many of which demonstrate co-benefits for climate change adaptation and mitigation, as well as biodiversity conservation (Smith et al., 2022). In addition to the Paris Agreement (Section 6.3.1), the EU is obliged to comply with the Kunming-Montreal Global Biodiversity framework, which was adopted at the Convention on Biological Diversity at the 15th Conference of the Parties in 2022. The most prominent targets include the restoration of 30 % of degraded ecosystems globally by 2030. Restoration refers to the process of halting the deterioration of ecosystems or reversing the effects of land degradation through activities such as reforestation, soil conservation and the protection of natural processes. The objective of these actions is to enhance biodiversity, recover ecosystem services and reduce the impact of climate change (Scholes et al., 2018). Austria is characterized by a considerable high diversity of landscapes, encompassing the Pannonian plains in the east and high alpine regions in the west, including wetlands and forest areas (Section 1.1). Consequently, it is one of the most species-rich countries in Central Europe. Human intervention, however, has been a significant factor in shaping Austria's biodiversity throughout history, particularly through agriculture, forestry, hunting, and fishing (Section 1.6.4). Among the main causes of biodiversity loss are habitat destruction, degradation, and fragmentation, in particular the sealing and fragmentation of landscapes due to human settlement and transport infrastructure expansion. Additional threats include the abandonment of traditional land use practices and the intensification of land use. According to BMK (2022), approximately one-third to half of all species are critically endangered.

### 8.2.2. Carbon budget analysis

The most directly relevant planetary boundary being transgressed regarding climate mitigation is the exceedance of the remaining global carbon budget. Such budgets are based on concepts from the physical sciences. The allocation of a global budget to regional levels, such as countries or sub-national regions, however, is a process driven by normative considerations (e.g., Friedlingstein et al., 2014; Pan et al., 2015; Rogelj et al., 2016; Millar et al., 2017; Xu and Ramanathan, 2017; Dooley et al., 2021; CCCA, 2022). Dividing budgets among subsidiary entities can be driven by any one, or a combination of, equity and fairness arguments (Caney, 2009; van den Berg et al., 2020). While a specific budget (or uncertainty range) may be feasible to determine at a global level, estimates of the remaining budget for Austria vary more widely and may change substantially due to different forms of emission accounting and allocation mechanisms at play (Steininger et al., 2022; Williges et al., 2022).

The means of accounting for emissions can lead to differing carbon budget allocations and emission reduction requirements. Several potential approaches exist, which can have different implications for countries when discussing the effects of their actions (i.e., production processes or consumption habits) on global mitigation efforts. The most common approaches are production- and consumption-based accounting. However, emissions could be attributed to the country that extracted the fossil fuels leading to the emissions (extraction-based), or to the countries that add value to a production process (income-based) recognizing that, e.g., labor and capital benefit from production-related emissions by earning income. Each approach implies a different perspective on the economy, agency, and responsibility for emissions (Steininger et al., 2016; Aigner et al., 2023e).

The primary framework used with respect to carbon budgets is production-based accounting. It follows a sector-based approach to measure emissions arising from production and consumption processes within the respective geographical borders and allocates them to the original producers such as industries, private households and public agents (e.g., 'source categories') (UNFCCC, 2009). Alternatively, consumption-based accounting measures emissions arising from a country's final demand (e.g., household consumption, government expenditures and capital accumulation through investment) along international supply chains. These emissions can be allocated to different consumption categories, thereby excluding territorial emissions from the production of goods and services that are exported. Since the production of emissions and the consumption of related goods and services occur in different regions, the two accounting frameworks tend to show different pictures of a country's GHG emissions (Steininger et al., 2018). Generally, **countries of the global North or high-income countries are net-carbon importers**. Consequently, their production-based are lower than consumption-based emissions. When using production-based distributions, these countries then have comparatively lower emissions levels (and thus, higher relative shares of a carbon budget) as compared to consumption-based approaches.

The **equity principles** underlying budget allocation to countries can also have a substantial impact on the mitigation effort required. Three broad equity aspects are relevant: (i) capability, (ii) responsibility and (iii) need (or equality) (Höhne et al., 2014; Williges et al., 2022). **Capability** considerations influence how a global budget is allocated by placing higher mitigation burden on those countries with the highest ability to pay or abate (Shue, 1999; Caney, 2009). Responsibility focuses on the 'polluter pays' principle by allocating higher mitigation burden to high-emitting countries (Gosseries, 2004). Finally, considerations of **satisfaction of need** focus on equality of opportunity, reduction of poverty, and focusing on those most vulnerable to climate change (Gough, 2015). Typically, budget allocation mechanisms use a combination of equity considerations, incorporating aspects of equality or need, historical responsibility and capability (Höhne et al., 2014; van den Berg et al., 2020; Steininger et al., 2022; Williges et al., 2022). Additional approaches to effort-sharing focus on equal marginal abatement costs, i.e., allocations arising from a global carbon price, or the idea of equal cumulative per capita emissions. In contrast to equality or equal cumulative per capita emissions, arguments have been made for convergence to equal per capita emissions at a future point in time (e.g., 'grandfathering'), which give some normative weight to the current unequal rates of emissions, which persists at a diminishing rate into the future (Williges et al., 2022).

Beyond the basic choice of equity principles employed, the manner in which these principles are interpreted and implemented can also have a large effect on the resulting budget (Steininger et al., 2022). This implies that there is not a single available carbon budget for a given temperature target for Austria. Rather, any result will be the product of a set of normative decisions as to what is deemed important when allocating a budget. Estimates for Austria do allow for drawing conclusions as to the likely range of the carbon budget left to achieve climate goals. Additionally, trends can be observed regarding how normative considerations and emission accounting choices affect the resulting budget.

Figure 8.2a illustrates historical Austrian emissions from 1995 onwards, differentiating between production- and consumption-based emissions to 2022, with 2022 to 2050 illustrating the range of possible emission pathways compatible with national carbon budgets derived from the literature. Such budgets correspond to either a 1.5 or 2°C temperature stabilization target, and take into account a range of historical responsibility, equality, and need considerations. As panel (a) shows, **consumption-based emissions consistently exceed production-based**, typically around 30 Mt per year. Given that most carbon budgets follow a production-based approach, considerations of consumption emissions could narrow future equity-compatible pathways even further. As it is, most budgets targeting 1.5 or 2°C would require net negative emissions at some point between now and 2050. A majority of budgets for the 1.5°C target would require overall negative budgets for the entire time period. As can be seen, the current WEM and WAM scenarios would not correspond to what the literature considers a fair allocation of a global carbon budget.

As noted previously, while a single budget estimate for Austria is incompatible with the normative concepts and their implementation when dividing the global budget, a range of estimates can be derived. Figure 8.2b depicts this range of estimated budget amounts in tons of $CO_2$ for two

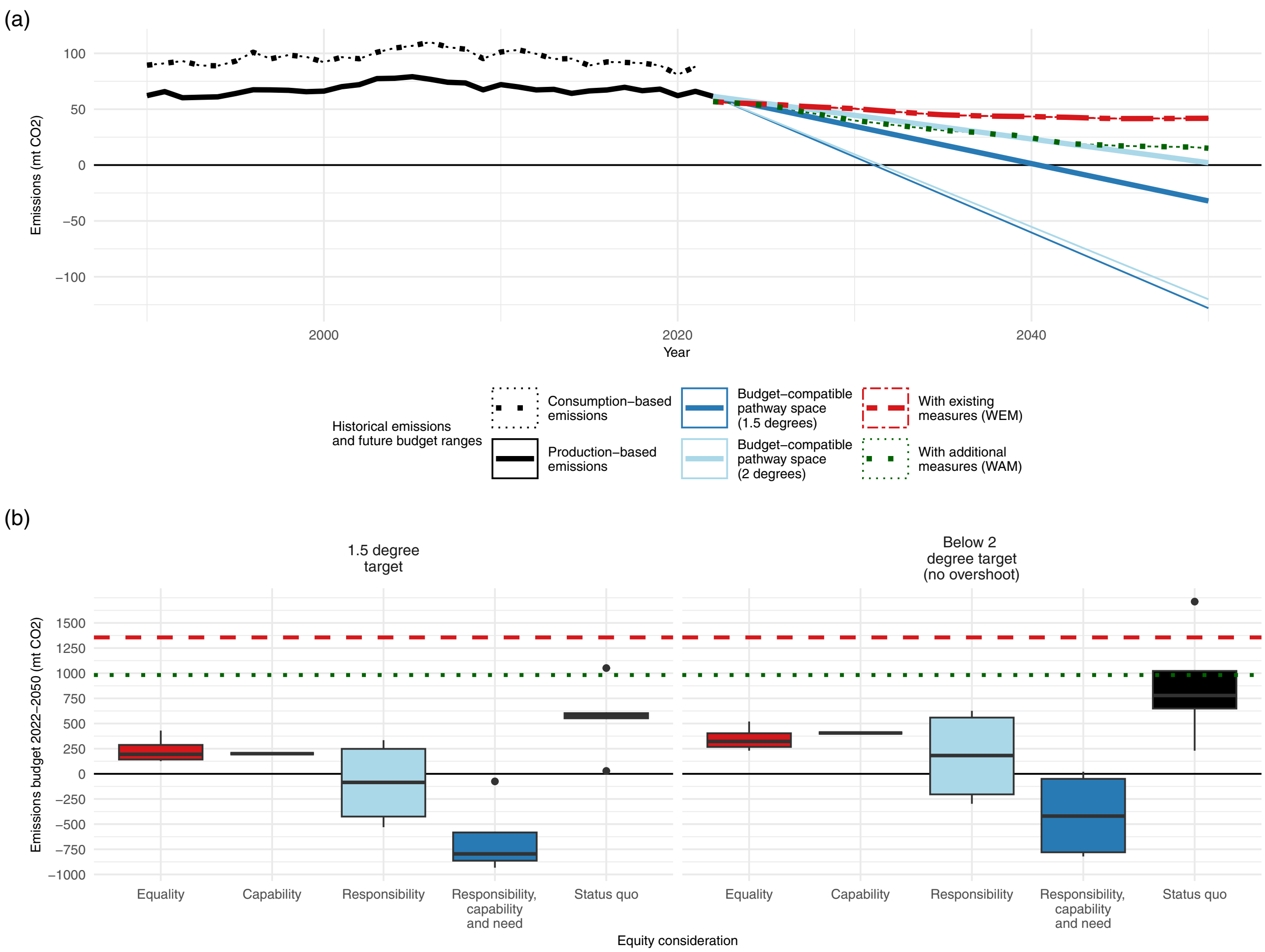



Figure 8.2 (a) Historical emissions and the range of future emissions pathways to 2050 (b) compatible with carbon budget allocations for 2022–2050. Panel (a) shows the difference in production- and consumption-based emissions from the period 1995 to 2022, and from that point forward the range of possible emissions pathways that would allow Austria to remain within a 1.5- or 2- degree compatible budget taking into account equality, capability, and responsibility considerations. The Environment Agency Austria's 'With Existing/Additional Measures' (WEM/WAM) scenarios are indicated, and do not align with fair allocations of a remaining carbon budget. Panel (b) indicates the range of such budgets, broken down by the major equity consideration driving the allocation mechanism, for both 1.5- (left) and 2- (right) degree global temperature targets, with the WEM and WAM scenarios again indicated by red dashed and dotted green lines (respectively) (Sources: Budget estimates: Robiou du Pont et al., 2017; Robiou du Pont and Meinshausen, 2018; CCCA, 2022; Williges et al., 2022; Territorial emissions: Friedlingstein et al., 2023; Consumption emissions: updated from Peters et al., 2012).

temperature targets: A 1.5°C target and a well-below 2°C target (66 % probability/no overshoot), with estimates derived from the literature on the allocation of global or regional (e.g., EU) budgets. Median values are represented by solid lines, while boxes represent values between the 25th and 75th percentile range, with whiskers indicating values within 1.5 times the interquartile range. Other values are depicted as points. Budgets are differentiated by the underlying equity considerations driving the allocation mechanism, in line with the categories mentioned above.

A report by the CCCA (2022) estimates the remaining carbon budget for Austria from 2022 to 2050 to be 240 Mt for a 1.5°C target (with 66 % probability) and 280 Mt for a 1.5°C target with overshoot (again with 66 % probability). This aligns with an equality approach to allocation, but it should be noted that this represents just one type of distribution mechanism. As Figure 8.2b shows, results can vary widely depending on the underlying equity considerations. Approaches emphasizing responsibility (e.g., historical emissions considerations) or capability interpretations such as increased effort for high GDP countries lead to extremely low budgets – in the case of historical emissions, budgets are often negative. Conversely, per capita convergence (or 'status-quo') approaches starting from today's levels of emissions lead to much higher allocations.

Given that Austria's $CO_2$ emissions in 2022 were roughly 57 Mt and future scenarios do not anticipate a steep immediate decline, it is highly likely the remaining budget will be rapidly depleted, if it is not already (due to the large number of negative budgets). As these budgets correspond to agreed-upon targets of well below 2°C of global change, they imply a need for **concerted effort to implement measures aligned with reaching net zero emissions as soon as possible to meet international obligations** (e.g., the Paris Agreement).

Going beyond the national level, recent work emphasizes the relevance of carbon budgets and accounting for sectors (Steininger et al., 2020b) and sub-national authorities such as cities and federal provinces (Salon et al., 2010; Anderson et al., 2018; CCCA, 2022; Hale et al., 2022; Kuriakose et al., 2022) but evidence for Austria is scarce. Such budgets and accounts can provide planning guidance for sub-national authorities and actor groups when designing, implementing, monitoring and adjusting local mitigation policies. The distinction between production- and consumption-based emissions gains in importance the smaller the regional scale. Hence, the (fair) allocation of carbon budgets across federal states is a complex task and needs to differentiate between production- and consumption-based accounting (CCCA, 2022). Research and debate as to the proper approach to downscaling national budgets and efficacy of, e.g., production- vs. consumption-based emissions in representing or obscuring globally interdependent value chains, multi-level production structures and the political or institutional mandates states and subnational regions is ongoing and makes determination of sub-national budgets a complex task with no exact results.

## 8.3. Synthesis and assessment of mitigation options

### 8.3.1. Mitigation options and the Sustainable Development Goals

Section 8.3.1 assesses how climate change mitigation options interact with sustainable development. It first evaluates the synergy and trade-off potentials between mitigation options considered in the quantitative scenarios of Section 8.4 and the Sustainable Development Goals (SDGs). It then provides an overview of the main interactions between key climate adaptations strategies and the SDGs.

To identify climate-friendly transformation pathways (Section 8.6), it is essential to take a systems perspective that goes beyond the mere decarbonization of the economy by including the SDGs. These goals were established in 2015, the same year that the Paris Agreement was signed, and came into effect in January 2016. The 17 SDGs encompass 169 targets related to sustainable development in the environmental, social and economic domain, with progress being measured by 169 indicators at the national, European and international level. The reported indicators on the different levels are defined by the statistics available on those levels. Following UN level indicators, Austria currently has an SDG Index Score of 82.3, ranking 5th out of the 166 countries, while Finland ranks highest with a score of 86.76, and South Sudan ranks lowest with a score of 38.68 (Sachs et al., 2023). Considering EU level indicators, Austria scores 77.7, placing it 4th of 34 countries. While Finland again ranks highest with a score of 80.64, Turkey ranks lowest with a score of 57.14 (Sachs et al., 2023).

Targets related to climate change mitigation and adaptation are mostly represented in SDG13: Climate Action. However, other SDGs also address climate-relevant aspects, such as emission reductions. Some SDGs and their respective targets directly relate to measures to reduce climate impacts (e.g., SDG7: Affordable and Clean Energy, SDG 12: Cleaner Production and Consumption), while others are only indirectly linked to climate change mitigation and adaptation (e.g., SDG6: Clean Water and Sanitation for All, SDG12: Life on Land). A growing body of literature assesses the interaction of achieving individual SDGs (Bennich et al., 2020), as many synergies and trade-offs result from strategies that aim to achieve specific goals or a subset of targets (Horvath et al., 2022). In Austria, a number of scientific options for achieving the SDGs were developed and their interactions assessed (Allianz Nachhaltige Universitäten in Österreich, 2021).

The latest IPCC reports (IPCC, 2022b; Pörtner et al., 2022) assessed the synergy and trade-off potentials between climate change mitigation options and the SDGs. The results from the global assessment by Roy et al. (2018) were used as a starting point for the Austria-specific assessment (for a more detailed description of the methods applied, see 8.A.1). The Austrian analysis, however, only considers interactions relevant for domestic SDG attainment. Therefore, SDG 14: Life below Water, SDG 16: Peace and Justice Strong Institutions, and SDG 17: Partnerships for Goals were excluded from the assessment (for discussion of spillover effects, see Section 8.4.5). Overall, the final results (Figure 8.3) align with those of the IPCC SR1.5 (Roy et al., 2018) in terms of synergy or trade-off potentials, but differ with regards to the strength of their interaction potential. Confidence in these interactions is medium to high (light and dark blue),

| Climate change mitigation measures and its interaction with SDGs | | | Relation with Sustainable Development Goals | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | social | | | | | | environmental | | | economic | | | |
| | | | 1 | 2 | 3 | 4 | 5 | 10 | 6 | 12 | 15 | 7 | 8 | 9 | 11 |
| DEMAND | Industry | Accelerating energy efficiency improvement | | | + | + | | + | x | + | | + | x | + | + |
| | | Low-carbon fuel switch | | | + | + | | | x | + | x | x | + | + | + |
| | | Decarbonisation/CCS/CCU | | | – | | | | – | + | | x | + | + | |
| | Buildings | Behaviorial response | + | | + | | | | | + | | + | + | + | + |
| | | Accelerating energy efficiency improvement | x | | + | | | | | + | + | + | x | + | + |
| | | Improved access & fuel switch to modern low-carbon energy | + | | + | | | | | + | | + | + | + | + |
| | Transport | Behavioural response | x | + | x | + | + | + | + | + | + | + | x | + | + |
| | | Accelerating energy efficiency improvement | x | | + | | | | x | + | x | + | x | x | + |
| | | Improved access & fuel switch to modern low-carbon energy | x | | + | | | + | + | + | | + | x | + | + |
| SUPPLY | Replacing coal | Non-biomass renewables solar, wind, hydro | + | | + | | + | x | x | + | x | + | + | x | + |
| | | Increased use of biomass | x | | + | | | | x | + | x | + | + | | |
| | | Nuclear/Advanced Nuclear | | | – | | | | x | | – | + | + | – | |
| | Advanced coal | CCS: Fossil | | | – | | | | – | | | + | – | + | |
| OTHER | Agriculture & Livestock | Behaviourial response: Sustainable healthy diets and reduced food waste | – | + | + | | | | + | + | x | + | x | + | |
| | | Land based greenhouse gas reduction and soil carbon sequestration | | + | | x | | | x | + | x | + | x | x | |
| | | Greenhouse gas reduction from improved livestock production and manure management systems | + | + | | | | | x | + | x | + | + | + | |
| | Forest | Reduced deforestation, REDD+ | + | - | | | | | x | + | + | x | | x | |
| | | Afforestation and reforestation | | x | + | + | | | + | | + | x | | | + |
| | | Behaviourial response (responsible sourcing) | | | | | | | + | + | + | + | + | + | + |

Type of relation:
- + Synergies
- - Trade-offs
- x Both synergies and trade-offs
- Blanks represent no interaction or assessment

Confidence level:
- High confidence
- Medium confidence
- Low confidence

Figure 8.3 Mitigation option and their respective SDG interactions. Figure adapted based on IPCC (2022d).

with a few low confidence (gray) cases. Nonetheless, further research is needed to understand whether missing interactions are a result of a lack of direct interactions or due to research gaps. The assessment reveals that most mitigation options have synergy potentials (+) or synergy and trade-off potentials (x) with the SDGs, while only a few mitigation options demonstrate trade-off potentials (-). However, it is important to emphasize that the realization of synergy or trade-off potentials depends on the specific means of implementation. Thoughtful policy design – such as in the case of carbon tax reforms – can maximize synergies and reduce trade-offs, enhancing climate-friendly living (Klenert et al., 2018; Großmann et al., 2019; Kirchner et al., 2019; Mayer et al., 2021). Complementing climate change mitigation strategies that show trade-off potentials with additional measures thus bears the potential to further reduce these trade-off potentials.

In line with the findings of Roy et al. (2018) on the international level, synergy potentials consistently outweigh trade-off potentials across all mitigation options. For energy system related (i.e., combined supply and demand side in Figure 8.3) mitigation options, **demand side mitigation options show greater synergy potential than supply side options** across the environmental, social and economic dimension (Figure 8.4). Across all mitigation categories, the potential synergies are greatest for SDGs within the economic domain, largely due to the strong synergetic potential of demand-focused mitigation options. Land-use-related mitigation options, in contrast, show the greatest synergetic potentials with environmental SDGs and generally have lower trade-off potentials than supply side options. Trade-off potentials remain minimal across all categories and most SDGs do not show any trade-off potential at all. While land-based mitigation options have lower overall interaction potential than energy system solutions, they still yield more synergy potentials than trade-offs.

Beyond the conventional categorization of supply, demand and land mitigation options, mitigation options can also be categorized according to the related ideal typical transformation pathways (Section 8.6). While some miti-

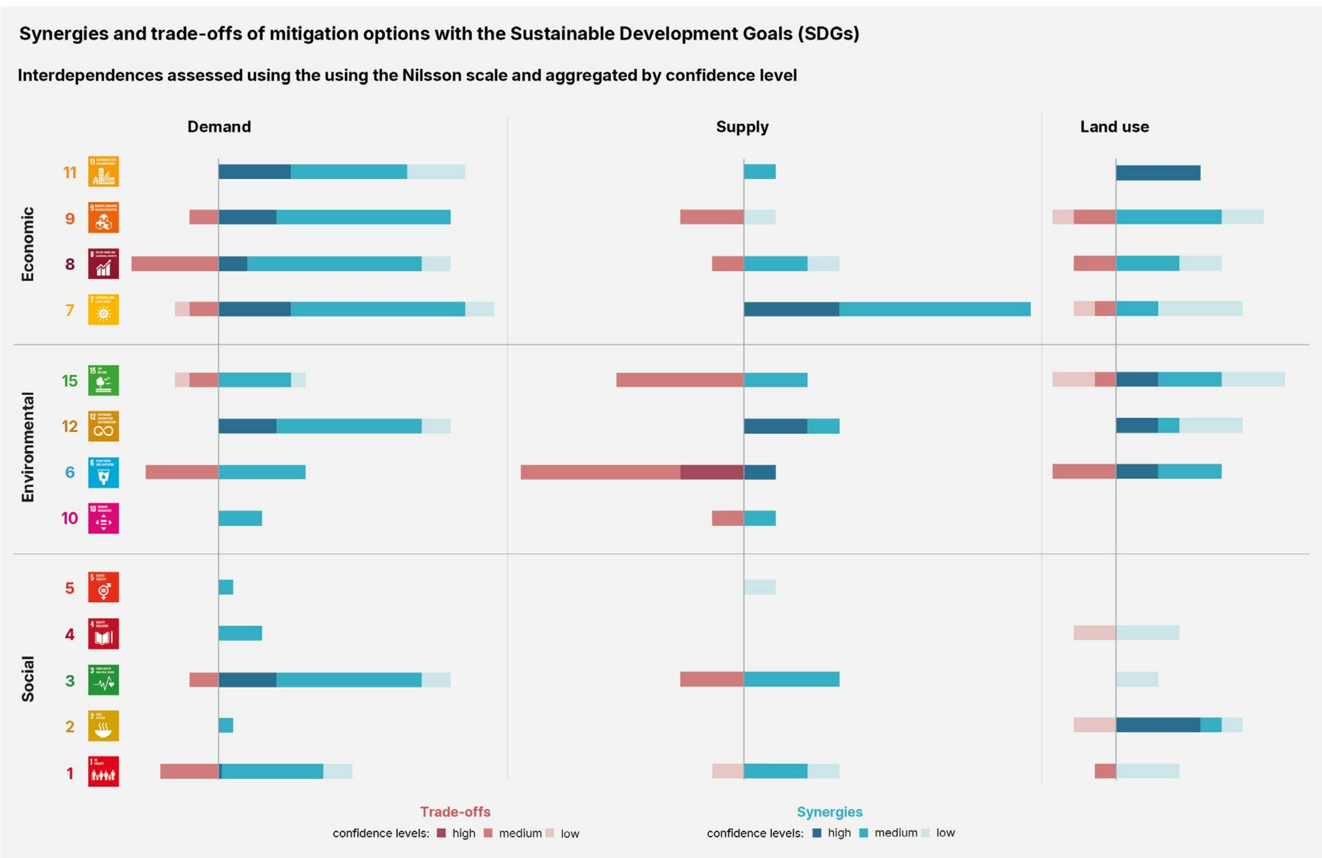



Figure 8.4 Indicative linkages between aggregated mitigation options and SDGs. Economic SDGs include SDG7, 8, 9 and 11. Environmental SDGs include SDG6, 12, 15. Social SDGs include SDG1, 2, 3, 4, 5 and 10. The bar length indicates respective synergy/trade-off potentials according to the Nilsson scale. Figure based on IPCC (2022c).

gation options relate to ecomodernism by improving components of the current system, others aim at degrowth by transforming existing system structures. Mitigation options that are more optimizing have higher synergy potentials with economic SDGs and mitigation options that aim at transforming the system have higher synergy potentials with social SDGs.

Adaptation measures are equally important to climate-friendly living. A limited number of key adaptation options were selected to investigate synergy and trade-off potentials. These point towards **climate change adaptation options showing high synergetic potentials with regards to the SDGs** across all domains (environmental, social, economic). Especially SDG11: Sustainable Cities and Communities, demonstrates high synergetic potential with adaptation options that address infrastructure, such as resilient water management, 'sponge cities', and information and warning systems. These adaptation strategies, however, can also support SDG 4: Quality Education, SDG 5: Gender Equality, SDG 6: Clean Water and Sanitation, SDG 7: Affordable and Clean Energy, SDG 9: Industry, Innovation and Infrastructure, and SDG 15: Life on Land. Resilient water management strategies for example do not only directly affect water management but also aim to make cities and human settlements inclusive, safe, resilient, and sustainable, by mitigating flood risks, enhancing green spaces through blue-green infrastructure, and ensuring a sustainable urban environment that can adapt to climate change challenges (Mikovits et al., 2017; Liu and Jensen, 2018).

## 8.3.2. Costs and potentials of mitigation options

Assessed costs and potentials of mitigation options, depicted in Figure 8.5, highlight that electrification accompanied by decarbonizing electricity supply and demand reduction measures are of key relevance for Austria to achieve carbon neutrality by 2040. Various mitigation options are available within each sector. Among those, electrification in transport, industry, and buildings shows a significant GHG saving potential and needs to go hand in hand with decarbonizing the electricity sector via renewables. While reducing final energy demand and cutting GHG emissions directly are also necessary, their potential has only been partly assessed for Austria.

The electricity sector (Section 4.5) exhibits the highest net emission reduction potential, with five different options ranging from 3.4–7.3 Mt$CO_2$eq per year at the lower bound, and from 4.8–29.4 Mt$CO_2$eq per year at the upper bound. Achieving these emission reductions, however, can only be achieved if sector-coupling between electricity and heating and cooling as well as with the transport sector (i.e., e-mobility) is pursued in the forthcoming years. The cost assessment indicates that the two options with the highest mitigation potential, namely wind and ground-mounted PV systems, can be implemented at relatively low costs. Specifically, ground-mounted PV systems can achieve mitigation potentials of 1.6–4.2 Mt$CO_2$eq per year at costs below the reference level, while additional mitigation potentials of 3.1–8.3 Mt$CO_2$eq per year are available at below $EUR_{2023}$ 50/t$CO_2$eq. Between 1.9–8.3 $CO_2$eq per year can be realized at a cost range between $EUR_{2023}$ 50 and 200 per t$CO_2$eq. Finally, an emission reduction potential of 0.7–2.3 Mt$CO_2$eq per year is available at more than $EUR_{2023}$ 200 per t$CO_2$eq. Wind energy, in contrast, presents zero-cost (i.e., lower than reference) mitigation potentials of 1–5.3 Mt$CO_2$eq per year, with additional potentials of 1.9–10.6 Mt$CO_2$eq per year being available at costs between $EUR_{2023}$ 0–50 per t$CO_2$eq. Costs of between $EUR_{2023}$ 50–200 per t$CO_2$eq are required to realize additional wind potentials of 2.6–10.6 Mt$CO_2$eq per year. Finally, potentials in the range from 0.6–2.9 Mt$CO_2$eq are realizable at costs approximately above $EUR_{2023}$ 200 per t$CO_2$eq. Apart from wind and ground-mounted PV systems, other options for decarbonizing electricity supply include rooftop PV, hydropower and biomethane. Despite offering lower potentials compared to ground-mounted PV and wind, making use of these sources appears of relevance from a system perspective.

The industry sector showcases the second highest potential. Here again five different options were identified, with individual potentials ranging from 1.5–8.5 Mt$CO_2$eq per year at the lower bound, and 1.7–11.6 Mt$CO_2$eq per year at the upper bound. Within this sector, steelmaking processes, particularly those involving a switch to methane- ($CH_4$) and hydrogen- ($H_2$) based direct reduction, show the highest mitigation potentials, ranging from 5.9–11.9 Mt$CO_2$eq per year for methane- and 4.3–11.6 Mt$CO_2$eq per year for hydrogen-based reductions. These options are applicable at costs between approximately $EUR_{2023}$ 50–200 per t$CO_2$eq ($CH_4$-based direct reduction) or above $EUR_{2023}$ 200 per t$CO_2$eq ($H_2$-based direct reduction), respectively. Assessed mitigation options for other industry subsectors include fuel and process switching in chemical industries, CCS via oxyfuel technology in clinker for cement production, and high-temperature heat pumps in paper industry. These alternatives demonstrate a similar order of magnitude as those for decarbonizing steel production processes.

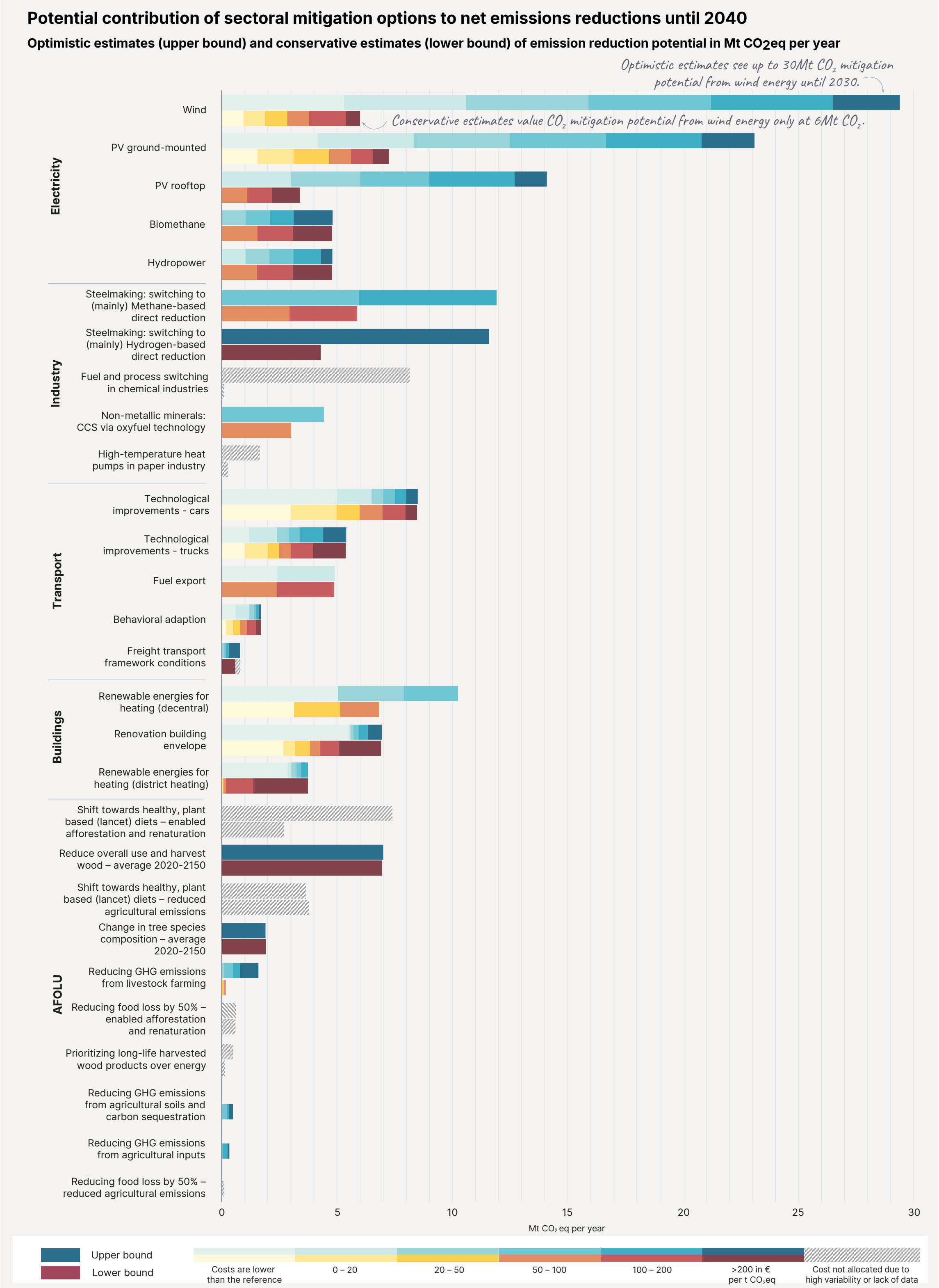



Figure 8.5 This panel illustrates the upper and lower bound of the assessed potentials and related costs of individual mitigation options. These options refer, with respect to expressed potentials, to the time horizon 2040 and beyond (in comparison to the status quo as of 2021), indicating the cumulative mitigation potential until then, whereas related costs reflect the current perspective, including a forward-looking component. Expressed costs represent additional costs in comparison to a conventional (fossil-based) reference option that reflects current practice in the respective field. Underlying data generally relies on literature, partly complemented by expert judgments (for further details, see 8.A.2). The uncertainty and, consequently, large bandwidth applicable in the data on both potentials and costs caused the expression as lower and upper bounds. Furthermore, due to the methodology used to assess costs and potentials, the mitigation potentials of different options should not be added up because of possible interactions between individual options.

The transport sector offers five distinct mitigation options, with individual potentials ranging from 0.8–8.5 $MtCO_2eq$ per year. According to the assessment, technological improvements in cars and trucks, implying a switch to e-mobility, offer the highest mitigation potentials. Raising fuel taxes and, in turn, phasing out fuel exports represents another promising option offering a comparatively high mitigation potential. Large parts of all previously mentioned potentials come at low costs, some even below zero. Other mitigation options in the transport sector include behavioral adaptation and improvements in freight transport framework conditions. For the building sector, three different mitigation options were assessed, including a switch to renewable energies in both decentral and district heat supply, for example via the use of electric heat pumps, and renovating building envelopes. Individual net emission reduction potentials range from 3.7–6.9 $MtCO_2eq$ per year at the lower bound, and from 3.7–10.2 $MtCO_2eq$ per year at the upper bound, respectively. In terms of costs, a major part of these potentials can be mitigated at costs below the reference level, specifically when adopting a more optimistic view on related costs and expenditures (upper bound).

Mitigation options in the sectors of agriculture, forestry and other land use (AFOLU) depend upon future scenarios. Ten different options were assessed, with individual mitigation potentials ranging from 0–7.0 $MtCO_2eq$ per year at the lower bound, and from 0.1–7.4 $MtCO_2eq$ per year at the upper bound. The two options with the highest mitigation potentials are: First, a shift towards healthy, plant-based (lancet) diets which, in turn, enables afforestation and renaturation, and; second, reducing overall wood use and harvest. Cost assessments furthermore indicate that mitigating AFOLU emissions can be expensive, with reducing GHG emissions from agricultural soils and carbon sequestration, agricultural inputs, livestock farming or related to the use and harvesting of wood being only available at above $EUR_{2023}$ 200 per $MtCO_2eq$. Against the background of Austrian mitigation scenarios failing to reach climate targets by 2040, partly due to residual emissions in the agricultural sector (Section 8.4), reducing AFOLU emissions will be important, despite relatively high marginal abatement costs.

The quantitative assessment of mitigation options in terms of their net emission reduction potentials and associated costs focuses only on those for which data is available for the Austrian context. The mitigation options assessed in Figure 8.5 therefore represent a non-exhaustive list. For example, the list lacks certain shift and avoid measures of demand-side sectors, such as reducing floor-space in the building sector.

## 8.4. Assessment of Austrian mitigation scenarios

### 8.4.1. Overview of Austrian mitigation scenarios

This section provides an overview of existing mitigation scenarios for Austria, assessing relevant scenarios according to key scenario properties. It begins with an overview on the available scenario literature on climate neutrality in Austria, introducing key studies included in the corresponding comparative assessment.

At present there is only a limited set of studies and accompanying scenarios available that take a holistic angle, assessing the transformation towards climate neutrality for the whole Austrian economy. To extend the scenario literature, this assessment also considers scenarios that include the whole energy sector and related industrial activities. Doing so allows for covering the activities responsible for the majority of GHG emissions at present, and for assessing the derived decarbonization scenarios in a comparative manner. While the number of studies and scenarios is larger, our assessment focuses on recently developed key scenarios for which the underlying data has been provided. In addition to these quantitative analyses having taken a holistic angle, there is a large variety of partial scenarios dedicated to specific aspects of the energy system, including the electricity sector and/or other parts of the energy domain. A more limited set of scenarios is available for sectors like industry, agriculture, buildings, and mobility.

To assess Austrian climate targets, including the 2030 targets and the current (as of September 2024) government target of climate neutrality by 2040, and in line with reporting as part of the monitoring mechanism laid down in EU Energy Union legislation, the Environment Agency Austria (EAA) coordinates a scenario process on integrated energy (Umweltbundesamt, 2023d) and emission scenarios for Austria[1] (Umweltbundesamt, 2023d). This process was commissioned and financed by the Austrian Ministry for Climate Protection (BMK). It involved several scientific partners, among others TU Wien, TU Graz, and e-think, and

1 This process is part of the monitoring mechanism laid down in EU Energy Union legislation (Regulation 2018/1999).

a broad range of stakeholders such as representatives from ministries and other governmental bodies, social partners, representatives from industry and the civil society. The EAA uses the macroeconomic-energy-emission model MIO-ES (Kratena and Scharner, 2020) as one of the main analytical tools for all its scenarios. This model is based on a hybrid IO-structure and is constantly developed and maintained by the EAA.

The monitoring mechanism conducted by the EAA for the EU and the BMK includes the construction of a *With Existing Measures (WEM)*, a *With Additional Measures (WAM),* and a *Transition* scenario (Umweltbundesamt, 2023c). A WEM scenario (Umweltbundesamt, 2023e) is a baseline or Business-As-Usual (BAU) scenario that depicts the continuation of the status quo of economic, energy and emission trajectories, and includes all policies that are part of current government legislation. A WAM scenario (Umweltbundesamt, 2023c), in contrast, describes a more ambitious scenario, where additional expert-defined climate policy measures are modeled that are likely to be included in governmental action plans. The WAM scenario typically serves as the reference for the Austrian National Climate and Energy Plan (NECP). A Transition scenario, such as the Austrian Transition 2040 (Umweltbundesamt, 2024), shows options for how climate targets can be reached under coherent, consistent, and feasible assumptions. All changes in emissions in this scenario are linked to various policy measures developed collaboratively with a broad range of stakeholders and aligned with existing legal frameworks.

The scenarios by the EAA serve as Austrian reference scenarios for two main reasons: (1) They are elaborated by a large number of experts from various institutions in collaboration and close coordination with above-mentioned key stakeholders in Austria, including input from participatory frameworks such as the Austrian Climate Council ('Klimarat') in case of the Transition 2040 scenario (Umweltbundesamt, 2024). (2) WEM and WAM scenarios are integral to the official monitoring mechanism of the EU Energy Union. The assessment of GHG emission includes two variants for WEM and WAM[2]: First, the 2023 variants, serving as basis for the detailed comparative analysis between WEM, WAM and Transition (Umweltbundesamt, 2024), and; second, the 2024 updates, which reflect the latest progress on achieved GHG emission reductions (as of 2022) and serving as basis for the latest available update of the Austrian NECP (as of 2024) (BMK, 2024). Additionally, a collaboration between EAA and the Austrian Ministry of Finance (BMF) resulted in holistic scenarios analogous to the WEM and the Transition 2040 scenarios, referred to as 'Base' and 'Activity' scenario. These scenarios were developed as part of a pilot project to integrate climate policy and emission scenarios into the long-term budget forecast (Gugele et al., 2022). The scenarios 'Transition 2040' for the BMK (Umweltbundesamt, 2024) and the 'Activity' scenario for the BMF (Gugele et al., 2022) aim to demonstrate how climate neutrality by 2040 could be targeted (but not necessarily reached), considering integrated economic, energy, and emission pathways. However, due to their overlap with the aforementioned EAA scenarios and a lack of accessible data, these scenarios are not considered in the subsequent comparative scenario assessment.

The recent ACRP project NetZero2040[3] (Schmidt et al., 2025) – a collaboration between the Austrian Energy Agency (AEA), BOKU and IIASA – aims to establish a set of comprehensive and consistent alternative emission pathways that can ensure reaching Austria's 2040 climate target. It considers the energy system, energy imports and energy demand by the agricultural, household, industry, service and transport sector. The four scenarios developed can be distinguished according to the degree of energy imports and total energy requirements: (1) Scenario A describes a combination of energy supply and demand measures that lead towards energy sufficient lifestyles and a rapid expansion in renewable energy sources; (2) Scenario B, in contrast, outlines a world characterized by a continuous increase in energy demand and international energy treaties enabling the import of carbon-neutral energy; (3) In Scenario C, the rapid expansion of domestic renewable energy sources leads to a situation of relative energy independence, while resource and energy consumption continuously increase due to rebound effects; (4) Finally, Scenario D is characterized by a shift towards energy-sufficient behavioral practices and a lack of renewable energy expansion being offset by increased levels of energy imports. While all scenarios achieve the goal of a climate neutral energy system in 2040, they do not address non-energy-related emissions from agriculture and Land Use, Land Use-Change and Forestry (LULUCF).

[2] Accessible detailed data for the latest (2024) update of WEM and WAM is limited to GHG emission balances. Thus, these variants could not be considered for energy-related comparisons or the assessment of economic impacts.

[3] netzero2040.at/szenarien-1

Four additional scenarios were modelled by the ACRP Project INTEGRATE[4] (Steininger et al., 2024) to develop cross-sectoral integrated pathways that achieve the 2040 goal of climate neutrality including the building, transport, energy and industry sector. Two high demand scenarios are used as reference differentiating between limited and unlimited carbon neutral energy imports. Additionally, two INTEGRATE scenarios are characterized by low energy demand, with differences between them being based on the availability of energy imports. INTEGRATE furthermore calculates the overall economic effects, such as GDP, income, sectoral effects and distributional effects. However, due to the lack of available data, the economic effects of INTEGRATE scenarios could not be integrated in the cross-scenario assessment.

## 8.4.2. Assessment of Austrian mitigation scenarios: GHG emissions and energy balance

### Total GHG emissions

At present, only the EAA scenarios can be classified as holistic, including energy and total GHG emission projections for LULUCF. These scenarios comprehensively cover energy-related emission sectors – i.e., energy, buildings, mobility, and industry – according to a consistent model-based methodology using the MIO-ES model (Kratena and Scharner, 2020). However, emission projections for agriculture and processes are usually based on different models, studies or expert judgements.

To put EAA scenarios on the future development of total GHG emissions in Austria into perspective, Figure 8.6a includes the historic development from 1990 in addition to future trends.[5] As visualized, total GHG emissions increased in the early years until 2005, mainly related to a strong increase in transport-related, and a comparatively moderate rise in industry-related activities and emissions. Since 2005, a reduction of GHG emissions could be achieved, with a reported 11 % decline in 2022 compared to 2005 (Umweltbundesamt, 2023b). Mainly responsible for the downward trend are the uptake of renewables in energy supply and energy efficiency improvements in buildings, leading to a decline in GHG emissions in energy supply and demand overall. Taking a look into the future, the WEM 2023 and 2024 scenarios (Umweltbundesamt, 2023e) include all mitigation and climate-related policy measures implemented before January 2022. The 2023 and 2024 variants of WEM as well as WAM differ in terms of their starting point for the prospective modeling. While the 2023 variants build on 2021 statistics, the 2024 variants acknowledge the recently achieved progress (as of 2022) of GHG emission reductions. Due to WEM's nature as a business-as-usual scenario, relying on currently implemented policies, its mitigation efforts are limited: The WEM 2023 (2024) scenario predicts a decrease in total GHG emissions by 32 (34) % by 2050 relative to 2005, reaching GHG emissions of 52.4 (50.6) $MtCO_2eq$ in 2050. In comparison, the WAM 2023 (2024) scenarios project a reduction of 32 (34) % already by 2030 (relative to 2005), indicating that planned measures would be effective in reducing GHG emissions also in the near future. By 2050, WAM 2023 (2024) achieves further emission reductions by 69 (71) % relative to 2005 to reach a level of 23.6 (22.4) $MtCO_2eq$. The EAA Transition 2040 scenario, in contrast, imposes more radical mitigation measures than currently adopted or planned, thus achieving stronger GHG reductions both in the short (2030) and long term (2040 and beyond) (Umweltbundesamt, 2023c, 2023e). Overall, total GHG emission could then be reduced by 54 and 92 % by 2050 compared to 2005 levels. Although significant, the Transition 2040 scenario does not achieve the emission reductions required to meet the Austrian policy target of achieving carbon neutrality in 2040 due to residual emissions of 11.0 $MtCO_2eq$ that originate mainly from hard-to-abate industries and agriculture. Negative emission potentials from land-based carbon dioxide removal (CDR) related to LULUCF (-4.6 $MtCO_2eq$) do not suffice to coun-

4 wegcwp.uni-graz.at/integrate/aims/

5 An update of the Austrian greenhouse gas inventory was published in January 2025 (Umweltbundesamt, 2025), after the literature cut-off deadline of this report. Due to a modification of the accounting method for GHG emissions related to land use, land-use change and forestry (LULUCF), historical emissions were altered significantly. This change was not considered in this chapter, because all prospective scenarios assessed in this section were based on former historic GHG inventories and underlying data.
For comparative reasons, Figure 8.6a includes net emissions according to the latest Austrian GHG inventory as published in January 2025 (Umweltbundesamt, 2025) – cf. the dotted black line in Figure 8.6a indicating past total GHG emissions until 2020. Latest data for 2023 (not shown in this panel) shows that the LULUCF sector has turned from an emission sink to a source in recent years. The change in methodology causes an increase of total GHG emission including LULUCF in 2020 by 4.3 $MtCO_2eq$ compared to the historical data according to the previous GHG inventory (Umweltbundesamt, 2023a) which was used to develop EAA's Transition scenario.

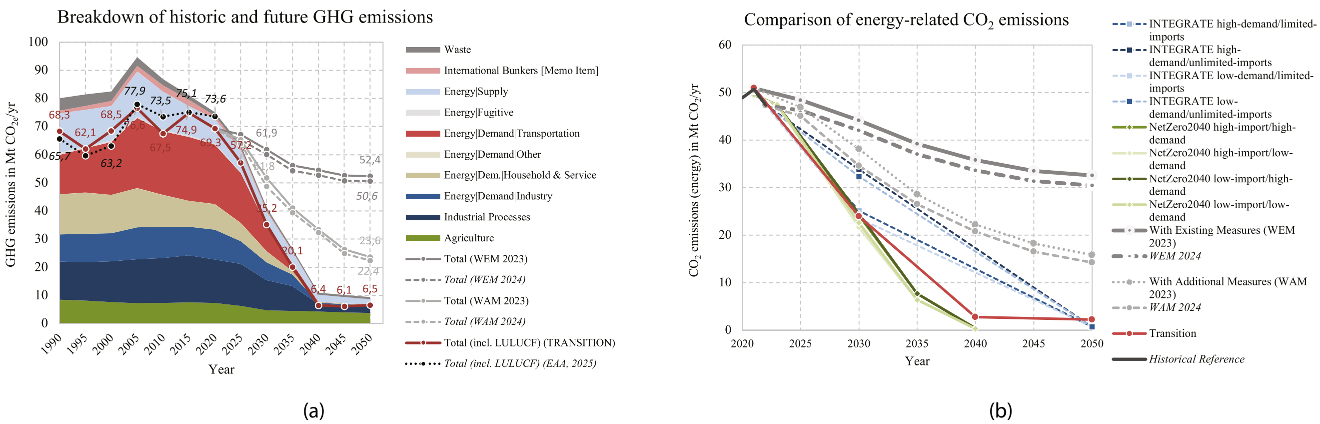



**Figure 8.6** (a) Breakdown of historic and future total GHG emissions trends in Austria according to EAA scenarios, with sectoral details for the EAA Transition 2040 scenario (left); (b) Comparison of energy-related $CO_2$ emission trends according to all assessed scenarios (right).

terbalance these residual emissions, requiring additional measures like Carbon Capture, Utilization, and Storage (CCUS) to counterbalance residual emissions, as no other technological mitigation options exist yet.

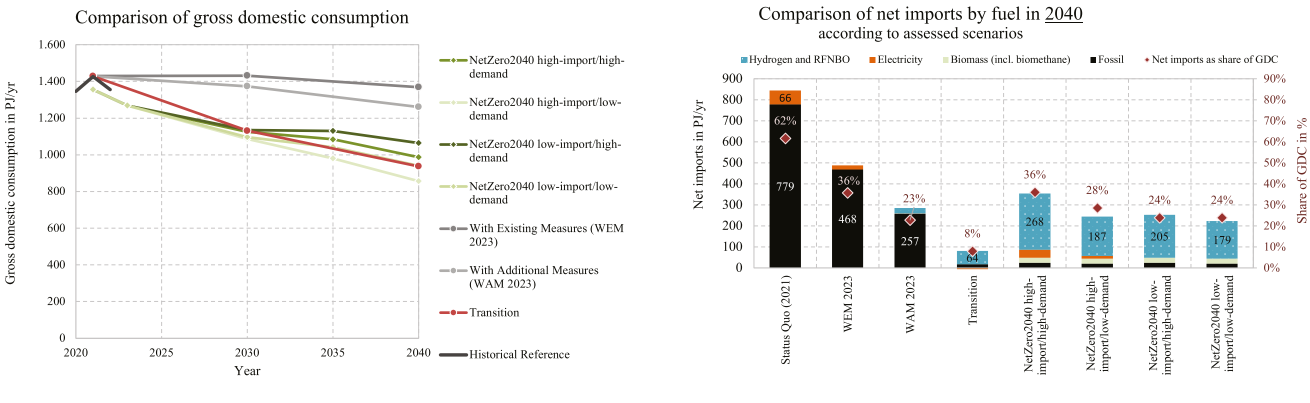
In the context of the 2030 climate policy targets imposed by EU regulation, the Effort Sharing Regulation (ESR) in accordance with the recent amendment as of 2023 (Regulation (EU) 2023/857), sets Austria a 48 % GHG emission reduction target (compared to 2005) for all non-ETS sectors[6] by 2030, with the transport and building sector being the largest ESR emitters at present. Predicted emission reductions by 38 (42) % in 2030 under the WAM 2023 (2024) scenario suggest that the strengthened ESR target will not be met. The Transition 2040 scenario, in contrast, predicts GHG emission reductions of 59 % by 2030, indicating that Austria could meet the legally binding EU target if more ambitious and far-reaching climate mitigation measures are implemented immediately.

## Energy-related $CO_2$ emissions

The energy sector is responsible for more than two thirds of Austria's total GHG emissions at present, with varying contributions from year to year[7]. Since not all assessed studies report on GHG emissions, energy-related $CO_2$ emissions serve as common basis for comparing the decarbonization ambition and underlying trajectory of assessed scenarios and studies. Figure 8.6b shows the future development of total energy-related $CO_2$ emissions for all assessed scenarios, including estimates the INTEGRATE and NetZero2040 in addition to EAA scenarios. According to these projections, minor differences appear in the emission 'endpoints' by 2040 or 2050. NetZero2040 scenarios are the most ambitious, reducing $CO_2$ emissions to 0.3 Mt already by 2040. INTEGRATE scenarios, in contrast, predict 0.7 $MtCO_2$ by 2050. The EAA scenario Transition 2040 shows a $CO_2$ emission reduction to 2.8 Mt by 2040, further declining to 2.2 Mt in 2050. Apart from differences in terms of endpoints and underlying mitigation ambition, there are both differences and similarities in the starting points and underlying trajectories. All studies and the corresponding scenarios acknowledge the upward trend in emissions from 2020–2021 as consequence of the global disturbances in economic activities during the COVID pandemic. For all scenarios and studies with strong GHG mitigation (i.e., Transition 2040, NetZero2040 and INTEGRATE), $CO_2$ emission show a downward trend towards 2030 starting in 2021, aligning with latest statistics for 2022. Beyond 2030, NetZero2040 scenarios maintain a strong GHG mitigation ambition until 2035, thereafter slowing down their pace for the final years towards 2040. The Transition 2040 scenario follows a similar trend but maintains a more constant GHG reduction path between 2030 and 2040. INTEGRATE scenarios do not provide 2040 data but demonstrate the achievement of climate neutrality by 2050. However, as stated above, none of the assessed scenarios demonstrates how climate neutrality could be achieved in Austria's entire economy by 2040 and beyond.

6 ETS sectors are already under direct control by EU climate policy.

7 For example, in 2021 energy-related $CO_2$ emissions held a share of 76 % on Austria's total GHG emissions whereas in 2022 that share declined to 69 %.




(a) (b)

Figure 8.7 (a) Comparison of gross domestic consumption trends according to all assessed scenarios (left). Note that NetZero2040 and INTEGRATE scenarios include non-energetic use of fossil fuels; (b) Breakdown of net imports by fuel in 2040 according to all assessed scenarios (right).

## Energy balance

This subsection provides an overview of trends in overall energy demand and supply across the assessed scenario landscape. Gross domestic consumption acts as the starting point for the comparative assessment, followed by a discussion of trends in final energy demand.

### *Gross domestic consumption and the role of imports*

Gross domestic consumption shows a downward trend in all scenarios aiming for decarbonization, as depicted in Figure 8.7a.[8] By 2040, reductions in gross domestic consumption ranges between 25–40 % compared to 2021, with only slight differences among the corresponding scenarios. In contrast, the WEM 2023 and WAM 2023 scenarios, reflecting existing and planned policy measures, indicate different trajectories: In WAM 2023, demand decreases by 12 % by 2040 (compared to 2021), whereas WEM 2023 predicts that demand initially increases until 2030 and then decreases, resulting in an overall demand reduction of only 4 % by 2040 (compared to 2021).

In addition to reductions in energy demand, important changes are expected on the supply side. Decarbonization implies an increase in renewable energies and, in turn, a phase-out of fossil fuels (Luderer et al., 2022; Umweltbundesamt, 2023c). This consequently affects the import dependency of Austria's energy supply. According to assessed literature (e.g., European Commission and Joint Research Centre (JRC), 2021) (Section 4.5.3), renewable energy sources like wind and solar PV or ambient heat (heat pumps) are economically viable and available at large scale domestically. They can furthermore be complemented by historically well-established renewable sources like biomass and hydropower for Austria to meet its respective energy needs, especially in the electricity sector and for heating and cooling. However, renewable gases like hydrogen and renewable fuels of non-biologic origin (RFNBO) may partly be imported due to competitive cost advantages abroad (Umweltbundesamt, 2023c; Steininger et al., 2024; Schmidt et al., 2025). In this context, Figure 8.7b compares net imports by fuel in absolute terms in 2040 and shows Austria's import dependency in relative terms. Today, Austria's energy import dependency (i.e., total amount of energy imports as share of gross domestic consumption) varies between 52 % (2020) and 75 % (2022) (BMK, 2023), with differences caused by stock management practices as well as weather-driven changes in domestic demand and supply. Most of these imports are fossil fuels like oil, gas, and coal, with a smaller share being attributed to electricity, where Austria is net importer at present. There is strong agreement in the assessed scenario literature about a decline in import dependency and a change in the underlying fuel mix. Thus, the available scenario literature agrees upon fossil fuel imports being largely replaced by hydrogen and other RFNBO by 2040. In addition, Austria is expected to become a net exporter of electricity or at least achieve an even balance, driven by the strong uptake of wind and solar PV. However, the extent of this change in import dependency varies among assessed decarbonization scenarios. By 2040, the Transition 2040 scenario projects the lowest import dependency (e.g., 8 %

[8] Due to a lack of INTEGRATE data on gross domestic consumption, they have been excluded from this comparison.

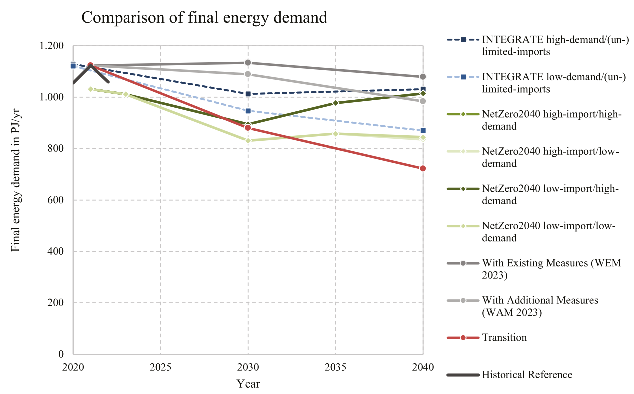



Figure 8.8 Comparison of final energy demand trends according to all assessed scenarios.

in relation to gross domestic consumption), while the NetZero2040 scenarios show higher import ratios, ranging from 24–36 %, depending on the underlying assumptions and the respective scenario conception (low or high imports).

*Final energy demand*

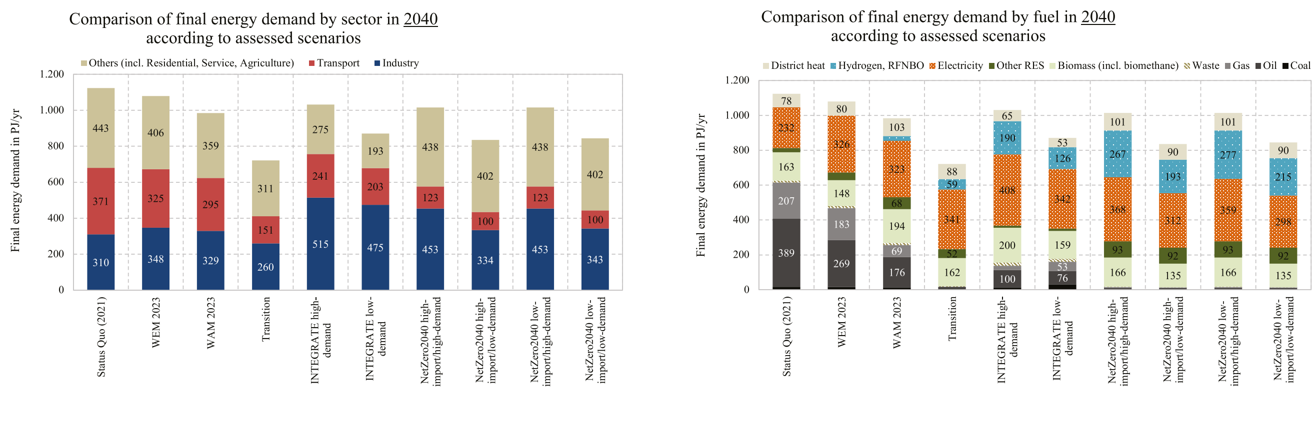
Similar to gross domestic consumption, the scenario literature agrees that reducing final energy demand is essential for effectively combating climate change (Figure 8.8). There are, however, strong differences in the amount of degrowth required across analyzed decarbonization scenarios. By 2040, reductions in final energy demand relative to 2021 levels range widely, with -8 % in the INTEGRATE high demand scenarios and -36 % in the Transition 2040 scenario. NetZero2040 scenarios fall within the expressed degrowth corridor, with differences being driven by varying scenario conceptions and underlying assumptions (e.g., high versus low demand scenarios). These scenarios also show distinct trends, with a comparatively strong decline in demand until 2030, followed by a demand increase in the period after 2030. These differences reflect variations in the emphasis placed on and the mix of underlying demand-side policy measures. The Transition 2040 scenario, for instance, places strong emphasis on demand-side measures as driver for final energy demand reductions.

Complementary to the dynamic evolution of final energy demand, Figure 8.9 explores the underlying decomposition of final energy demand for 2040 by sector (Figure 8.9a) as well as by fuel (Figure 8.9b). The sectoral breakdown provides an indication of the emphasis on demand-side measures and highlights underlying macroeconomic and technological trends:

- **Transport**: The **assessed scenario literature outlines that final energy demand in the transport sector** will decline as decarbonization progresses. The observed (de-)growth rates from 2021 to 2040 vary between -35 % (INTEGRATE high demand scenarios) and -73 % (NetZero2040 low demand scenarios), with EAA's Transition 2040 scenario achieving a 59 % decrease. Key drivers are technological improvements (e.g., switch to e-mobility) and anticipated behavioral changes, such as increased use of public transport and active climate-friendly mobility.
- **Industry**: There is **no consensus in the available scenario literature regarding the future development of industrial final energy demand.** While EAA's Transition 2040 scenario assumes a demand decline by 16 % by 2040 relative to 2021, the INTEGRATE scenarios project a tremendous increase of 53–66 % – but their modeling also builds on a significantly higher industrial demand for the status quo (i.e., more than 40 % above data reported in Statistik Austria) (Luderer et al., 2022). The NetZero2040 scenarios also assume an increase in industrial final energy demand but at a comparatively smaller rate, ranging from 8–46 %.
- **Other sectors**: Final energy demand of other sectors – including residential, service and agriculture or, according to a different classification, buildings and (electrical) appliances – is expected to decrease according to the assessed literature. Scenarios differ, however, in terms of the extent of decline. Growth rates, comparing 2040 with 2021, vary between -1 % (NetZero high demand scenarios) and -56 % (INTEGRATE low demand scenarios), while the Transition 2040 assumes demand reductions of 30 %, lying in between the two extremes.

In addition to the sectoral breakdown of 2040 final energy demand, the decomposition by fuel reveals important technological trends:

- First, the assessed literature agrees that **phasing-out fossil fuels represents a prerequisite for climate neutrality**. However, INTEGRATE scenarios retain oil and natural gas usage by 2040, reflecting their goal of achieving climate neutrality ten years later than other studies, namely by 2050 instead of 2040.
- **Second, electrification is a predominant decarbonization strategy** across all scenarios, helping to decarbonize fossil-fuel intensive sectors like transport, buildings or industry. Electricity demand will consequently grow




(a) (b)

Figure 8.9 (a) Breakdown of final energy demand by sector in 2040 according to all assessed scenarios (left); (b) Breakdown of final energy demand by fuel in 2040 according to all assessed scenarios (right).

between 2021 and 2040, varying between 29 % (NetZero2040 low-demand/low-import scenario) and 76 % (INTEGRATE high-demand scenario), whereas the Transition 2040 scenario expects electricity demand to grow by 47 %.

- Third, **green hydrogen and RFNBO are key pillars for decarbonizing Austria's energy sector** and economy. The extent to which this – from today's perspective – expectably costly option (Luderer et al., 2022) is taken up differs across the assessed scenarios. Since the use of these fuel options is not yet visible in current energy statistics (as of 2021), no growth rate for the corresponding 2040 use pattern can be expressed. Instead, the EAA's WAM scenario serves as an alternative anchor point for the scenario comparison. The Transition 2040 scenario expects hydrogen and RFNBO use to double compared to WAM levels. An even higher uptake is observable in the INTEGRATE scenarios, where 3 to almost 6 times higher amounts are used in 2040. NetZeto2040 shows the strongest uptake of hydrogen and RFNBO, ranging from a 7- to a 10-fold increase compared to WAM.
- Fourth, **biomass**, in various forms (solid, liquid and gaseous), serves as another pillar for a decarbonized energy system, especially for uses that cannot be electrified through abiotic renewable energies and for balancing the volatility of solar and wind. The use of biomass for energy, however, induces trade-offs, such as reducing carbon sequestration in ecosystems and in societal structures and affecting biodiversity (Sections 2.3.2, 4.5.3). In the Transition 2040 scenario, the total direct use of biomass remains stable between 2021 and 2040, although its applications shift from heat fuels in buildings towards fuel- and material-use in industry (which is however not accounted in the energy balance) (Umweltbundesamt, 2024). Other scenarios indicate either comparatively small increases of up to 23 % (INTEGRATE high demand scenarios), or slight decreases of 17 % (NetZero2040 low demand scenarios) when comparing 2040 results with the status quo (2021).
- Fifth, district heating (and cooling) is another key technology option for decarbonizing heating and cooling supply in urban or peri-urban areas. The Transition 2040 scenario assumes a 13 % increase by 2040 relative to 2021. The NetZero2040 scenarios align with this trend, predicting increases in district heat demand between 15 % to 30 %. Contrarily, the INTEGRATE scenarios predict a decline in district heat demand of 17 % to 32 % when comparing 2040 with the status quo (2021). Note that this can be partly explained by INTEGRATE reporting a lower uptake of district heat for the status quo than other scenarios.

## 8.4.3. Spotlight on key energy carriers

Complementary to the above, this section examines two key energy carriers/sectors that are crucial for achieving climate neutrality.

### Electricity sector

According to existing literature, the electricity sector will become the key energy sector in Austria, as well as at the European and global scale (Del Granado et al., 2020; Resch et al., 2022). As sector coupling and efforts to decarbonize electricity supply continue, electrification may help in de-

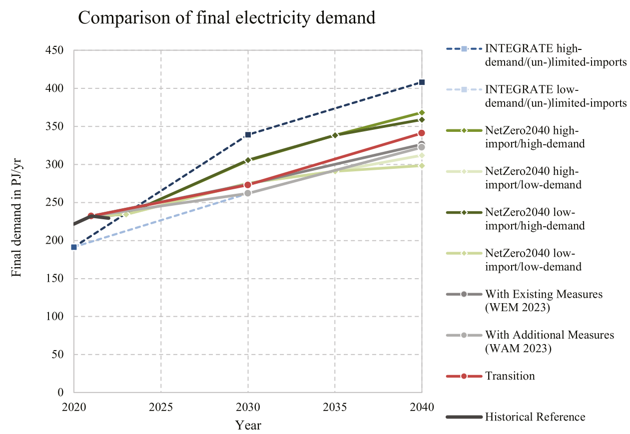


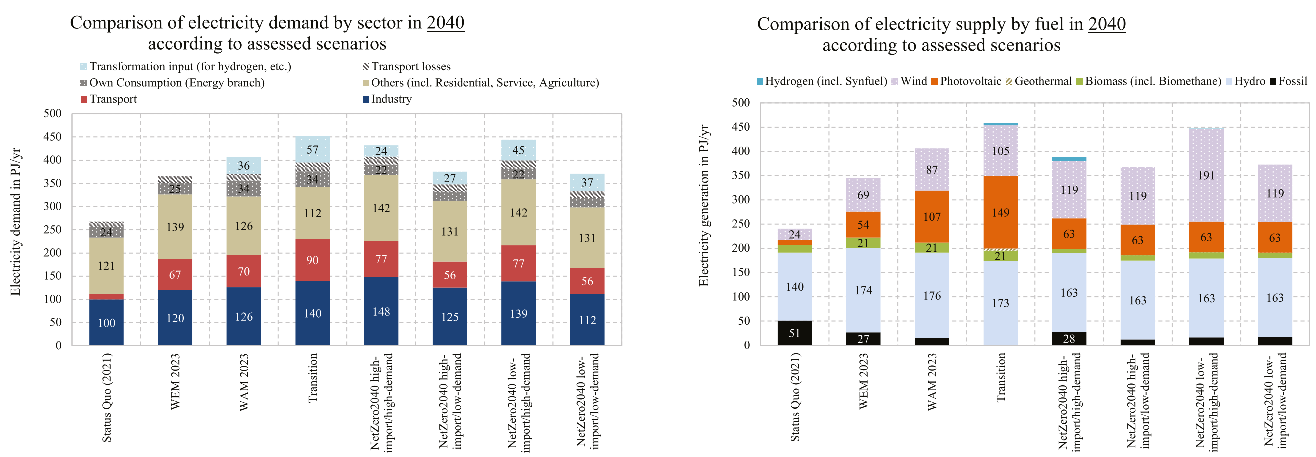

**Figure 8.10** Comparison of final electricity demand trends according to all assessed scenarios.

carbonizing fossil-fuel intensive sectors such as transport, buildings and industry. Consequently, there is a strong consensus across the assessed scenarios that electricity demand will grow in the forthcoming years. This trend is observable in Figure 8.10, which illustrates the development of final electricity demand in Austria up to 2040. There are, however, differences in projected demand growth across the assessed scenarios, partly driven by varying scenario conceptions and corresponding assumptions. The comparison of expected demand increases between 2021 and 2040 reveals a wide range, with projections varying between 29 % (NetZero2040 low-demand/low-import scenario) and 76 % (INTEGRATE high-demand scenario).

In addition to the evolution of final electricity demand, Figure 8.11 illustrates the underlying decomposition of demand and supply patterns in the assessed scenarios.[9] More precisely, Figure 8.11a provides a breakdown of gross electricity demand in 2040 by sector or category, while Figure 8.11b illustrates the composition of domestic electricity supply in 2040, indicating fuel types for scenarios that provide this level of detail.

Key trends on the demand side include the following: First, the projected uptake of e-mobility increases the electricity demand in the transport sector significantly, with projections rising from currently (2021) 12 PJ to 56–90 PJ in 2040. Second, depending on the scenario, the industry sector will become either the largest or second largest consumer of electricity. For the demand category 'others', encompassing the residential, service and agriculture sector, no clear trend is observable. Demand in these sectors may either decline by 9 PJ (Transition 2040 scenario) or increase by 10–21 PJ (NetZero2040 scenarios) by 2040 relative to 2021. Additionally, there is consensus that a new demand category may emerge, with renewable electricity being used for producing green hydrogen domestically in the range from 24–45 PJ (NetZero2040 scenarios) to 57 PJ (Transition 2040 scenario). No clear trend can be identified from the scenario comparison for losses and own electricity consumption within the energy sector. There is, however, a broad set of complementary sector-specific literature available that indi-

9 Due to a lack of corresponding data, INTEGRATE scenarios were excluded from this comparison.




(a) (b)

**Figure 8.11** (a) Breakdown of gross electricity demand by sector in 2040 according to assessed scenarios (left); (b) Breakdown of domestic electricity supply by fuel in 2040 according to assessed scenarios (right).

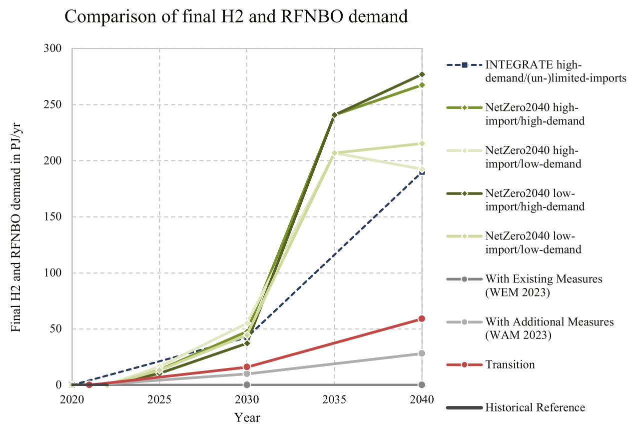



**Figure 8.12** Comparison of final $H_2$ and RFNBO demand trends according to all assessed scenarios. Note that the INTEGRATE low-demand/(un-)limited-imports scenarios project the same final $H_2$ and RFNBO demand as the WAM 2023 scenario.

cates increases both in transport losses and own consumption because of ongoing electrification (Section 4.5.2).

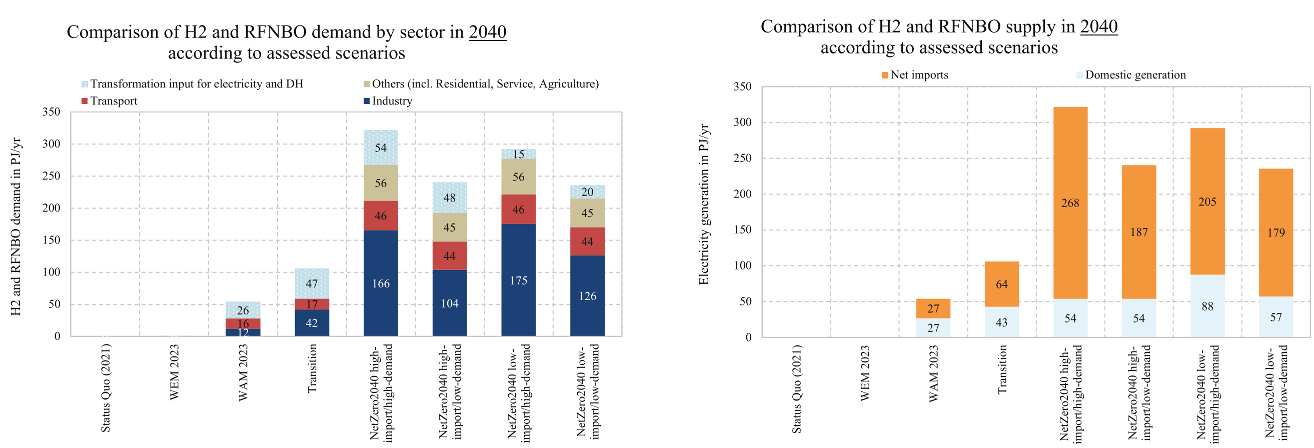
On the supply side, the scenarios assume a strong uptake of renewable energies in the period up to 2040 (Figure 8.11b). Complementary to hydropower, which is Austria's traditional renewable source for electricity supply, wind and solar PV are expected to act as key pillars for meeting growing electricity demand. This is supported by the available literature, although there are significant differences regarding the scale of wind and solar PV deployment by 2040. The strong uptake of weather-dependent renewable energies and preferred technology selection influence infrastructural needs (e.g., grids, storages) and required demand-side solutions. A detailed discussion of these aspects is provided by Chapter 4 (Section 4.5).

## Hydrogen and renewable synthetic fuels

Green hydrogen and renewable synthetic fuels are another key solution for Austria's efforts to decarbonize its energy sector and the whole economy. However, as stated above, the available scenario literature provides no clear answer on the required amounts of these – from today's perspective – relatively costly options (Luderer et al., 2022). Figure 8.12 illustrates the projected final demand for $H_2$ and RFNBO up to 2040 across the assessed scenarios. At the lower end, the Transition 2040 scenario projects moderate levels of final energy demand for hydrogen and RFNBO of 59 PJ by 2040. At the upper end, the NetZero2040 high-import/high-demand scenario shows significantly higher final demand of 267 PJ by 2040, with other NetZero2040 scenarios approaching but not reaching this level of demand.

Figure 8.13 illustrates the decomposition of demand and supply patterns for the assessed scenario literature. More precisely, Figure 8.13a displays the sectoral breakdown of the overall demand for $H_2$ and RFNBO in 2040, including – in contrast to Figure 8.12 – the transformation input to electricity and district heating and cooling. Complementing this, Figure 8.13b demonstrates how this demand can be met, either via domestic production or imports.

On the demand side, the available scenario literature suggests that the industry and the transport sector will require




(a) (b)

**Figure 8.13** (a) Breakdown of $H_2$ and RFNBO demand by sector in 2040 according to assessed scenarios (left); (b) Breakdown of $H_2$ and RFNBO supply in 2040 according to assessed scenarios (right).

hydrogen and/or RFNBO for decarbonization. By 2040, industry demand is expected to be two to three times higher compared to that in transport. However, the projected overall demand for hydrogen and RFNBO varies significantly across scenarios, with NetZero2040 scenarios indicating a three to four times higher demand (236–322 PJ), driven primarily by industry and transport, in comparison to the Transition 2040 scenario (106 PJ). Discrepancies among available literature are furthermore observable with respect to the demand category 'others', which includes the residential, service and agriculture sector. While the Transition 2040 scenario does not foresee any uptake of hydrogen or RFNBO, the NetZero2040 scenarios project demand increases comparable to that of the transport sector. They agree, however, regarding the use of hydrogen for the electricity sector and district heat supply, especially for peak loads during times of low renewable infeed.

On the supply side, assessed scenarios agree that imports will meet most of the hydrogen and RFNBO demand, though the extent of imports required varies among scenarios, corresponding to the overall projected demand for types of fuels.

### 8.4.4. Economic impacts

This section assesses and compares existing holistic scenarios for Austria that include macroeconomic effects in terms of their economic impacts. In general, there is limited Austrian-specific literature that combines holistic energetic-emission scenario analysis with the assessment of economic impacts of scenario measures (Gugele et al., 2022; Umweltbundesamt, 2023c, 2023e, 2024).

#### The EAA's WEM, WAM, Transition 2040 scenarios for the Austrian Ministry of Climate Protection (BMK) and EU monitoring mechanism

In order to estimate the macroeconomic consequences of EAA's mitigation scenarios (Umweltbundesamt, 2023c, 2023e, 2024) in terms of employment, value creation, private consumption and income distribution, the MIO-ES model (Kratena and Scharner, 2020) was employed. The results of the WAM 2023 scenario are compared with those of the Transition 2040 scenario. The WEM 2023 scenario serves as the reference scenario or base scenario for both cases. The


Figure 8.14 Changes in macroeconomic variables in the WAM 2023 and Transition 2040 scenarios compared to the WEM 2023 reference scenario (Umweltbundesamt, 2023c).

scenarios are based on assumptions regarding energy and $CO_2$ prices, investments, and sectoral measures.

In all three scenarios, employment and value creation increases between 2023 and 2050. However, investment requirements for the climate-relevant measures included in the WAM 2023 and Transition 2040 scenario result in higher economic growth rates than in the WEM 2023 scenario (Figure 8.14). The WAM 2023 scenario indicates that, on average, approximately 37,000 additional full-time equivalent jobs will be created per year between 2023 and 2040 compared to the baseline WEM 2023. Transition 2040, on the other hand, suggests that there will be around 50,000 additional full-time equivalent jobs created per year over the same period. Thus, average employment figures for the period 2023–2040 are 0.85 % (WAM 2023 scenario) and 1.15 % (Transition 2040 scenario) higher than in the WEM 2023 scenario. The average unemployment rate in the WEM 2023 scenario is 4.9 % between 2023–2040, while it is slightly lower in the WAM 2023 scenario at 4.3 % and in the Transition 2040 scenario at 4.2 %. WAM 2023 and Transition 2040 furthermore outperform the WEM scenario in terms of value added.

The drivers of value creation and employment in the scenario WAM 2023 and Transition 2040 are investments in the areas of energy supply, transport, buildings, and industry that are included in the modeled sectoral measures. On average, the investment level is 4.8 % higher in the WAM 2023 scenario and 6.4 % higher in the Transition scenario than in the WEM 2023 reference scenario. As a result of the additional production and employment stimulated by the investments, private consumption also increases.

Considering industry-level effects, the additional investments in the WAM 2023 and Transition 2040 scenario yield positive outcomes with respect to value creation and employment, among others in the construction sector and the economic sectors upstream. These sectors are stimulated due to the infrastructure expansion of public transport, cycling infrastructure, the building sector (renovation and boiler replacement) as well as renewable electricity generation, electricity storage and transmission. Notably, construction is a labor-intensive industry, requiring more workers per unit of production unit compared to other industries, which further supports domestic jobs creation.

In terms of the distributional effects, the impact assessment presents a positive outlook, indicating that the disposable household income of all income groups remains above the levels projected in the baseline WEM 2023 scenario well into the 2030s (Figure 8.14). Thereby, disposable income growth is more pronounced among the lower-income than among upper-income quintiles. This can be attributed to low-income earners deriving greater benefits from the increase in employment than their more affluent counterparts. Additionally, reimbursement measures like the climate bonus ('Klimabonus'), which slightly benefits lower-income households, and income-based subsidies, such as the government's 'Clean Heating for All' initiative to address energy poverty, have a dampening effect because they reduce the energy costs of low-income households. From the mid-2030s onwards, electricity prices in the Transition 2040 scenario are projected to be approximately 10 % higher than in the WEM 2023 and WAM 2023 scenario. This increase may place added financial pressure on the low-income households. However, in line with the principles of a Just Transition, targeted subsidies are provided to compensate negative side effects of the transformation for the lower-income groups.

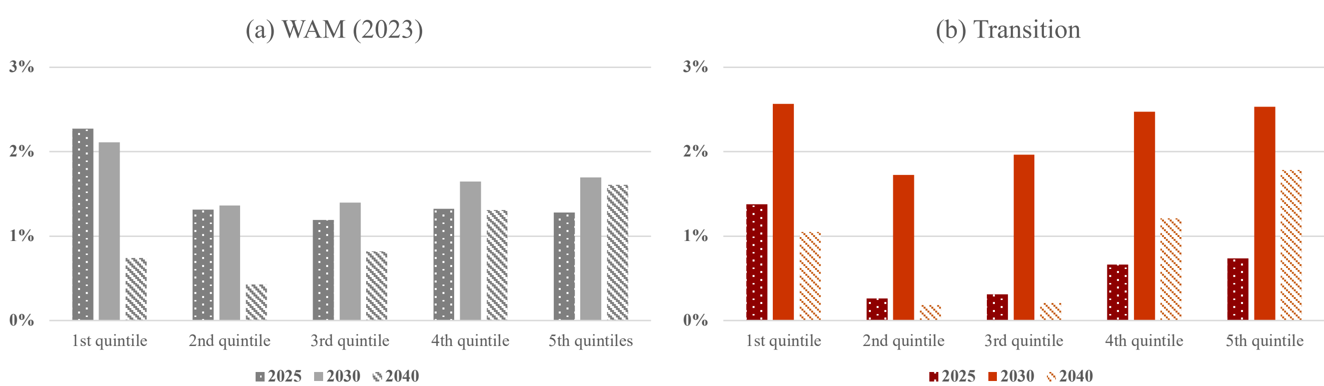



**Figure 8.15** Changes in disposable income by quintile in the WAM 2023 and Transition scenarios compared to the WEM 2023 scenario (Umweltbundesamt, 2023c).

## Base and activity scenarios for long term budget forecast for the Austrian Ministry of Finance (EAA-BMF scenarios)

The economic impacts of the WEM 2023, WAM 2023, Transition 2040 (Section 8.4.4) scenarios are comparable to those of the scenarios conducted by the EAA for the Austrian Ministry of Finance (EAA-BMF scenarios) (Gugele et al., 2022). In the latter scenarios, the economy in the Activity scenario demonstrates greater annual and cumulative growth than in the Base scenario. The additional cumulative value added in the Activity scenario amounts to approximately 1.3 % in 2050, compared to the Base scenario. In addition to investment requirements, the expansion of renewable energy infrastructure in Austria reduces the import requirements for fossil energy sources, which lowers expenditures on fossil energy imports. Finally, government subsidies, some of which are distributed directly to households as transfers and some of which trigger investments in climate protection measures, have a direct and indirect growth-promoting effect.

Figure 8.16 shows the cumulative macroeconomic effects (the levels of variables in the two scenarios are compared over the simulation horizon) as compared between Base and Activity scenario. In the Activity scenario, the investments required for the transformation increase by approximately 8 % compared to the Base scenario until 2035, which represents the peak of investments in decarbonization. Thereafter, investments stabilize at a higher level. From 2040 onwards, the combination of low inflation and lower fossil imports, along with the expansion of renewable energy sources, contributes to economic growth despite a decline in investments. The positive growth effects, reduced import costs for fossil fuels and new taxes, such as increased $CO_2$-taxes compensating for falling tax revenues from fossil sources, result in an overall government deficit and debt-to-GDP ratio that remains almost the same in the Activity scenario as compared to the Base scenario (Gugele et al., 2022).

It should be emphasized that GDP growth effects are contingent upon the rapid expansion of renewable electricity generation capacity. In particular, the favorable development of electricity prices from 2040 onwards, determined by model assumptions, represents as significant driving force for additional economic growth. Given that electricity will be by far the most important energy source in Austria from 2040 onwards, electricity prices are expected to have a major impact on the national economy. In addition, two areas warrant particular attention with regard to investment. On the one hand, investments in the expansion of renewable electricity production. Initially, this entails the implementation of the Austrian directive on the expansion of renewable electricity (‘Erneuerbaren Ausbau Gesetz’). Thereafter, investments must be maintained at a high level or increased until 2040. From 2040 onwards, investment in renewable electricity production declines as the economy has largely converted to a primarily electricity-based energy supply. On the other hand, the Activity scenario highlights investments in the building sector (implementation of the ‘Heating Fu-

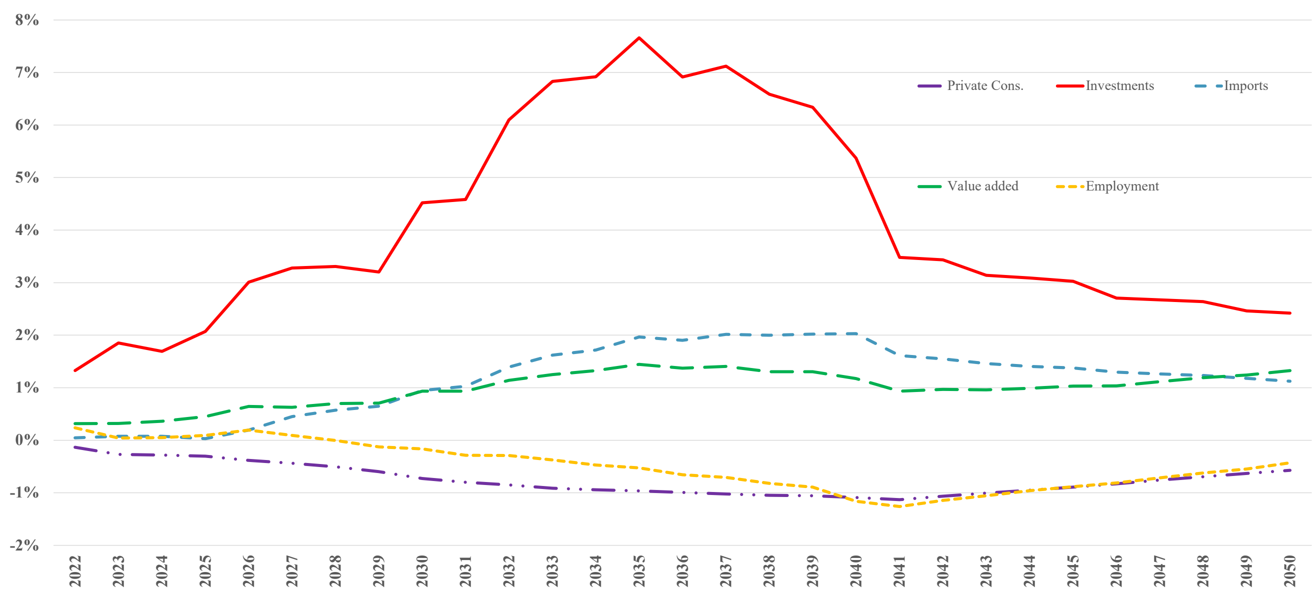



**Figure 8.16** Overview of macroeconomic effects – cumulative change in the Activity scenario compared to the Base scenario (Gugele et al., 2022).

Table 8.1 Total and additional investments in the Austrian economy (transition scenario, 2024–2040/2050; $EUR_{2023}$ billion) (Weyerstraß et al., 2024).

| Emissions sector | Total investments (mean) | Additional investments (lower bound) | Additional investments (upper bound) | Additional annual investments (lower bound) | Additional annual investments (upper bound) |
|---|---|---|---|---|---|
| Industrial production | 21.4 | 8.4 | 15.0 | 0.5 | 1.0 |
| Energy production | 160.5 | 37.4 | 80.7 | 2.3 | 5.1 |
| Transport/mobility | 323.0 | 43.8 | 63.5 | 2.7 | 4.0 |
| Buildings | 360.6 | 10.0 | 14.6 | 0.7 | 0.9 |
| **Total** | **865.6** | **102.5** | **173.7** | **6.2** | **10.9** |

ture for Buildings 2050' scenario), which will be highest in the first half of the 2030s. Thereafter, investment declines from 2035 (exit from oil heating systems completed) and 2040 (exit from gas heating systems completed). After 2040, investments remain for building renovations.

In 2040, the levels of employment and private consumption in the Activity scenario are about 1 % below the Base scenario. This can be attributed to the interaction of several factors. First, the relatively stronger increase in energy prices in the Activity scenario ($CO_2$ price, electricity prices) induces higher wages, which moderately retard employment growth due to labor being substituted by capital in the production process. Second, higher energy prices dampen private consumption, especially among low-income deciles. Third, the high capital intensity of the work required for the transformation contributes to a shift in the production structure from labor to capital. While some of the measures, such as the thermal refurbishment of buildings, have a high share of labor input, others demonstrate high capital input requirements (e.g., the expansion of wind turbines for renewable electricity production). Rising electricity prices are a further important driver of consumption prices. This can be attributed to wage-price spirals implemented in MIO-ES, whereby all energy prices also co-determine wages and thus employment as well as consumption.

## Investment needs

The most recent estimation of additional investment requirements for the Transition 2040 scenario that almost achieves climate neutrality by 2040 differentiates between total investments and additional investments. The sectoral coverage encompasses industrial production (in particular, the steel, cement and chemical industries), energy production (wind, PV, biomass, hydrogen, energy networks [electricity, hydrogen]), buildings (energetic-thermal retrofitting), and transportation (public transport, E-mobility).

Additional investments are defined as investments in addition to the usual sector-specific investment cycles. The investment in an electric blast furnace, for instance, would only be considered additional if the investment costs exceed that of a coal-fired blast furnace. In contrast, if the investment were cost-neutral and aligned with the investment cycle of the steel-producing company (i.e., if a new blast furnace were necessary regardless of climate policies), additional investment costs would be minimal and potentially negative if carbon-neutral investments were more cost-effective than fossil ones.

Table 8.1 provides a summary of total and additional investments for the Transition 2040 scenario for the period 2022–2050. Further details are documented in Weyerstraß et al. (2024).

The estimates displayed in Table 8.1 are based on a broad range of assumptions, including those pertaining to investment cycles, carbon prices, technological planning and choices. Furthermore, some investments extend into the period of 2040–2050 (e.g., industrial production). Investments and policies in other sectors (e.g., land use, agriculture, forestry) are not included in the table. It is noteworthy that additional investments for climate neutrality in 2040, according to the underlying scenario, amount to approximately 14–17 % of total investments.

In relation to GDP, additional investment requirements amount to approximately to $EUR_{2023}$ 6.2 to 10.9 billion (roughly 1.1 to 1.9 % of GDP in relation to cumulative forecast GDP for 2024 to 2040).While only one recent Austrian estimation study is available on the total and additional investments necessary to achieve emission reductions outlined in the Transition 2040 scenario, the range of the GDP share of investments is broadly in the same order of magnitude as that of similar Austrian studies (e.g., Stern, 2007; Miess et al., 2022; Bröthaler et al., 2023). One of the most recent international studies on additional investments for decarbonization in Europe, published by Institut Rousseau (2024), estimates that additional annual investments amount to approximately 2.3 % of European annual GDP until 2050. It should be noted that an important prerequisite for all estimates is that current fossil investments must be shifted towards decarbonization.

### 8.4.5. Scenario assessment with regard to sustainable development and available carbon budgets

#### Austrian mitigation scenarios and the Sustainable Development Goals

This section assesses and compares Austrian mitigation scenarios based on their contribution to the SDGs. Due to the fact that only two scenarios include mitigation options beyond the energy system (Section 8.4.2), analysis is limited to energy-related supply and demand options. Due to data limitations regarding the relevant proxies, only the NetZero2040 scenarios and the EAA's WAM and Transition 2040 scenario were evaluated. To ensure comparability, the assessment is restricted to energy system mitigation options (for a detailed description of the methodology, see 8.A.1). As discussed in Section 8.3.1, synergy potentials between individual mitigation options and SDGs generally outweigh trade-off potentials. As shown in Figure 8.17, the scenario analysis also reflects this, with the cumulative synergy potential of modeled mitigation options exceeding trade-off potential. However, the mitigation options are not all implemented to the same extent in the different scenarios. Dark green or red interactions thereby indicate the highest and light green or red the lowest synergetic and trade-off potential compared to other scenarios.

The quantitative assessment reveals that the Transition 2024 scenario has the highest trade-off potential, while the NetZero2040 scenarios with low demand show the highest synergy potentials. This reflects the high synergy potentials identified for demand side mitigation options (Section 8.3.1). How considered mitigation options are implemented is key realizing synergy or trade-off potentials. The NetZero2040 high-import /low-demand scores high for SDG synergy potentials, primarily due to externalized negative spillovers.

As the current assessment only indicates the synergy and trade-off potentials that exist within Austria, it is important to mention that any scenario with high import and export levels may have negative impacts on global SDG attainment due to spillover effects. The expansion of renewable energy infrastructure, for instance, depends on the availability of critical materials and could introduce trade-off if those materials are sourced from countries with low environmental and employment standards. Hence, although domestic synergy potentials may be high, trade-off potentials might be higher if spillovers beyond Austria are considered. As spillovers are context specific, they were not assessed within this framework but need to be considered and assessed when designing mitigation strategies. The *Spillover Index* tracks these impacts along the three dimensions of (a) environmental spillover, (b) social impacts embodied into trade, economic activities and finance, and (c) security. Thereby, a higher score reflects more positive spillover effects from Austria to the rest of the world with regards to the SDGs. Currently, Austria scores 59.9, ranking as low as 152 of 166 countries (Sachs et al., 2023) and 64 on the European index, placing 19th of 31 countries (Lafortune et al., 2024).

As adaptation options were not included in the assessed scenarios, they could not be assessed here but should be considered for climate-friendly transformation pathways.

| | SDG1 | | SDG2 | | SDG3 | | SDG4 | | SDG5 | | SDG6 | | SDG7 | | SDG8 | | SDG9 | | SDG10 | | SDG11 | | SDG12 | | SDG13 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | T | S | T | S | T | S | T | S | T | S | T | S | T | S | T | S | T | S | T | S | T | S | T | S | T |
| NetZero2040 high-import/high-demand | + | - | + | | + | - | + | | + | | + | - | + | - | + | - | + | - | + | - | + | | + | | + | - |
| NetZero2040 high-import/low-demand | + | - | + | | + | - | + | | + | | + | - | + | - | + | - | + | - | + | - | + | | + | | + | - |
| NetZero2040 low-import/high-demand | + | - | + | | + | - | + | | + | | + | - | + | - | + | - | + | - | + | - | + | | + | | + | - |
| NetZero2040 low-import/low-demand | + | - | + | | + | - | + | | + | | + | - | + | - | + | - | + | - | + | - | + | | + | | + | - |
| UBA Transition 2040 | + | - | + | | + | - | + | | + | | + | - | + | - | + | - | + | - | + | - | + | | + | | + | - |

| | |
|---|---|
| S | Synergies |
| T | Trade-offs |
| + | Synergies |
| - | Trade-offs |

Very high interaction potential
High interaction potential
Medium interaction potential
Low interaction potential

Figure 8.17 Relative implications of different Austrian mitigation scenarios for the SDGs. Shading indicates strength of synergy, with darker shading representing the highest and lighter shading the lowest interaction potential.

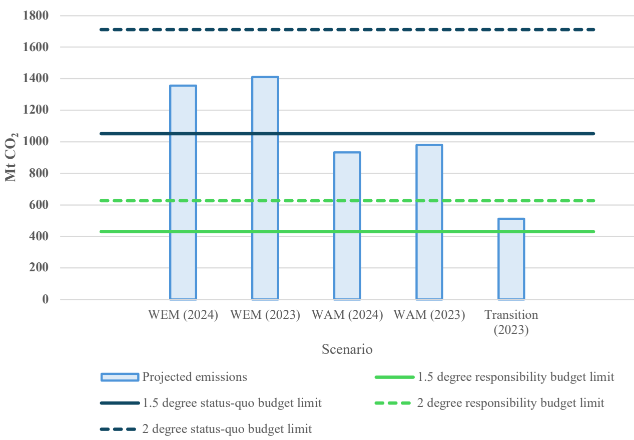



**Figure 8.18** Projected emissions from specified scenarios, for the period 2022 – 2050, and respective adherence to equity-based carbon budgets for the same period.

### Austrian mitigation scenarios and carbon budgets under varying fairness criteria

As illustrated in Section 8.2.2, most distributions of a remaining global carbon budget to Austria for the period 2022–2050 are negative, implying net carbon removals for the entire period. As negative emission technologies, e.g., carbon capture and storage, are yet not technically or politically feasible in Austria, this would imply that most budget allocations targeted at 1.5°C or well below 2°C of temperature rise are unachievable for the country without significant changes in the political landscape. For both 1.5°C and 2°C targets, the only fairness principle leading to allocations still achievable is responsibility – some interpretations of this principle result in budgets of up to ~430 $MtCO_2$ (1.5°C target) or ~626 $MtCO_2$ (2°C target) (CCCA, 2022) (third quartile values of responsibility budget estimates from Figure 8.2b). Both the WEM and WAM scenarios from the EAA would exceed these thresholds, with the WAM scenario approaching the 2°C limit. The Transition 2040 scenario, in contrast, would be compatible with a 2°C budget in some manner recognizing responsibility for past emissions. However, allocations based on status quo approaches, e.g., grandfathering, would allow for significantly higher budgets – but these are not considered to be consistent with considerations of fairness. Status quo approaches targeting 2°C of temperature rise would lead to budgets with more emissions than those projected in both WEM and WAM.

## 8.5. Politico-economic and socio-cultural feasibility challenges for climate-friendly transformation pathways

So far, little attention has been paid in climate research to the political, economic, social, and cultural conditions necessary for successful transformations – both within Austria and in the context of broader developments that affect the country. This section complements the literature on technological feasibility by assessing the social science literature on the politico-economic and socio-cultural feasibility challenges of achieving climate targets. This will contribute to closing the implementation gap resulting from the difficulty to implement effective measures due to societal and political resistance.

Given the broad agreement among researchers in favor of broader climate targets, the APCC (2023) introduces the concept of 'climate-friendly living', which seeks to foster a good life for all within planetary boundaries. In line with this definition, climate-friendly transformation pathways aim to reduce both direct and indirect emissions to achieve mitigation targets (climate neutrality), limit vulnerability to climate change through adaptation (climate resilience), and, more broadly, ensure decent living standards (Aigner et al., 2023d). This section assesses factors that potentially hinder or enable climate-friendly transformation pathways, which in turn affect the likelihood of achieving climate targets.

Currently, there is considerable societal acceptance for democratic climate governance, with high levels of acceptance for more ambitious climate actions in Austria (Margotti, 2024), in Europe (Abou-Chadi et al., 2024) and globally; 73 % would be even willing to contribute 1 % of their income (Andre et al., 2024). In Austria, 86 % of respondents indicated that they believe democracy to be the best form of political organization (Zandonella, 2021). Additionally, 73 % expressed trust in science (ÖAW, 2023) and 75 % of people expressed concerns that necessary measures to combat climate change have not been implemented in time (INTEGRAL, 2022).

Notwithstanding this support, effective climate policymaking is confronted with various forms of climate-action-delaying practices. Although the outright denial of (the effects of) climate change has been marginalized in public debate, discourses of climate delay – defined by Cass et al. as "arguments in public discourse for climate inaction by governments, individuals, and other actors" (2023, p. 2) – have increasingly influenced climate policies. These discourses tend to redirect responsibility, ignore the costs of inaction,

Table 8.2 Overview on inhibitors and enablers of climate-friendly transformations.

| Meta-level policy fields | Inhibitors of climate-friendly transformations | Enablers of climate-friendly transformations |
|---|---|---|
| **Global governance** | • Contested global climate governance<br>• Market-biased governance limiting policy space<br>• Precedence of national security policies over cooperative governance | • Effective democratic policy space<br>• Increasing strategic autonomy and reducing import dependency through sufficiency and avoid-measures |
| **Democracy, law and science** | • Democratic climate-action-delaying policies<br>• Science skepticism and culture war-rhetoric | • Linking representative with deliberative and participatory forms of democracy, and scientific expertise<br>• Emphasizing benefits of climate action alongside costs of inaction<br>• Climate litigation and lawsuits |
| **Politico-economic framework conditions** | • Macro- and micro-economic growth imperatives<br>• Power of incumbent business interests<br>• Dominance of de-risking policies<br>• Contested European Green Deal | • Coordinated economic planning to foster innovation and exnovation<br>• Limiting incumbent business interests<br>• Fiscal, monetary and industrial policies combining a ‘sticks and carrots’ policy mix |
| **Socio-cultural framework conditions** | • Status quo bias (defending unsustainable and inegalitarian consumption patterns)<br>• Awareness-action gap<br>• Advertisement promoting fossil fuel-based overconsumption | • Eco-social policies to reduce inequalities and enhance well-being for all<br>• Broader alliances based on benefits for everyday life |
| **Adaptation** | • Implementation gap due to missing sense of urgency, insufficient political leadership, and lack of dedicated budgets<br>• Limits to adaptation shrink the action space for policy | • Iterative climate risk management can leverage the scale, scope and speed of implementation<br>• Transformative adaptation can substitute incremental adaptation if it becomes unable to limit residual damages to acceptable levels |

advocate for non-transformative solutions (Lamb et al., 2020), or justify high-carbon lifestyles by referring to luck and merit rather than privilege (Cass et al., 2023).

## 8.5.1. Global governance

### Inhibitors of climate-friendly living

A key inhibitor for climate-friendly living is the ineffectiveness of global climate governance. Veto coalitions, formed by fossil fuel lobbies, continue to block progress and hinder the implementation of existing commitments (Hollaus et al., 2023; Romanello et al., 2023; Zeller, 2023; Bärnthaler et al., 2024) (Sections 6.2, 6.4.2). COP28, held in Dubai as part of a series of three consecutive COPs organized by oil-exporting countries, saw record-high participation of fossil lobbyists. This resulted in delays to climate action, tolerated by key political players (Global Witness, 2022; Green et al., 2022; Romanello et al., 2023; Zeller, 2023; Bärnthaler et al., 2024). While some nations in the Global South, particularly the BRICS countries, have gained influence in climate negotiations (Skjærseth et al., 2021), many low-income countries have experienced a decline in negotiation power due to increasing debt (UNCTAD, 2023). Actors from the Global North continue to demonstrate reluctance in terms of concretizing and implementing the principle of ‘common but differentiated responsibilities’ (UN General Assembly, 1994; Fisher, 2015). Despite numerous commitments, including those made by the EU, compliance with climate financing obligations remains to lack behind (Fanning and Hickel, 2023), as does the pledged support for loss and damage compensation (Baumann, 2024). COP28 furthermore reinforced discourses that delay climate-action, focusing on gradual decarbonization such as ‘transitioning away from fossil fuels’ (Wise, 2023) and ‘phasing out of fossil fuels’ (Engels et al., 2023b). These discourses support maintaining carbon-based infrastructures (Durrant et al., 2023; Hansen, 2023), while emphasizing Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU) technologies (Pichler et al., 2021; Global Witness, 2022; Green et al., 2022; Romanello et al., 2023; Zeller, 2023; Bärnthaler et al., 2024). The emphasis on CCS and CCU, along with the broader structural preference for techno-economic interests, is reinforced by scientific research that promotes these technologies without adequately addressing their limited potential, associated risks, and high costs (Anderson, 2015; Anderson et al., 2018; Stoddard et al., 2021).

Over the past four decades, neoliberal globalization has significantly shaped global institutional frameworks, actor constellations, and power relations (Jessop, 2004; Lorek and Fuchs, 2013; Brand et al., 2020). Market-biased governance has limited national public institutions and created global economic institutions, equipped with strict legal remedies, including mandatory dispute settlement mechanisms for international trade (Rodrik, 2011, 2017). While being entitled to enforce rules on economic governance, they lack the power to enforce rules for effective climate actions (Streeck, 2014; Fremstad and Paul, 2022). As a result, sustainable development targets remain voluntary, and mitigation targets are subject to ineffective enforcement mechanisms (Rajamani, 2016; Rajamani and Bodansky, 2019).

Geopolitical rivalries are impeding progress on SDG17: Partnerships for the Goals, and undermine global governance, particularly rules- and rights-based frameworks (Keohane and Victor, 2011; Keohane, 2015), which in turn further weakens UN institutions (Elsig et al., 2016). This has resulted in stagnant foreign direct investment (Reiner and Edlinger, 2023), the emergence of new forms of multi-scalar global production networks (Fischer, 2020; Novy, 2022; Fischer et al., 2023), and increased competition for critical raw materials such as cobalt and lithium (Brand and Wissen, 2024; Tröster et al., 2024). There has furthermore been a precedence of national (energy) security policies over cooperative climate governance (Streck and Terhalle, 2013; Selby and Hoffmann, 2014; Baumgartner et al., 2023; Hitzl, 2023; Pagnone et al., 2023) and the achievement of decarbonization targets (Roy and Schaffartzik, 2021; Baumgartner et al., 2023). Moreover, rising military expenditure frequently diverts funding from other public investments needs (Ikegami and Wang, 2023; Tipping Point North South, 2023; Tian et al., 2024). The significant social-ecological 'externalities' of standing armies, conflicts, and wars (Bonneuil and Fressoz, 2017; Rajaeifar et al., 2022) are thereby frequently overlooked. This dynamic reinforces delays in implementing climate measures, exemplified by the sentiment of 'in principle yes, but not now', and even fosters a 'fossil backlash', as European governments expand their liquefied natural gas (LNG) infrastructures (InfluenceMap, 2023; Zeller, 2023). In Austria, fossil energy imports averaged EUR 9 billion annually from 2010 to 2021, rising to EUR 10.7 billion in 2023, highlighting the vulnerability of the Austrian economy due to its heavy dependence on fossil fuel imports (Section 6.7.2). In parallel, profits of Austrian companies such as Schoeller-Bleckmann Oilfield and OMV boomed in 2022 and were accompanied by increased emissions and close to zero alignment activities (Bukold, 2023; Zeller, 2023).

### Enablers of climate-friendly living

The resurgence of strategic and better planned economic policymaking that relies on more coherent state intervention may facilitate climate-friendly living. This 'return of the state' is underscored by initiatives such as the US Inflation Reduction Act, China's Belt and Road Initiative, the Net Zero Industry Act of the EU, and the increased protection of critical resources in the Global South – all of which may expand policy space at the EU and national level (Aiginger and Rodrik, 2020; van Apeldoorn and de Graaff, 2022; AK Europa, 2023; McNamara, 2023). Forms of re-, near- and friend-shoring are proliferating (Fischer et al., 2023), such as the shift from Russian gas to US-LNG, with imports rising from 73.7 million $m^3$ (2021) to 122.8 million $m^3$ (2022) (Zeller, 2023). If grounded in international cooperation and a comprehensive understanding of climate policy as part of sustainable development (Skjærseth et al., 2021; UNCTAD, 2023; Brand and Wissen, 2024), this expanded policy space can help overcome departmental thinking and silo approaches to climate policymaking. Strategic autonomy and reducing reliance on fossil fuel imports can be pursued through sufficiency and avoid-strategies (Hache, 2022; Brizga et al., 2023; Hitzl, 2023; Statistik Austria, 2023), as well as by promoting circular economy approaches (Nature Editorial, 2023). This broader approach to protection from harm and security extends beyond military considerations (Mandelli, 2022; Bohnenberger, 2023; Koch et al., 2023) and integrates climate justice (Brand and Wissen, 2024). Ultimately, these efforts can unlock the synergistic potentials between climate action and the SDGs.

## 8.5.2. Democracy, law and science

### Inhibitors of climate-friendly living

Although Austria has formally committed to the Paris Climate Agreement (Hollaus et al., 2023; Steurer et al., 2023) (Section 6.3.1), climate politics up until 2019 exhibited notable tendencies toward delaying climate action. Emissions remained consistently above 60 $MtCO_2$ per year, demonstrating little change from the 1990s through 2020 (Aigner et al., 2023e) (Section 8.2.2). The absence of enforceable implementation rules in the climate law ('Klimaschutzgesetz', Section 6.3.3) indicates the ineffectiveness of climate measures (Nash and Steurer, 2021), largely due to the lack of clearly assigned responsibilities and enforceable rules (Hollaus et al., 2023). Social partners, the federal government, and the provincial governments prioritized short-term socio-economic gains over long-term mitigation and adaptation efforts (Wieser and Kaufmann, 2023). Following 2019, global civil society mobilization, the European Green Deal (EGD), and the formation of a new Austrian federal government – comprising conservatives and Greens – led to the implementation of climate policies designed to be more effective. These measures included the introduction of a climate bonus (‘Klimabonus’), energy communities, and a carbon tax in Austria (APCC, 2023). As a result, there has been notable sectoral policy progress (Section 6.4.2) and reductions in $CO_2$ emissions. Some social partners, particularly those representing employees (trade unions and the Chamber of Labor), became more amenable to transformative climate policies, establishing institutions like the ÖGB-Klimabüro and drafting transformation plans such as the AK-Umbauplan (AK Wien, 2024) (Section 4.8). However, following the pandemic, the war in Ukraine, and the cost-of-living crisis, Austria experienced a resurgence of climate-action-delaying policies, also of social partners (Section 6.4.1). Measures with long-term impact – such as binding regulations on land use, biodiversity and $CO_2$-pricing – were deferred, jeopardizing the progress on the relevant SDGs, including SDG7: Affordable and Clean Energy and SDG12: Life on Land. Employer-oriented stakeholders called for less ambitious climate measures regarding the phase-out of oil and gas (Arnecke, 2024), missing opportunities to enhance long-term resilience (Hüther et al., 2024). Meanwhile, unions have been calling for an economic stimulus package that includes resource-intensive measures such as subsidies for single-family homes (Arnecke, 2024). As a consequence, opportunities for social-ecological forms of basic provisioning, redistribution, and progressive options to design such policies have been missed (Brand and Niedermoser, 2019; Bärnthaler et al., 2021; Büchs et al., 2021; Keil and Kreinin, 2022; Oswald et al., 2023; Chancel et al., 2024).

In Austria, a significant gap remains between its self-image as a country with high environmental standards and the reality of unsustainable practices across many sectors (Section 6.4). In their study of climate delay discourses in Austria, Frühwald et al. (2024) identify various tactics employed to impede climate action. Political actors dominate the climate debate in the media, representing 34 % of all statements and being the most frequent users of delaying rhetoric. In contrast, civil society contributes most constructive statements, accounting for approximately 25 % of contributions. Among political actors in Austria, six out of ten delaying statements originate from the ÖVP, while the FPÖ is responsible for three. Notably, the only instances of explicit climate change denial in the sample also originate from the FPÖ. The most discussed topics – such as the Climate Protection Act (‘Klimaschutzgesetz’), the European Green Deal, and the Renewable Heat Act (‘Erneuerbare-Wärme-Gesetz’) – are disproportionately subject to delays. This suggests that the defense of the status quo intensifies as pressure for change increases in these areas. Common delaying tactics include emphasizing perceived disadvantages while ignoring the costs of inaction (e.g., in Pearson, 2024).

Discourses of climate delay are also prevalent in emerging forms of reactionary politics, as exemplified by Donald Trump (USA, 2017–2020) and Jair Bolsonaro (Brazil, 2019–2022). These leaders promote anti-liberal, anti-egalitarian and anti-science political agendas (Lockwood, 2018; Novy, 2022; Jaeggi, 2023; Sælen and Aasen, 2023). Their rejection of anti-discrimination policies and hostility towards scientific expertise distinguishes them from other types of climate delaying practices (Kulin et al., 2021; Ekberg et al., 2022; Dannemann, 2023). These actors instrumentalize climate policies as part of a broader culture war, framing climate action as an ideological battleground (Abou-Chadi et al., 2024). Such an approach induces a backlash in climate policymaking by rigidly defending the convenience of certain existing forms of life (Brand and Wissen, 2017; Blühdorn, 2022) (Section 6.2), capitalizing on a ‘status quo bias’ (Börjesson et al., 2016) and exploiting ‘trigger points’ to provoke opposition (Mau et al., 2023). Traditional and social media further amplify these delays (Theine et al., 2023), often driven by their reliance on advertising revenue from incumbent political and economic actors. This leads them to prioritize sensationalist and negative news to attract attention (Kalpokas, 2018; McIntyre, 2018), reinforcing the disconnect between newsworthiness and the actual usefulness of the information presented (Perga et al., 2023).

## Enablers of climate-friendly living

Liberal constitutional democracies mediate between individual freedom and social order to balance between sectional interests and freedoms (Kelsen, 2006). While fundamental rights constrain political decision-making, democratic rulemaking can impose restrictions on individual freedoms when they obstruct the freedoms of others (Kelsen, 2006), including those of specific social groups or future generations. Fundamental rights protect individuals and qualified minorities from disproportionate interference, obligating lawmakers to impose only proportional restrictions and to carefully weigh competing rights and freedoms (Kelsen, 1929). In the context of climate change, legislators must consider fundamental rights and the principle of proportionality when imposing climate-related bans and restrictions (e.g., diesel bans or bans on advertisement) that impact economic and property rights. Especially, since courts at various levels (domestic, European and international) have established connections between the harmful effects of climate change and fundamentals rights, as well as other constitutional environmental provisions (Hollaus et al., 2023).

Over the past years, individuals and NGOs have filed numerous lawsuits addressing the lack of climate action. Climate litigation is thus another important enabler of climate-friendly living (Section 6.6). There are several key take-aways from climate cases: From an intertemporal perspective, lawmakers may be required to implement emission reduction measures in a timely manner and establish rules and targets that provide clarity and certainty for societal transformation towards climate-neutrality. This duty is reflected in rulings such as the German Federal Constitutional Court's Climate Protection Order (24.3.2021, BVerfGE 157,30, Cf Human Rights Law Journal HRLJ 299–326 (2021) (Hollaus et al., 2023). Additionally, human rights can impose a duty of care on the state, mandating legislators to protect citizens from the negative effects of climate change. The Dutch Urgenda ruling (ECLI:NL:HR:2019:2007) took a lead in this direction. In a landmark ruling ('Verein KlimaseniorInnen Schweiz and others vs Switzerland', 04/09/2024) the European Court of Human Rights (ECHR) established a fundamental right for individuals **to effective protection from serious adverse effects of climate change on their life, health, well-being and quality of life** (ECHR, 2024). The ECHR determines that states have a positive obligation to adopt and to apply coherent climate mitigation regulations in a timely manner (Arntz and Krommendijk, 2024). While the ECHR grants national legislators considerable discretion in the choice of climate protection instruments, it declared a science-based, plan-led climate policy a fundamental right (Hollaus, 2024).

Although several courts have identified inadequate climate laws, climate litigation also faces challenges and limitations (Section 6.6). In various jurisdictions, courts have adopted a restrictive interpretation of the right to bring cases to court, leading to the dismissal of several climate cases (e.g., the US Juliana case; the Carvalho decision of the Court of Justice of the European Union or the Children and Youth's Climate Case decision of the Austrian Constitutional Court) (Hollaus et al., 2023; Madner, 2023a). Overall, while climate policies must uphold fundamental rights, lawmakers and administrators retain considerable discretion in their decision-making. In rule-of-law-based societies, constitutions can only govern the transformation processes to a limited extent, leaving many specific decisions regarding the choice of means to tackle climate change – such as the policy framework and the choice of sectoral field – to political deliberation and (simple) majority voting (Hollaus et al., 2023; Madner, 2023a). Accordingly, the ECHR highlighted that "judicial intervention […] cannot replace or provide any substitute for the action, which must be taken by the legislative and executive branches of government" (ECHR, 2024, para. 411). However, the court also held that "democracy cannot be reduced to the will of the majority of the electorate and elected representatives, in disregard of the requirements of the rule of law" (ECHR, 2024, para. 411).

Linking representative with deliberative (e.g., climate assemblies) and participatory (e.g., at the workplace and in the neighborhood) forms of democracy can contribute to the implementation of more effective climate measures (Duvic-Paoli, 2022; Gough, 2022; Aigner et al., 2023d; Bärnthaler, 2023; Clar et al., 2023; Lage et al., 2023). This is particularly true if institutional mechanisms are established to translate deliberative democratic decision-making into public policy (Clar et al., 2023) and if corporate influence on political decisions is limited (Section 8.5.3). By integrating deliberative and participatory approaches into representative democracy, it becomes more likely to reduce status-quo biases, overcome transformational deficits (Haberl et al., 2020; Hammond, 2020), and bridge awareness-action gaps. Deliberative processes can shift people's fundamental norms and outlooks, fostering socio-cultural transformations (Hammond, 2020). Such a revitalized democracy does not merely reflect existing preferences but seeks to reorient them, promoting social acceptance by implementing policies that yield beneficial eco-social outcomes (Bärnthaler, 2024a) (Cross-Chapter Box 4). However, strengthening participatory forms of democracy needs to be aware of possible biases in participant recruitment, as this may limit democratic legitimacy (Blühdorn, 2024).

Increasing the newsworthiness of climate change research requires changes in mediatization, political communication, and science collaboration (Section 6.8.3) (Perga et al., 2023; Theine et al., 2023). First, to be more effective, news coverage can emphasize the benefits of climate action alongside the costs of inaction (Frühwald et al., 2024). This involves shifting the focus from individual actions toward the need for collective structural changes (Aigner et al., 2023d; Cass et al., 2023). Second, instead of focusing on end-of-the-century projections rooted in the natural sciences (Pielke and Ritchie, 2021), news can highlight local, present-day consequences of climate change. It can also illustrate how collective actions can contribute to transformative changes that reduce emissions in the long-run while making short-term progress towards the SDGs by capitalizing on potential synergetic effects (Overland and Sovacool, 2020; Perga et al., 2023; Theine et al., 2023) (Section 8.3.1). Effective climate science communication can be strengthened by integrating (quantitative) empirical research with insights from social sciences about institutional challenges (Biermann et al., 2012; Carey et al., 2014; Victor, 2015; Porak and Reinke, 2024; Spash, 2024). This requires a more contextual approach to climate science that evaluates various place-based alternatives through transdisciplinary research (Görg et al., 2017; Jahn et al., 2020; Plank et al., 2021; Aigner et al., 2023e), recognizing that science-society interaction must be honored in academic careers.

## 8.5.3. Politico-economic framework conditions

### Inhibitors of climate-friendly living

Key politico-economic factors inhibiting climate friendly transformation pathways are the micro and macro-economic growth imperative and related corporate strategies (Section 6.2). The growth imperative is rooted in the political economic structure of capitalist economies and actualized through interconnected mechanisms, including corporate competition, rent extraction, technological unemployment, state dependence on growth, positional consumer behavior, and rebound effects (Stratford, 2020; Wiedmann et al., 2020; Corlet Walker et al., 2021; Koch, 2022) (Cross-Chapter Box 7). They also manifest on a sectoral level, particularly in environmentally harmful industries such as aviation and the automotive industry, as staying competitive requires profit and continuous growth (Mattioli et al., 2020; Keil and Steinberger, 2023; Huwe et al., 2024). Additionally, powerful industries, often tied to carbon-intensive activities, exert political influence to weaken or obstruct climate regulations, entrenching growth-oriented agendas that conflict with systemic changes necessary to mitigate emissions (Newell and Paterson, 2010). In Austria, land use decisions are especially susceptible to these politico-economic influences based on the growth paradigm (Getzner and Kadi, 2020; Müller et al., 2024; Getzner et al., n.d.).

In this framework, corporate strategies tend to be insufficient for addressing climate change as many companies lack intrinsic motivation to support climate policies unless incentivized by win-win solutions or competitive advantages that benefit them and national industries in the short run (Engels et al., 2023a; Steurer et al., 2023; Wieser and Kaufmann, 2023). Despite a significant increase in financial incentives to boost efficiency (Fischer et al., 2023), sufficiency strategies tend to be underrepresented in climate mitigation (Zell-Ziegler et al., 2021; Lage et al., 2023). Specific timelines for phasing out harmful practices, such as fossil subsidies, for instance, are often missing (Kletzan-Slamanig et al., 2022). The influence of incumbent business interests – particularly the automotive industry, e.g., reinforcing car-dependency (Pichler et al., 2021; Bärnthaler et al., 2024), and the meat-based food industry (Penker et al., 2023) – inhibit and delay progress (Seto et al., 2016; Newell, 2019; Schaffartzik et al., 2021). Additionally, distribution of spending in EU lobbying is heavily skewed, with corporate lobbying far surpassing spending of labor and public-interest groups (Porak, 2023).

The European Climate Act aims to reduce GHG emissions by at least 55 % by 2030 compared to 1990 levels (Section 6.3.2). The European Green Deal promotes decarbonization through initiatives, including the 'Fit for 55' package, the 'Circular economy action plan' (focused on reducing non-renewable throughputs), the 'Biodiversity Strategy 2030', green public procurement, a more ambitious Emission Trading Scheme (ETS), the Carbon Border Adjustment Mechanism (CBAM), the 'Net Zero Industry Act', the EU taxonomy and the CSRD (Corporate Sustainability Reporting Directive) to promote ESG (environmental, social and corporate governance) accounting and investment strategies (Fischer et al., 2023) (Section 6.3.1, Table 6.1). However, EU climate policies tend to prioritize subsidizing new technologies and enabling markets while largely ignoring co-benefits and geopolitical advantages of demand reduction (Section 8.5.1). This can be partly explained by 'push' measures, e.g., bans and regulations, frequently encountering strong public opposition (AK Europa, 2023). The business-friendly 'Green Industrial Plan', for example, passed with minimal opposition (Gerasimcikova, 2023), whereas more ambitious proposals of the 'Farm to Fork Strategy' were significantly weakened by agro-industry lobbying (Corporate Europe Observatory, 2020; Holland and Tansey, 2022). Similarly, the 'EU Biodiversity Strategy 2030' was delayed and watered down due to pressure from business associations. Fossil corporations also lobbied against key legislative efforts such as the 'Energy Performance of Buildings Directive', 'Energy Efficiency Directive', and 'Hydrogen and Gas Decarbonization Package' (InfluenceMap, 2023). If the influence of political and business actors that oppose or delay climate action is not restrained – and if they even continue to gain influence – European climate policies risk becoming unpredictable, potentially delaying long-term investments and necessary exnovations (e.g., the deliberate phasing out of emission-intensive practices and business models) (Kubeczko et al., 2023). Wealthy fossil-fuel interests prioritize protecting their financial holdings over facilitating the energy transition, although wage earners would face minimal impact from potential pension fund losses due to stranded fossil assets (Colgan et al., 2021; Semieniuk et al., 2022).

Greening public finance is proceeding slowly and tends to focus on mitigation, thus neglecting expenditures for adaptation (Section 6.7.3). Public financing in general is constrained by strict fiscal rules in the EU, which jeopardize crucial public investments. Public climate financing tends to neglect further environmental objectives, in particular reducing resource use (including soil), protecting biodiversity, and supporting the circular economy (Kubeczko and Krisch, 2023; Mang and Caddick, 2023; Miess and Ornetzeder, 2023; Weber and Kubeczko, 2023) (Section 6.7.3). Green finance de-risking policies designed to attract private capital and facilitate green investment contain loopholes. Consequently, 'brown' investments (i.e., those tied to carbon-intensive industries) continue to dominate in absolute terms (Christophers, 2023; UNCTAD, 2023). Globally, de-risking strategies rely on voluntary pledges from a small group of highly polluting companies, known as the Carbon Majors (Carbon Majors, 2024). They primarily comprise fossil fuel, cement, and mining companies, being well aligned with major financial institutions, including the three largest asset management firms BlackRock, Vanguard and State Street (Baines and Hager, 2023). However, the role of green finance in achieving climate targets remain contested (Baines and Hager, 2023; Dziwok and Jäger, 2024; Kalinowski, 2024). Despite the increasing cost-competitiveness of renewable energy compared to fossil fuels, companies continue to invest in the exploitation of fossil energy sources. This can be attributed to private investment decisions being driven by expected return on investment rather than investment costs, with renewables remaining less profitable than their fossil alternatives (Christophers, 2024). The effectiveness of de-risking policies is limited due to weak conditionalities, the retention of veto power by private capital, and the lack of differentiation between investment in essential and non-essential sectors (Gabor, 2023; Gabor and Braun, 2023; Mazzucato and Rodrik, 2023).

## Enablers of climate-friendly living

In a just transition, effective planning of climate, economic, social and land use policies can enhance synergetic potentials with the SDGs and broaden the scope for climate policy action beyond market-driven approaches (Cerniglia et al., 2023; Gabor and Braun, 2023) (Section 6.8.1). The inaction and lack of coordination not only jeopardizes the achievement of climate targets but also threatens making progress on the SDGs, including goals on economic development and human well-being. On a global level, the projected economic costs of climate-related damages supersede the financial resources required to limit global temperature rise to 2°C by a factor of 6 (Kotz et al., 2024). In Austria, the monetized costs of inaction are expected to range between $EUR_{2023}$ 7.3 and 14.6 billion annually until 2050 (Steininger et al., 2020a). However, this estimate only accounts for monetized costs thus representing only a fraction of the actual costs of inaction, as so far not all impacts could be quantified in monetary terms. The health sector is anticipated to bear the highest costs, particularly in the form of lost healthy life years. In addition, other health impacts (e.g., injuries and deaths due to extreme events (floods) and increasing numbers of waterborne and foodborne diseases) have so far not been monetized (Steininger et al., 2015). In contrast, the expected annual additional investments for reaching carbon neutrality by 2040 in Austria are estimated to range between $EUR_{2023}$ 6.4 and 11.2 billion (Weyerstraß et al., 2024) (Section 8.4.4). Until 2030, annual investments of an additional 3.6–4.8 % of GDP are required to reach climate neutrality, which is expected to generate annual value-added effects of 2–2.7 % of addition GDP and create between 60,000 and 80,000 additional jobs each year (Miess et al., 2022). At the EU level, green public investment can be bolstered through various mechanisms, such as exemptions from fiscal spending restrictions, a 'Green Investment Golden Rule' to permanently exempt green investments from budgetary constraints, the creation of an EU Climate Fund (Pekanov and Schratzenstaller-Altzinger, 2023), or 'public green securities' (Section 6.7.3). A large share of the required additional investments can be mobilized be reallocating funds from fossil fuels to renewables (Section 6.7.1, Cross-Chapter Box 8).

The European Green Deal can be strengthened and inaction limited (Gough, 2017, 2022; Schulze Waltrup, 2023) by coordinated economic planning that adopts a 'sticks and carrots policy mix framework' (Dafermos and Nikolaidi, 2023) that curtails corporate power (Haas and Sander, 2020; Haberl et al., 2020; Fuchs and Dolinga, 2022; Vogel and Hickel, 2023; Bärnthaler et al., 2024). Monetary and financial policies could reduce capital requirements for green loans while increasing them for 'dirty' loans, facilitating a transition of the economic and financial sector (Dafermos and Nikolaidi, 2023; Gabor and Braun, 2023). In addition, **credit guidance** would enable central banks to steer private sector behavior towards socially and ecologically beneficial sectors. Industrial and labor market policies can guide companies in their decarbonization strategies, as outlined in the EU Net Zero Industry Act (Section 4.7), while creating high-quality jobs and protecting workers affected by restructuring through initiatives like a job guarantee and training programs (Froy et al., 2022; Upham et al., 2022; Schuberth and Soder, 2024). Furthermore, technological innovations must be paired with exnovations (i.e., the deliberate phasing out of outdated and harmful practices) (Lütkenhorst et al., 2014; Arnold et al., 2015; Kivimaa and Kern, 2016; Altenburg and Assmann, 2017; Haberl et al., 2020). Integrating employees and social partners in transition processes not only enhances legitimacy (Hofbauer et al., 2023), but helps prevent information failure (Pichler et al., 2021; Schuberth and Soder, 2024).

Climate-friendly fiscal policies can enhance progressivity through measures, including a wealth tax on the top 1 %, a tax on unrealized capital gains, and an increase of the minimum corporate tax. These initiatives could generate additional revenues of approximately 1.9–2.9 % of EU GDP annually (Guzzardi et al., 2023). Furthermore, eliminating climate harming public subsidies could save Austria between $EUR_{2023}$ 4.9–6.9 billion (Kletzan-Slamanig et al., 2022). To support low-income households, direct transfer payments can be implemented alongside initiatives promoting climate-friendly household appliances, subsidizing repairs, and facilitating the transition to efficient heating systems. Expanding access to high-quality public services and infrastructure, as a form of collective consumption, can further improve wellbeing while reducing energy demand (Vogel et al., 2021, 2024; APCC, 2023; Vogel and Hickel, 2023; Die Armutskonferenz and Ökobüro, 2024) (Section 6.5.1).

### 8.5.4. Social and socio-cultural framework conditions

#### Inhibitors of climate-friendly living

The current consumerist and inegalitarian mode of living obstructs climate-friendly living. Existing provisioning systems both arise from and reproduce inequalities of class, gender, and ethnicity (Brand and Wissen, 2017; Markkanen and Anger-Kraavi, 2019; Aigner et al., 2023a, 2023b, 2023f). Inequality, on the one hand, is a key driver of climate change, with wealthier households contributing disproportionately to the crisis (Chancel, 2022; Chancel et al., 2022; Theine et al., 2022; Millward-Hopkins and Oswald, 2023). At the same time, affluent households are less affected by the effects of climate change and related policies, while possessing greater adaptive capacity (Seebauer, 2021; Engels et al., 2023a; Essletzbichler et al., 2023; Dang et al., 2024; Gilli et al., 2024). Global emissions are also distributed unequally. In 2022, average annual per capita emissions in the EU27 and Austrian exceeded the world average by 1.5 and 2.2 $tCO_2$ respectively (Our World in Data, 2023). Despite being sustained at the expense of others (Brand and Wissen, 2021), the Western mode of living is often considered 'non-negotiable' (Blühdorn, 2022; Hausknost, 2023). On the other hand, inequality hampers effective climate action. Wealthy elites, for instance, can obstruct climate policies by undermining societal support and increasing political resistance, thereby eroding the social foundations necessary for collective action (Green and Healy, 2022; Aigner et al., 2023d). If economic and social policies fail to provide adequate social protection, support for climate measures declines, as seen during the cost-of-living crisis (Andreoni, 2017; Carattini et al., 2019; Budolfson et al., 2021; Feindt et al., 2021; Lampl et al., 2024). Short-term relief measures, such as fossil fuel subsidies, often take precedence over long-term structural change. In 2022, most of the implemented compensation measures for rising energy prices had negative effects on climate mitigation (Section 6.5.1). These short-term measures may also fail to successfully target low-income households and children (Aigner et al., 2023a).

Although Austrians are relatively well-informed and concerned about the climate crisis (European Commission and Directorate-General for Communication, 2021), there is widespread emphasis on the negative social impacts of climate policies, which contributes to climate delay (Lamb et al., 2020). Similarly, while societal support for expanding renewable energy is strong (INTEGRAL, 2022), the implementation of related projects near one's own residence is often blocked by the 'Not in my backyard' (NIMBY) effect (Sniatynski, 1980; Segreto et al., 2020; Stagl et al., 2024). Further, currently large fractions of advertisement push and legitimize fossil fuel-based forms of overconsumption (Theine et al., 2023). This contributes to the awareness-action gap, where high levels of climate awareness fail to translate into meaningful action. These tendencies are further reinforced by a 'status quo bias', as acceptance of climate measures often only increases after implementation (Andersson and Nässén, 2016; Börjesson et al., 2016; Thaller et al., 2021; Stagl et al., 2024). Recent psychological research (Burroughs and Rindfleisch, 2002; Christopher et al., 2009; Rees, 2010; Amel et al., 2017) suggests that current underlying perspectives, such as mindsets or worldviews, are key inhibitors of collective societal transformation (Kimmerer, 2013; Lent, 2017, 2021; Bridle, 2023). Shifting perspectives is thus a critical lever for transformational change, alongside changes in infrastructures and societal institutions (Meadows, 1999; Abson et al., 2017).

## Enablers of climate-friendly living

Collectively shaping framework conditions – such as underlying perspectives, infrastructures, institutions, discourses, and social norms – is a prerequisite for enabling changes in individual behavior, attitudes, and preferences (Brudermann, 2022; Aigner et al., 2023d). Since effective change is difficult to achieve at the individual level (Brudermann, 2022), collective action becomes crucial. The promotion of collective forms of provisioning can thus facilitate climate-friendly living (Millward-Hopkins et al., 2020; Vogel et al., 2021). However, shaping these framework conditions can lead to conflicts, as more effective measures tend to face greater system resistance, especially from incumbent actors (Geels, 2014; Bärnthaler et al., 2024). While some conflicts can be minimized with win-win solutions capitalizing on potential co-benefits, avoiding them entirely limits implementation to those popular measures that tend to be less effective (Stagl et al., 2024). Two key conflicts must be collectively addressed. First, distributional conflicts (Jorgenson et al., 2019), which align with SDG10: Reduced Inequalities. Second, disputes over the legitimacy of rules that determine which freedoms are promoted or restricted, and for whom (Novy, 2019; Bärnthaler, 2023).

Resistance and conflict are inherent to any transformation (Fuchs and Lederer, 2007; Avelino, 2017). Democratic climate policy requires institutional frameworks that actively engage with conflict and enable compromise (Aigner et al., 2023c) (Section 6.2). Eco-social policies (e.g., Koch and Mont, 2016; Gough, 2017; Koch, 2018; Büchs, 2021; Cucca et al., 2023; Khan et al., 2023; Koch et al., 2023) can help reconcile the needs for social protection with climate mitigation efforts, turning trade-offs into synergies (Mandelli, 2022; Schneider, 2023; Schulze Waltrup, 2023), unlocking co-benefits (Karlsson et al., 2020), and addressing inequalities (Mandelli, 2022; Bohnenberger, 2023). Consumption corridors (e.g., Di Giulio and Fuchs, 2014; Pirgmaier, 2020; Sahakian et al., 2021; Bärnthaler, 2024b) ensure everyone meets basic needs while preventing individuals "from consuming in quantities or ways that hurt others' chances to do the same" (Fuchs et al., 2021, p. 4). Eco-social policies thus go beyond the traditional 'compensatory' role of the welfare state, emphasizing its transformative and enabling potential, e.g., through the public provision of social-ecological infrastructures (Großer et al., 2020; Bärnthaler et al., 2021, 2023; Bohnenberger, 2023; Novy et al., 2023b) or harnessing the potential of specific forms of climate-social work (Aigner et al., 2023f).

Broader alliances for climate-friendly living can emerge from actions with benefits for everyday life and the SDGs, such as affordable housing and energy, quality care, health, and educational infrastructure, local amenities, time prosperity, and caring social relationships (Armutskonferenz et al., 2021; Bohnenberger, 2023; Bärnthaler, 2023; Schneider, 2023; Dengler et al., 2024). Benefits for everyday life result from focusing on service levels rather than on energy or material input. This facilitates achieving not only net-zero but also distributional objectives with respect to affordability, energy poverty and improvements in terms of health, jobs, and energy security (Cross-Chapter Box 3). Since nature conservation and a connection to nature are highly valued across various social strata, there is potential for alliances based on rewilding, preserving green spaces, revitalizing village-, town- and city-centers, and improving local leisure facilities (Barth and Molina, 2023; Borgstedt, 2023; Schleer et al., 2024). Recognizing nature's plurality of values for humans (Pascual et al., 2021, 2023) can facilitate changes in the local environment, like 'sponge cities' or stopping habitat destruction due to the sealing and fragmentation of landscapes, that, over time, contribute to broader systemic shifts (Meadows, 1999; Macy, 2007; Abson et al., 2017). Individuals with an ecologically grounded worldview can play a vital role in informing and educating others about potential collective actions and climate friendly transformation pathways (Martin et al., 2016; Kohler et al., 2019; Wyborn et al., 2021; McGreevy et al., 2022).

## 8.5.5. Adaptation

### Inhibitors of climate-friendly living

Adaption efforts in Europe and Austria are lagging in scale, scope, depth, and speed (Bednar-Friedl et al., 2022). With Europe warming faster than any other continent and temperature increases in the Alpine region surpassing the European average, a range of climate risks have already reached critical severity levels and could approach catastrophic levels by the end of this century (European Environment Agency, 2024). So far, however, adaptation efforts and societal preparedness fall short of quickly increasing risk levels, creating an urgent need for more decisive, coordinated and precautionary adaptation action (European Environment Agency, 2024). While there has been progress in assessing climate impacts, raising awareness and policy formulation, implementation continues to lag behind, revealing a persistent policy-action gap, which is most pronounced at municipal levels (Aguiar et al., 2018; European Environment Agency, 2020; CDP Worldwide, 2021; Dodman et al., 2022; Pörtner et al., 2022; Jacobi et al., 2024). The majority of planned or implemented adaptation measures tend to be 'soft' and incremental (Lexer et al., 2020; Berrang-Ford et al., 2021), focusing on awareness-raising, knowledge provision, capacity-building or risk monitoring (European Environmental Agency, 2020; Jacobi et al., 2024) rather than preventive, transformative action (Buschmann et al., 2022). Investment in upgrading structural flood protection, for instance, continues to be preferred over avoiding the expansion of settlements in flood-prone areas.

Although evidence on the feasibility of different adaptation options has grown substantially over the past decade (Berrang-Ford et al., 2021), measuring and evaluating their success in reducing climate risks remains challenging (European Environment Agency, 2022; Leitner et al., 2023). Key barriers to effective implementation include a lack of urgency, political leadership, dedicated budgets, and financing (Adger et al., 2005; Bednar-Friedl et al., 2022). Consequently, the costs of adaptation have to be covered mostly from regular public budgets in competition with funding other public tasks (Balas et al., 2024b). In contrast to a growing number of other European countries (e.g., Germany, Switzerland, Ireland, Portugal, Spain, Greece) (European Environment Agency, 2022; Leitner et al., 2023), federal and state-level adaptation strategies in Austria tend to be non-binding 'soft' policies (Clar and Steurer, 2019), lacking enforceability at subnational and local level. Furthermore, it lacks the integration of climate risks and adaptation goals into sector policies ('mainstreaming') and infrastructure projects ('climate-proofing'), vertical and horizontal coordination mechanisms, and mandatory reporting or revision cycles (Clar and Steurer, 2017, 2019; Leitner et al., 2023). Institutionalized multi-level coordination arrangements are thus rather poorly developed, and horizontal policy integration is predominantly voluntary, collaborative, and dependent on the attractiveness of adaptation solutions to sectors and their self-interest (Lexer and Buschmann, 2018; Clar and Steurer, 2019). Although Austria benefits from a well-developed culture of informal, cooperation-based, 'soft' governance modes (Lexer and Buschmann, 2018; Lexer et al., 2018; Steurer and Clar, 2018), the absence of a binding governance framework, such as Germany's Klimaanpassungsgesetz (KAnG), may jeopardize coherent and accelerated adaptation.

Even with immediate and strong mitigation efforts, the need for adaptation will continue to grow in the short- to medium-term due to the accelerating impacts of climate change. Additionally, adaptation strategies may reach their limits as global temperatures rises. In the case of 3°C of global warming, for instance, certain regions and systems may face adaptation limits (Bednar-Friedl et al., 2022). Vulnerable ecosystems (APCC, 2014), flood-prone areas (Schinko et al., 2022), regions facing water scarcity and falling groundwater levels or (seasonal) drought (Schinko et al., 2022; Balas et al., 2024b), and Alpine locations facing natural hazards and land shortages for active or passive adaptation measures (Balas et al., 2024b) are particularly at risk. Current adaptation strategies and risk management systems are also insufficiently prepared for coping with compound climate impacts and cascading risks by extreme weather events. Such events can trigger domino effects across systems or regions, potentially causing complex, long-lasting or even irreversible consequences (European Environment Agency et al., 2018; European Environment Agency, 2024). Examples include mega-droughts leading to water and food insecurity, disruptions of critical infrastructure, and threats to financial markets and stability (European Environment Agency, 2024).

Many smaller Austrian cities and municipalities, especially those outside the KLAR! climate adaptation program, often lack anticipatory, foresighted adaptation planning based on climate scenarios and assessment of impacts, vulnerabilities, and risks (Lexer et al., 2020; Buschmann et al., 2022). Among others, barriers include limited problem awareness and adaptive capacities, low political relevance in comparison to other issues, scarce resources (in terms of authority, financing, personnel, work time, expertise, access to relevant actor networks) and difficulties in accessing funding, the lack of mayoral support and administrative responsibilities, reliance on a few committed actors, and missing legal requirements making adaptation a voluntary task (Wamsler and Brink, 2014; Rauken et al., 2015; Vogel and Henstra, 2015; Lexer et al., 2018, 2020; Buschmann et al., 2022). As a result, adaptation efforts tend to focus on short-term, pragmatic responses to extreme events, rather than adopting preventive, transformative and long-term adaptation pathways (Lexer et al., 2020; Buschmann et al., 2022).

Austria, like many other countries, continues to face challenges in planning and implementing integrated climate actions that pursue both mitigation and adaptation, while supporting sustainable development. Despite the Austrian National Adaptation Strategy and Action Plan (Balas et al., 2024a, 2024b) prioritizing adaptation measures with co-benefits for mitigation, adaptation and mitigation policies remain mostly implemented in decoupled ways across all levels of governance (Aguiar et al., 2018; Reckien et al., 2018; European Environment Agency, 2020). This disconnect is typical across Europe, where coordinated planning and implementation remains rare (European Environment Agency, 2020). Main barriers include a lack of national requirements, institutional inertia, and entrenched communities in research, administration, and practice that operate within 'departmental thinking' or policy silos – often reinforced by fragmented institutional responsibilities (e.g., Kern et al., 2001; Tews, 2005; He, 2013; Runhaar et al., 2018; Landauer et al., 2019; European Environment Agency, 2020).

## Enablers of climate-friendly living

Austria's adaptation policy so far relies on a 'soft', collaborative governance model supported by broad national participation in developing its first national adaptation strategy (Lexer and Buschmann, 2018; Prutsch et al., 2018). This approach includes 'soft' impacts (e.g., awareness-raising, agenda-setting, communication, motivation, legitimation, orientation framework, knowledge base) (Lexer and Buschmann, 2018; Steurer and Clar, 2018; Probst et al., 2019; Lexer et al., 2020), pro-active climate coordinators (Lexer et al., 2020), and national initiatives like the KLAR! Program for local adaptation support, the Natural Hazard and Climate Change Check[10], and local adaptation advisory services of the federal states (Lexer and Buschmann, 2018; Lexer et al., 2020). While a 'soft', collaborative governance model can strengthen adaptive capacities in Austria, a binding regulatory framework – enacted via a climate or adaptation law – could be a key driver for more effective and coherent adaptation measures across levels and sectors. Institutionalizing adaptation policy processes and formal framework conditions increase the political relevance of adaptation, strengthens the legitimacy of adaptation actors and bears the potential to complement and strengthen more informal governance modes (European Environment Agency, 2022; Leitner et al., 2023). Legal provisions may comprise mandatory climate risk assessments and adaptation plans for subnational levels, sectoral adaptation plans, cross-level coordination bodies and mechanisms, monitoring and reporting obligations, and financing mechanisms. Stronger coercion, however, requires additional support structures for local adaptation efforts (Jacobi et al., 2024).

To enhance adaptive capacities of municipalities and smaller cities and shift from small-scale, reactive and incremental measures towards integrated solutions, several enabling factors have been identified (Biesbroek et al., 2010; Rauken et al., 2015; Vogel and Henstra, 2015; Bausch and Koziol, 2017; Clar and Steurer, 2017; Lexer and Buschmann, 2018; Lexer et al., 2020; Buschmann et al., 2022; Jacobi et al., 2024). The KLAR! program successfully demonstrated many of these factors, including utilizing 'policy windows' created by extreme weather events to initiate adaptation efforts, securing leadership support from mayors and municipal councils, establishing clear responsibilities for local adaptation, offering public financial incentives with low barriers to access, engaging professional external expertise, participating in inter-municipal networks and transnational local authority networks, creating supportive and enabling governance framework with higher administrative levels, implementing 'soft coercion' through binding funding requirements for good adaptation practices (e.g., climate risk assessments and anticipatory adaptation planning), and integrating adaptation into existing municipal development processes. In particular, committed and pro-active coordinators with institutionalized coordination responsibilities are key facilitators for local adaptation efforts. To support 'change agents' (Kristof, 2010), funding should be directed towards strengthening local and regional coordination capacities (Buschmann et al., 2022), including the funding of

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dedicated personnel, promoting cross-department coordination, and ensuring adequate qualification and training. This may also involve exploring new and innovative governance models.

Transformative adaptation can substitute incremental adaptation if the latter becomes unable to limit residual damages to acceptable levels. A key enabler for effective adaptation is developing an iterative climate risk management strategy that supports transformative adaptations by encouraging broad, reflexive, and participatory debates on adequate instruments and solutions (Colloff et al., 2017; Fedele et al., 2019). Integrating disaster risk management that can leverage the scale, scope and speed of implementation of adaptation policies (Reiter et al., 2022). In stakeholder-oriented and transformation-focused approaches (Hanger-Kopp et al., 2022) the emphasis shifts from finding 'optimal' solutions to creating robust and resilient strategies. Public funding should also prioritize prevention and preparedness measures and protective infrastructures, rather than focusing on the ex-post compensation of losses (Schinko et al., 2017). Established 'good practices' in adaptation policy making, as reflected in the Austrian national adaptation strategy, aim to enhance feasibility by prioritizing win-win, no-regret, co-benefit, multiple-benefit, or collateral-benefit adaptation outcomes, while realizing potential co-benefits with mitigation. Adaptation measures offering additional societal benefits (i.e., synergetic potentials with the SDGs) are more likely to gain societal and political support. Successful implementation of adaptation measures hinges on the consideration of the diverse impacts on different social groups and their specific needs, as well as affected provisioning systems (Aigner et al., 2023f). Effective adaptation often requires short-term yet foresighted and transformational action to avoid lock-ins and maladaptation risks that can arise from incremental measures, which fail to achieve long-term climate resilience (Lexer and Novy, 2024). Furthermore, transformative adaptation policies can extend the mission of health-care systems to promote human and planetary health. This includes strengthening preventive care, which remains marginal in terms of total health expenditure (0.8 % in 2015) (APCC, 2018), leveraging the co-benefits of time-prosperity (Dengler et al., 2024) and aligning health-care provision with transport and spatial planning (Weisz et al., 2020).

### Chapter Box 8.1. Perspectives, multi-perspectivity, narratives and qualitative transformation pathways

Perspectives represent fundamentally different approaches to making sense of the world. They may be conceptualized as paradigms (Kuhn, 1967), thought collectives (Fleck, 1980), or epistemic communities. These perspectives are characterized by a set of shared values, interests, mindsets, assumptions, concepts, theories, and methods. They typically adhere to common research programs, agendas, problem diagnoses, target horizons, and design options. At the same time, perspectives tend to resonate with specific socio-cultural groups, facilitating in-group communication while challenging communication across different perspectives. Perspectivism posits that cognition, research, and policymaking, and their underlying narratives are shaped by frames of reference (von Sass, 2019; Aigner et al., 2023e). **Multi-perspectivity** is therefore crucial for bridging such cognitive gaps and to mediate between social groups with different backgrounds (Thompson et al., 1990; Burroughs and Rindfleisch, 2002; Rees, 2010; Amel et al., 2017; Lent, 2017; Kohler et al., 2019; Lenton et al., 2019; Pascual et al., 2021; Wyborn et al., 2021). Cognitive gaps frequently result in structural misunderstandings and the formation of 'echo chambers' in politics, science, (social) media, and the broader public discourse (Abram, 1997; Dittmar et al., 2014; Cinelli et al., 2021; Pascual et al., 2021; Cinus et al., 2022). Multi-perspectivity seeks to integrate different frames of reference, thereby enhancing mutual understanding and expanding the range of possible actions (Novy et al., 2023b). The APCC Special Report on 'Structures for Climate-Friendly Living' (APCC, 2023) introduces four perspectives for assessing structures for climate-friendly living:

> "From a **Market perspective**, price signals that encourage climate-friendly consumption and investment decisions are central to climate-friendly living. If there are appropriate framework conditions that regulate markets in a climate-friendly way, then the polluter pays principle and true costs contribute to decarbonisation. … [Focusing on socio-technical renewal,] (t)he **Innovation perspective** focuses on the impact of different forms of innovation and their application on social and economic practices and thus on the environment, on climate (un)friendly living and economic activity. … From a **Provisioning perspective**, provisioning systems that facilitate sufficiency and resilience practices and forms of life, and thus make them the new status quo, are central to climate-friendly living. The Provisioning perspective is based on a broad understanding of economics, according to which economics concerns the joint organisation of livelihoods. … From the **Society-Nature perspective**, knowledge about key drivers of the climate crisis (e.g., human-nature dualisms, capital accumulation, social inequality) is essential for climate-friendly living. Theories in the Society-Nature perspective do not consider the social and (biophysical) nature as independent from each other, but as closely intertwined" (Aigner et al., 2023c, p. 9).

Multi-perspectivity facilitates differentiated decision-making processes and enables the identification of synergies and trade-offs. To operationalize the four perspectives, Haas et al. (2023) use the concept of leverage points (Meadows, 1999) – specific points in a system where a small action can produce profound changes. This framework allows for the classification of actions based on their transformative potential. Shallow leverage points focus on altering parameters and feedback mechanisms, while deep leverage points aim to change the overall design and intent of a system, i.e. the direction of transformations (Abson et al., 2017). Based on this distinction, Haas et al. (2023) distinguish four qualitative transformation pathways relevant to Austria. These pathways vary according to their underlying narratives, key actors, and central characteristics:

> "(1) **Guard rails for a climate-friendly market economy** (pricing of emissions and resource consumption; abolition of climate-damaging subsidies, openness to technology) (2) **Climate protection through coordinated technology development** (state-coordinated technological innovation policy to increase efficiency) (3) **Climate protection as public provision** (state-coordinated measures to enable climate-friendly living, e.g., through spatial planning, investment in public transport; legal regulations to restrict climate-damaging practices). (4) **Climate-friendly quality of life through social innovation** (social reorientation, regional economic cycles and sufficiency)" (Aigner et al., 2023c, p. 9).

In contrast, the IPCC highlights two perspectives with differing assumptions and diverging policy proposals, namely ecomodernism and degrowth:

> "Two contrasting schools of thought, called **ecomodernism** and **degrowth** (D'Alisa et al., 2014), offer important bounding narratives for 'green economy' approaches that aim achieve the SDGs and Paris Agreement goals. Ecomodernism aims to decouple GHG emissions and other environmental impacts from GDP growth (WGIII Section 1.4.1; Desrochers and Szurmak, 2020) through three primary strategies: (a) 'green' technological innovation, (b) resource efficiency or productivity improvements and (c) the sustainable intensification of land use in both rural and urban areas (Asafu-Adjaye et al., 2015; Isenhour, 2016)... Degrowth proponents question the feasibility of decoupling at a scale and rate sufficient to meet Paris Agreement goals (Kallis, 2017; Parrique et al., 2019; Gómez-Baggethun, 2020; Hickel and Kallis, 2020). Using precautionary principle-rooted arguments (Latouche, 2001), degrowth aims for intentional decreases in both GDP and coupled GHG emissions (Kallis, 2011) using policy mechanisms such a 'cap and share' framework for distributing emissions permits on an annually declining basis with legislation to prohibit the overshoot of established carbon budgets (Douthwaite, 2012; Kallis et al., 2012). Degrowth thus seeks to minimise reliance on negative emissions technologies, such as the large-scale deployment of BECCS... and aims to generate progress toward achieving the SDGs by prioritising redistribution rather than GDP growth" (Ara Begum et al., 2022, p. 173).

Ecomodernism primarily concentrates on optimizing the current system by *improving* energy and resource efficiency. Degrowth, in contrast, advocates for a radical transformation of current systems, their rules and underlying structures, with the objective of *avoiding* harmful activities (Cross-Chapter Box 7).

## 8.6. Climate-friendly transformation pathways

Section 8.6 explores transformation pathways to achieve climate-friendly living. In general, transformation pathways present narratives on the transition to a future state, in which broader societal goals are accomplished (IPCC, 2022a). This section assesses the potential for transitioning towards climate-friendly living (APCC, 2023) by departing from two ideal-typical transformation pathways that were derived from the IPCC's distinction between eco-modernism and degrowth (Ara Begum et al., 2022) (Chapter Box 8.1), as well as from different perspectives including the Market and Society-Nature perspective (APCC, 2023; Aigner et al., 2023c).

Section 8.6.1 starts by delineating minimum requirements for planning climate-friendly transformations, thereby addressing the politico-economic and socio-cultural inhibitors and enablers identified in Section 8.5. The four minimum requirements for planning climate-friendly transformation pathways are as follows: (1) Broadening climate policies; (2) Adopting climate-friendly governance models; (3) Expanding the mix of instruments, and; (4) Increasing societal and political support (Novy et al., 2024a).

Section 8.6.2 discusses the 'eco-modernist' transformation pathway, starting with its underlying perspectives. The section then examines the pathway's strengths, weaknesses, and potentials with regard to the four minimum requirements for climate-friendly living. Due to 'eco-modernist' reflecting a single thought collective, advancing towards a more climate friendly transformation pathway requires addressing the limitations of eco-modernist and the Market perspective (APCC, 2023).

Section 8.6.3 explores the 'system change' transformation pathway, following the same proceedings as Section 8.6.2. It is argued that for transitioning to climate-friendly living, more pragmatic solutions that address the shortcomings of degrowth and the Society-Nature perspective (APCC, 2023) are required. Doing so can help garner broader societal and political support for the transition.

### 8.6.1. Planning climate-friendly transformations

As ideal-typical transformation pathways are inherently limited to specific perspectives, they tend to resonate primarily with particular socio-cultural groups (Aigner et al., 2023c; Novy et al., 2024a). This is confirmed by mitigation scenarios currently modeled for Austria (Sections 8.4, 8.7), with scenarios combining multiple perspectives demonstrating greater feasibility in achieving climate targets (Section 8.4). Considering various perspectives can thus contribute to "problem diagnoses, target horizons and design options [to] be understood in a differentiated manner, priorities [to] be set in an informed manner and incompatibilities and synergies [to] be identified" (Novy et al., 2023d, p. 196). Multi-perspectivity in scientific discourse and a willingness to compromise within liberal democracies are therefore crucial to achieving climate goals. (Chapter Box 8.1).

Governing multi-perspectivity requires planning as an initial and essential step for coordinated and goal-oriented action (Aigner et al., 2023d; Durand et al., 2023). Planning is already a standard practice across various climate-relevant policy fields, including spatial, land use, transport, urban and energy planning (Getzner and Kadi, 2020; Svanda and Zech, 2023). The EU-mandated National Energy and Climate Plans (NECPs) are designed to facilitate coordination of national efforts in decarbonization, energy efficiency and security. There is furthermore a growing tendency for climate adaptation policies to move away from optimization and single-goal oriented approaches towards more robust strategies that align with the SDGs (Schinko et al., 2017; Schirpke et al., 2023). Despite these efforts, the federal structures in Austria present a significant obstacle to effective planning (Steurer et al., 2023) (Section 6.4.1). Current actions frequently prioritize reactive responses, such as ex-post natural disaster management, over proactive measures. Improving the use of existing planning instruments and fostering reflexive, climate change education and participatory learning processes can facilitate climate-policy integration (Plank et al., 2021) (Section 6.8.3).

While improved planning does not guarantee success in achieving climate targets, it makes success more plausible by designing and orchestrating bundles of measures that also align with the SDGs. This allows for realizing potential synergetic effects between the SDGs and mitigation as well as adaptation options. Based on the analysis of political-economic and socio-cultural feasibility challenges (Section 8.5), four minimum requirements for planning climate-friendly transformations can be identified (Novy and Barlow, 2022; Riahi et al., 2022; Haas et al., 2023; Heyen and Wicki, 2024).

First, **broadening climate policies** is an effective policy lever to avoid 'silo' approaches to climate policymaking. Climate policies are more feasible if they are part of sustainable development, thereby broadening their scope and objectives (Haas et al., 2023). Thus, climate-friendly transformations integrate not only adaptation and mitigation policies, but also broader socioeconomic policy fields that benefit every-

Table 8.3 Minimum requirements for planning climate-friendly transformations.

| Minimum requirements for planning climate-friendly transformations | Key politico-economic and socio-cultural framework conditions for enabling climate-friendly transformations |
|---|---|
| **Broadening climate policies** | • Climate policies as part of sustainable development to avoid 'silo' approaches to climate policymaking (Section 8.5.1, 8.5.2)<br>• Empowering democratic policy spaces and limiting incumbent business interests (Section 8.5.1, 8.5.2) |
| **Adopting climate-friendly governance models** | • Linking representative with deliberative and participatory democracy in implementing enforceable administrative rules and provisions (Section 8.5.2)<br>• Acknowledging multi-perspectivity in climate research and accepting conflicts and compromises as unavoidable (Section 8.5.1, 8.5.2) |
| **Expanding the mix of measures** | • Combining mitigation and adaptation measures (Section 8.5.5)<br>• Combining efficiency- and sufficiency-measures (Section 8.5.3)<br>• Combining incremental and radical measures (Section 8.5.1) |
| **Increasing societal and political support** | • Highlight the co-benefits of climate action, such as promoting human and planetary health, as well as costs of inaction (Section 8.5.2, 8.5.4, 8.5.5)<br>• Fostering new narratives and unconventional alliances that benefit everyday life (Section 8.5.4) |

day life. This makes climate measures less susceptible to instrumentalization by incumbent business interests by using war rhetoric. As climate policy integration is much more a question of political priorities and power than of well-designed policies, expanding democratic policy spaces can facilitate climate policy integration by limiting the power of incumbent interests (Bärnthaler et al., 2024) (Section 6.5.3).

Second, **adopting climate-friendly governance models** can serve as effective by linking climate policy integration with multi-level governance, ensuring climate issues are mainstreamed across multiple levels and all policy areas (Section 6.5.4). Such models can combine representative, deliberative and participatory forms of democracy, while simultaneously employing enforceable administrative rules (Jessop, 2010; Lorek and Fuchs, 2013). It is a minimum requirement to ensure that enforceable administrative rules and provisions remain compatible with safeguarding individual rights (Hollaus et al., 2023; Madner, 2023b). They furthermore facilitate the identification of strategies of how to address power dynamics and resistance in societal, business, and political contexts (Fuchs and Lederer, 2007; Lorek and Fuchs, 2013). Climate-friendly governance models also enable a balance between top-down and bottom-up approaches (Novy et al., 2022; Durand et al., 2023), integrate civil society initiatives (Moulaert and MacCallum, 2019), and public bureaucracies (Kattel and Mazzucato, 2018; Kattel et al., 2022). By connecting social, socio-technical, and system innovations (Köhler et al., 2019; Weber and Kubeczko, 2023), they can help to build, formulate, and negotiate a novel forward-looking social consensus across diverse societal groups. Key instruments include climate change education (Section 6.8.3), citizen (climate) assemblies (Lage et al., 2023), role-play simulations to promote transdisciplinary social learning (Schinko and Bednar-Friedl, 2022), and participatory foresight processes (Weber and Kubeczko, 2023). Well-planned cooperation between various stakeholders at different levels, based on a common narrative of feasible transformation pathways, is therefore essential.

Third, **expanding the mix of measures** to include adaptation and mitigation, efficiency and sufficiency, and both incremental and radical measures is essential for overcoming delays in climate-action (Sections 6.5.3, 8.5.2). Currently, climate policy is centering around efficiency improvements that mitigate emissions and incremental adaptations, that focus on addressing single risks and lack anticipatory approaches. Both reinforce the status quo (Section 8.5.4, 8.5.5). Transformative pathways can better plan systemic changes by linking measures for long-term mitigation and transformative adaptation. This not only increases feasibility but brings immediate benefits for everyday life, e.g., nature-based solutions to tackle a broader range of impact domains like 'sponge cities' that green neighborhoods (Section 8.3.1, 8.5.5). Thus, combining incremental and radical measures, e.g., radical (Frenken and Punt, 2023) and disruptive innovations (Kivimaa et al., 2021), becomes an effective policy lever. For instance, by combining efficiency-improving and sufficiency-enhancing measures like investing in EV research while restricting car use in city centers (Gough, 2017; Haas et al., 2023; Heyen and Wicki, 2024). Climate-friendly transformation pathways combine directionality, sustainability and inclusivity, a more holistic view on innovation processes, investment in new infrastructures, new markets, and structural conditions supporting skills and capabilities.

Fourth, **increasing societal support**, i.e., societal acceptance that is articulated in policy space, **and political support**, i.e., political will of decision makers, is decisive for the feasibility of climate actions. This support hinges upon the ability to communicate costs of inaction and the advantages of climate action, such as improved human and planetary health (APCC, 2018; Weisz et al., 2020). Building unconventional alliances and new narratives that improve everyday life by supporting transformative adaptations can garner wider support. Examples include the use of $CO_2$-tax revenue recycling to funding redistribution to poorer households (Budolfson et al., 2021), to improving public infrastructures (Hausknost, 2023; Lage et al., 2023; Fritz and Eversberg, 2024) or to funding adaptation measures, all of which bear potentials to enhance progress towards the SDGs.

## 8.6.2. Advancing from an 'eco-modernist' to a climate-friendly transformation pathway

### Underlying perspective of an 'eco-modernist' transformation pathway

The 'eco-modernist' transformation pathway is rooted in an ecomodernist approach (Desrochers and Szurmak, 2020), based on the Market perspective (APCC, 2023) and the transformation pathway 'Climate protection through coordinated technology development' (Chapter Box 8.1). By relying on green growth and technological optimism (Asafu-Adjaye et al., 2015; Isenhour, 2016; Symons, 2019; Ara Begum et al., 2022), this approach prioritizes market-based governance (Lorek and Fuchs, 2013; Hausknost and Haas, 2019; Bärnthaler, 2023) to achieve the optimal allocation of scarce resources by maximizing consumer utility (Brand-Correa and Steinberger, 2017; Gough, 2017) and profit (Zeller, 2020). Adequate market design, according to this perspective, is a form of 'soft' governance that focuses on pull measures (e.g., subsidies and nudging) to incentivize actors to reduce emissions (Getzner, 2009; Steinberger et al., 2013; Getzner and Kadi, 2020; Bröthaler et al., 2024), switch to new business models (e.g., sharing-economy) (Wieser and Kaufmann, 2023), and invest in low-emission technologies (Kubeczko et al., 2023). Price signals are expected to increase the relative attractiveness of low-emission products and services, guiding consumers towards climate-friendly lifestyles (e.g., denser living) (Novy et al., 2023c). As $CO_2$ pricing has distributional impacts on the cost of living and production costs, it is implemented cautiously. Greater emphasis is placed on promoting green growth. Accordingly, socio-economic progress and environmental sustainability can be aligned by decoupling GDP growth from emission and resource use, with renewable energy, bioeconomy, genetic engineering, and CCS offering promising short-term solutions (Nordhaus, 2019; Danaher, 2022).

### Advancing to an effective and feasible climate-friendly transformation pathway

*Broadening climate policies*

A key strength of this transformation pathway is its focus on socio-technical innovations and market price mechanisms, alongside measures of social compensation. It insists on the importance of incremental improvements in global governance, such as the commitment made at COP 28 'to work together to triple the world's installed renewable energy generation capacity to at least 11,000 GW by 2030, taking into consideration different starting points and national circumstances' (United Nations Climate Change, 2023). The European Green Deal exemplifies this approach by aiming towards improvements in European competitiveness while promoting the goal of climate neutrality by 2050 (Zeller, 2021). Thereby, facilitating a 'just transition' to 'leave nobody behind' is central, going beyond sole employment creation (McCauley and Heffron, 2018) (Section 6.7.1). This is supported by funds like the Just Transition Fund (JTF) and the Social Climate Fund (SCF). Among the EU-27, Austria leads in terms of renewable job creation with fair conditions (McCauley et al., 2023). It furthermore offers broad incentives for businesses and households, including income-based support for equipment replacement and compensation payments like the climate bonus ('Klimabonus') and repair bonus ('Reparaturbonus'). Introducing green vouchers can achieve similar distributional effect as compensation payments but may reduce potential rebound effects better (Büchs et al., 2021) (Section 6.5.1).

A key weakness of this pathway is its neglect of insights from the Society-Nature perspective (APCC, 2023; Haderer et al., 2023), particularly ignoring society-nature relations, the growth imperative and its exploitative impacts on nature and parts of the Global South (Cross-Chapter Box 7) (Fischer-Kowalski and Haas, 2014; Görg et al., 2017; Hickel, 2020a). Its incremental approach tends to add sustainable technologies to an unsustainable structure (Section 6.5.4) and prioritizes immediate economic goals – such as GDP growth, industrial competitiveness, and public debt reduction – over broader climate goals. Contrary to recommendations by the European Commission (2023b), it tends to disregard long-term sustainable competitiveness and the need for multilateral cooperation for a global just transition (Pollex and Lenschow, 2018). Increased geopolitical rivalries, for instance, have contributed to European policies prioritizing (energy) security and global access to resources over climate targets (Section 8.5.1). This is further reinforced through corporate lobbying to retain climate-damaging subsidies (Brulle, 2018; Brulle et al., 2020; Kletzan-Slamanig et al., 2022; Bärnthaler et al., 2024), increase technology-open innovation funding and favor private green finance via de-risking policies (Kedward et al., 2024).

A lever of this pathway to contribute to transitioning towards climate-friendly living consists thus in better alignment with the multilateral sustainable development agenda, linking ambitious decarbonization targets with social targets for decent living (Clarke et al., 2022; Otto, 2023; UNEP, 2024).

*Adopting climate-friendly governance models*

A key strength of the 'eco-modernist' transformation pathway is its use of well-established policy approaches focusing on incentives and efficiency improvements. Proposed measures in this transformation pathway are relatively easy to implement as they do hardly change existing framework conditions. As these measures result in minimal behavioral changes (e.g., e-fuels in comparison to shifting towards public transport), they tend to lead to weak institutional resistance which increases the feasibility of their implementation (Section 8.5.3).

However, its reliance on market and technology solutions is also a major weakness due to widespread market failures and institutional lock-ins in using existing technologies (Hausknost and Haas, 2019; Schulze Waltrup, 2023). Market-based governance, focusing on voluntary, incentive-based measures, as often promoted by Austrian social partnership and federal decision-making structures, can contribute to climate delay (Section 8.5). The current Science, Technology, Innovation (STI) policy focus tends to prioritize technological efficiency (Weber and Kubeczko, 2023). As an 'eco-modernist' pathway fails to challenge the concentration of power by incumbent business interests, it tends to underestimate the power of reactionary forms of climate delay strategies to inhibit climate policy integration (Bärnthaler et al., 2024) (Section 6.5.3). Incumbent interests tend to instrumentalize climate science in a culture war-rhetoric that deviates public debate to conflictive socio-cultural issues and trigger points (Mau et al., 2023). This often impedes collective learning processes of how to organize necessary transitioning processes (Jaeggi, 2014). If the power of incumbent market actors that benefit from climate delaying tactics remains unchecked, the ability of public decision-makers to use national and international policy spaces remains restricted (Section 8.5.2, 8.5.4).

The full potential of this pathway can be actualized by acknowledging that conflicts and compromises are inherent in pluralist societies and liberal democracies (Mouffe, 2005). Decision-makers are required to balance present and future interests and freedoms, including a duty to protect the public from the consequences of inaction (Hollaus et al., 2023). The feasibility of implementing enforceable administrative rules and provisions can be increased by linking representative with deliberative and participatory democracy. Transformative innovation policies (OECD, 2024), informed by the socio-technical Multi-Level-Policy (MLP) theory and other sustainability transition approaches (Geels, 2011; Köhler et al., 2019) increasingly focus on system innovations (Weber et al., 2008). These policies promote mission-oriented instruments (Kubeczko et al., 2023) and an 'entrepreneurial state' (Kattel and Mazzucato, 2018; Kattel et al., 2022). Organizational frameworks may include 'realigned strategic niche management' (Geels and Raven, 2006), 'technological innovation systems' (Markard and Truffer, 2008; Andersson et al., 2023), 'challenge-oriented regional innovation systems' (Tödtling et al., 2022) or 'regional transformation management' (Lexer and Novy, 2024). Meta-governance involving both private and public actors (e.g., through road-mapping with participatory foresight) can steer research and innovation by means of regulation (e.g., green and innovation-oriented procurement), experimental testing (e.g., with the help of real-world laboratories and regulatory sandboxes) and monitoring and evaluation (Weber and Kubeczko, 2023; Bauknecht and Kubeczko, 2024).

*Expanding the mix of measures*

A key strength of this pathway is that people have experience with proven and tested mitigation and adaptation measures which rely on socio-technical solutions that are reliable in implementing known goals, such as thermal rehabilitations, dams and flooding zones. Reoccurring planning cycles (e.g., reinvestment cycles for public infrastructure, budgetary planning cycles) can enable the integration of climate risk assessments and adaptation funding, such as the European Structural and Investment Funds' 30 % spending target on climate action (European Commission, 2024). Additionally, extreme weather events may increase urgency and political will, creating additional windows of opportunity for adaptation (Section 8.5.5).

A major weakness of this pathway is its reliance on soft governance and a limited set of primarily efficiency-enhancing incremental mitigation measures, along with informational strategies to nudge consumer behavior, autonomous adaptation, and 'piggy-backing' onto existing measures. 'Soft' measures only include voluntary measures and market-based instruments that do not constitute deep interventions in the economic structure of society or in consumer practices (Section 6.4). However, incremental changes alone are insufficient to achieve "fundamental change in society" (Ara Begum et al., 2022, p. 171) (Section 5.3.1). Adaptation policies in this pathway are often reactive, responding ex-post to issues as they arise (e.g., post-disaster recovery). They typically focus on specific sectors, such as flood risk management, agriculture, or other high-risk domains, and emphasize structural protection measures that defend existing – often maladaptive – development pathways against changing climatic and environmental conditions. This approach tends to neglect cases of overload and increasing residual risk (Hartmann et al., 2021) and limits the scope of adaptation measures, as they do not address broader systemic vulnerabilities across various domains. Ultimately, this may lead to maladaptation, if adaptation in one sector (e.g., irrigation in agriculture) amplifies risks in other sectors (e.g., increasing water stress) (European Court of Auditors, 2024). Furthermore, as private insurance against climate risks is central to this approach, adaptation policies often remain confined to incremental improvements, failing to address underlying vulnerabilities emerging risks adequately (Section 8.5.5).

The potential of this pathway is actualized by implementing a better orchestrated mix of measures in line with multi-perspectivity (Novy et al., 2023e) (Chapter Box 8.1). Lawmakers and public administrations can improve climate policy integration by leveraging their regulatory power to elaborate effective and enforceable bundles of measures, including phasing-out emission-intensive technologies, business models, and practices (Madner, 2023b). Bundles of measures that combine incremental and radical measures can drive change across multiple levels. By experimenting with social and socio-technical innovations across policy areas, such an approach can achieve effectiveness already in the short-run by promoting diverse incremental changes without abandoning the transformative long-term goal to overcome environmental degradation and foster inclusive socio-economic renewal, resilience, and security (European Commission, 2023c; Bauknecht and Kubeczko, 2024; OECD, 2024; ÖROK, 2024).

An additional key lever that can be implemented in the short-run to increase pathway effectiveness is combining efficiency-enhancing with cost-saving sufficiency measures for rapid, low-cost emission reductions (e.g., speed limits). To "disrupt existing developmental trends" (Pathak et al., 2022, p. 72) that impede climate-friendly living, measures that avoid or shift emissions can complement efficiency-enhancing strategies.

*Increasing societal and political support*

A key strength of the 'eco-modernist' transformation pathway is its reliance on existing preferences, values, and activities, such as strong support for green products and technologies (Schleer et al., 2024). It furthermore relies primarily upon pull-measures that tend to encounter broad societal and political support. This pathway mainly resonates with the middle- and upper-class milieus – the Established, Performers and the Cosmopolitan Avant-Garde – who are inclined towards technological innovations as well as voluntary, quality-of-life-enhancing behavioral changes (Barth and Molina, 2023; Borgstedt, 2023; Schleer et al., 2024). This is both a strength and a weakness. It is a strength because it garners political support from powerful actors, but a weakness due to opposition from lower-income groups and the Nostalgic milieu, who are concerned about affordability and access to social infrastructure.

This pathway can reach its full potential by expanding its appeal to other milieus, especially to the middle-classes like the Adaptive-Pragmatic milieu (Barth and Molina, 2023; Borgstedt, 2023). Clear communication of individual benefits (Barth and Molina, 2023; Borgstedt, 2023), including greener neighborhoods and reduced costs of living, could attract allies. Such alliances, however, require narratives to include perspectives that are agnostic of green growth ('a-growth'), such as Innovation perspective (APCC, 2023; Kubeczko et al., 2023) and Green Keynesianism (Gough, 2017; Tienhaara and Robinson, 2022; Schulze Waltrup, 2023). Institutionalizing such alliances might lead to a renegotiated social contract for sustainable and inclusive development (European Commission, 2023a; UNEP and Stockholm Environment Institute, 2023).

## 8.6.3. Advancing from a 'system change' to a climate-friendly transformation pathway

### Underlying perspectives of a 'system change' transformation pathway

The 'system change' transformation pathway is grounded in a degrowth approach (Cross-Chapter Box 7) and the Society-Nature perspective (APCC, 2023; Novy et al., 2023d) that advocates for avoid and shift measures (Cross-Chapter Box 4). It emphasizes that the planet's finite ecosystems cannot support endless growth in material consumption and emissions (Vogel and Hickel, 2023). Consequently, some economic sectors are required to shrink (e.g., the automotive sector), while others need to expand (e.g., the care and repair sector) (Krisch et al., 2020; Mattioli et al., 2020; Pichler et al., 2021; Keil and Steinberger, 2023).

The 'system change' transformation pathway argues that climate-friendly living requires overcoming the 'status quo bias' and proposes sociotechnical and socioeconomic transformations to reduce resource demand and lower emissions (Durand et al., 2023). It envisions an economy oriented towards human flourishing (eudaimonia) (Brand-Correa and Steinberger, 2017) and respecting planetary boundaries (O'Neill et al., 2018) (Section 8.2.1). This can be achieved by shifting economic activity towards providing (i.e., producing, consuming and distributing) the infrastructure, services, and goods necessary for a good life (Polanyi, 1977; Jo and Todorova, 2019; Novy et al., 2023a) (Cross-Chapter Box 4).

Over the past 200 years, the limits of sustainable use of ecosystems have been continuously surpassed (Rockström et al., 2023), with Austria being among the affluent countries with high and increasing ecological overshoot (Section 8.2.1). Rising global GHG emissions and material consumption reveal the persistence of a harmfully expansive global socioeconomic system. As problematized by the Society-Nature perspective (APCC, 2023), structural factors such as the growth imperative, commodification and the modern extractivist and exploitative societal relationship with nature (Haderer et al., 2023) contribute to this development. Empirical evidence furthermore points towards absolute decoupling rates of emissions from economic growth being anywhere near the speed and scale required to achieve even less ambitious climate goals globally (Haberl et al., 2020; Vogel and Hickel, 2023) as well as in Austria (Aigner et al., 2023e).

### Advancing to an effective and feasible climate-friendly transformation pathway

*Broadening climate policies*

A key strength of the 'system change' transformation pathway is its integrated and comprehensive approach to the climate crisis by embedding it in the more comprehensive doughnut model (Raworth, 2017; O'Neill et al., 2018) that shows that Austria is not only characterized by a high, and increasing ecological overshoot, but also by hardly improving its social indicators (Section 8.2.1). Investigating society-nature relationships stresses the importance of power and policy priorities (Section 6.5.3), demonstrating that environmental degradation results from politico-economic processes of extractivism and unequal ecological exchange (Gorz, 1993; Brand et al., 2021; Fanning and Hickel, 2023; Fraser, 2023; Otto, 2023; UNEP, 2023) (Section 8.5.1). Transformative adaptation measures, prioritizing structural and systemic changes, can reduce exposure and vulnerability by promoting public investment in nature restoration and stronger social safety nets, complementing voluntary emergency services like fire brigades and neighborhood initiatives. This pathway seeks deep transformations (Meadows, 1999), questioning the targets and design of current socioeconomic systems. Key aims include transforming the dominant mode of living and production (Brand and Wissen, 2021, 2024; Hickel, 2021; Buch-Hansen and Nesterova, 2023), addressing unequal ecological exchange (Hickel, 2020b), ending neoextractivism (Canterbury, 2018) and land grabbing (Yang and He, 2021; Gabor and Braun, 2023). Moreover, given huge inequalities with respect to historical emissions (Section 8.2.2), this pathway advocates for increased international support and compensations from high- to low-emitting countries (Hickel, 2020b) (Section 8.5.1).

While there are scientific proposals and best practices of effective measures for transforming the socioeconomic system in a climate-friendly way (Schneidewind and Zahrnt, 2013; Die Armutskonferenz and Ökobüro, 2024; Sachverständigenrat für Umweltfragen, 2024a), a key weakness of this transformation pathway remains its lack of practical experience in shifting away from the current institutional order. These proposals often focus on changing parameters (e.g., taxes and incentives) and the design of provisioning systems in Austria (Haas et al., 2023). Limited experiences exist in changing the 'intent', i.e., the direction of change, systemic logics, and organizing principles (Meadows, 1999;

Abson et al., 2017). Examples include the lack of proposals of how to reduce Austria's dependence on global locational competition and the resultant vulnerabilities of its export economy (Streeck et al., 2016; Kapeller and Hubmann, 2023). Instead, the status quo incentivizes free riding and climate delay, including social and ecological dumping, thereby favoring short-term incumbent business interests (e.g., the automotive industry or fossil industry) (Pichler et al., 2021; Bärnthaler et al., 2024). Additionally, while reduced international trade can facilitate long-term self-sufficiency of the Global South (Hickel, 2021; Gabor and Sylla, 2023), it may have short-term adverse effects on export-dependent economies due to reduced markets for raw material exports (Graebner-Radkowitsch and Strunk, 2023).

The 'system change' pathway can advance towards a climate-friendly transformation by exploring the advantages of sufficiency and peaceful international cooperation. Sufficiency approaches can increase resource independence and thus foster strategic autonomy in times of geopolitical rivalries (Durand et al., 2024) (Sections 6.6.2, 8.5.1). Furthermore, export-oriented Austrian economy benefits from peaceful international cooperation, including accepting the principle of 'common but differentiated responsibilities' (UN General Assembly, 1994; Fisher, 2015) that could sustain a fair global economy and facilitate access to green energy imports.

*Adapting climate-friendly governance models*

A key strength of this pathway is its focus on overcoming the 'status quo' bias that preserves climate-harmful structures or leads to maladaptation. Identifying and addressing the structural causes of climate delay is a decisive starting point for deep transformations (Buch-Hansen et al., 2024; Spash, 2024), directing efforts toward structural changes. Examples include limiting the power of incumbent business interests (Geels, 2014; Bärnthaler et al., 2024) and exnovations (David, 2017; Krüger and Pellicer-Sifres, 2020; Kivimaa et al., 2021). By highlighting how difficult it is to live climate-friendly in Austria (Section 8.5), this pathway emphasizes the importance of collectively changing framework conditions (e.g., laws, institutions, or infrastructures), as well as gender, income and production relations (Shove et al., 2009; Stoddard et al., 2021; Aigner et al., 2023c; Smetschka et al., 2023; Aykut et al., 2024).

A key weakness of this pathway is the lack of implementable transition strategies (Barlow et al., 2022). By means of advertising and lobbying powerful incumbent actors tend to stabilize the status quo (Lorek and Fuchs, 2013; Avelino and Wittmayer, 2016). Often democratically legitimized decision makers, supported by the electorate, block changes and defend unsustainable consumption patterns if they endanger unsustainable routines and the profit interests of power complexes (Baines and Hager, 2023). Integrating elements of representative, participatory, and deliberative democracy can help reduce public opposition, especially if supported by appropriate communication and scientific support (Hausknost et al., 2017; Gough, 2022; Heyen and Wicki, 2024) (Section 8.5.3, 8.5.4).

To advance towards a climate friendly transformation pathway the 'system change' pathway can facilitate governance approaches based on a **'whole of government'** approach that combine top-down and bottom-up approaches by linking sectoral, spatial, and macroeconomic planning (Stöhr and Taylor, 1981; Friedmann, 2005; Adaman and Devine, 2017; Gabor, 2020; Durand et al., 2023; Schmelzer and Hofferberth, 2023; Aoki et al., 2024). This facilitates overcoming 'silo approaches' to climate policymaking as well as localism that solely relies on civic bottom-up initiatives (Kazepov et al., 2019; Krähmer, 2022).

The advantage of public measures 'from above' is that public decision makers – such as governments, parliament, courts, or administrations – have the resources (due to taxation and personnel) and the constitutional legitimacy (due to legal prerogatives) to change framework conditions. Becoming 'slower by design, not disaster' (Victor, 2019) requires planning and governance models that ensure societal acceptance (via public participation and providing desired outcomes with benefits for everyday life) as well as the integration of experts in public deliberation (via policy learning processes, transdisciplinary research and climate change education) (Lorek and Fuchs, 2013; Aigner et al., 2023e; Durand et al., 2023; Nohrstedt and Parker, 2024) (Section 6.8.3). Effective strategies require **enforceable rules** (Jessop, 2010; Hollaus et al., 2023), including a binding adaptation framework. Experience from climate councils shows that citizens often support more disruptive sufficiency measures in deliberative processes, even though these tend to be underrepresented in policymaking (Lage et al., 2023).

The advantage of bottom-up initiatives, in contrast, is that they can connect multiple levels and diverse actors, fostering broader societal support. Such bottom-linked actions can pool resources, represent collective political interests, and facilitate the cooperation with public policy institutions (Moulaert and MacCallum, 2019), including workers in planning processes and abolish workplace hierarchies

(Harnecker and Bartolomé, 2019; Sorg, 2023). Municipal enterprises (e.g., 'Stadtwerke') can become central due to their potential to democratize the provision of essential infrastructures, such as energy and mobility (Foundational Economy Collective, 2018).

*Expanding mix of measures*

A key strength of this transformation pathway is that it adopts a broader perspective of climate policy integration. This pathway promotes transformative adaptation, advocating for spatial planning reforms that limit land use, soil sealing ('land use sufficiency'), and promote ecosystem-based adaptation through green spaces along with stricter monitoring, evaluation and learning processes. It proposes sufficiency as the guiding principle (i.e., the 'intent' of climate-friendly systems), thereby addressing inequalities in material and energy consumption as the main drivers of climate change (Buch-Hansen and Nielsen, 2020; Spash, 2024). By prioritizing avoid over shift and improve measures (Princen, 2003; Fuchs et al., 2023; Gough, 2023), this approach enables immediate emissions reductions while satisfying human needs. Deeply rooted intersectional inequalities of class, gender, and ethnicity are also key drivers of climate change on a global (Chancel, 2022; Chancel et al., 2022; Millward-Hopkins and Oswald, 2023) and national level (Theine et al., 2022; Essletzbichler et al., 2023). A key weakness of this pathway is that sufficiency measures are instrumentalized as trigger points (Mau et al., 2023) in a culture war rhetoric, framing climate policy as threats to 'normal' life, freedom, and prosperity. Due to the currently low level of acceptance of measures that oppose 'everyday imaginaries' (Kaika et al., 2023) and interfere with the 'imperial mode of living' (Brand and Wissen, 2021), even incremental measures like speed limits face opposition and could lead to the broader rejection of climate policy (Stagl et al., 2024).

An important lever for climate-friendly transformation pathways is embracing multi-perspectivity (Novy et al., 2023d), as this facilitates the effective mediation between conflicting claims and seemingly incompatible worldviews (Meadows, 1999; Christopher et al., 2009; Rees, 2010; Abson et al., 2017; Lent, 2017, 2021; Kohler et al., 2019; Pascual et al., 2021, 2023). This helps to vindicating both incremental and radical change. While small steps tend towards ineffective activism within given framework conditions, radicalism often lacks anchoring in the current institutional framework, which is a necessary starting point for transitioning to a new system (Gorz, 1968, 1993; Novy et al., 2022; Soder, 2024).

Combining efficiency-enhancing with sufficiency-enhancing, and pull- with push-measures offers potential for win-win solutions (Heyen and Wicki, 2024). Expanding PV systems does not conflict with reducing energy demand, nor does increasing EVs conflict with collective forms of provisioning that satisfy needs with lower energy requirements (Creutzig et al., 2018; Vogel et al., 2021) (e.g., by reducing car-dependency) (Mattioli et al., 2020). Examples include the provision of universal basic services (Coote and Percy, 2020), commons (Edelmann et al., 2020; Villamayor-Tomas and García-López, 2021) and social-ecological infrastructures (Bärnthaler et al., 2021; Novy et al., 2023b). Additionally, services and goods can be subsidized for low-income households while expanding foundational 'blue' and 'green' infrastructures in neighborhoods (De Castro Mazarro et al., 2023).

Taking sufficiency as the organizing principle (Princen, 2003; Sachverständigenrat für Umweltfragen, 2024b) and a collective endeavor (Schneidewind and Zahrnt, 2013; Jungell-Michelsson and Heikkurinen, 2022; Lage, 2022) can secure that everyone has 'enough' by means of systemic solutions, e.g., by providing existential services and goods in an accessible and sustainable way, and avoid individualizing and moralizing responsibilities (Sachverständigenrat für Umweltfragen, 2024b). Collective sufficiency is operationalized trough production and consumption corridors, which establish 'minima' for decent living standards and 'maxima' to avoid over-production and -consumption (Pirgmaier, 2020; Bärnthaler and Gough, 2023). Stressing 'enough' as a 'floor' that ensures affordable and sustainable foundational infrastructures, services, and goods for all residents (e.g., housing and energy) can reduce resistance (O'Neill et al., 2018; Millward-Hopkins et al., 2020; Vogel et al., 2021). 'Ceilings', in contrast, can limit overconsumption by a few (Lehtonen and Heikkurinen, 2022; Gough, 2023), e.g., by imposing bans or other regulations. Redistributive measures, such as progressive income and wealth taxes or fees for high energy and resource use (Millward-Hopkins and Oswald, 2023; Chancel et al., 2024), can be justified on fairness grounds and increase financial leeway for public investment (Bröthaler et al., 2023).

*Increasing societal and political support*

A key strength of this pathway is its focus on the good life in its multiple dimensions (O'Neill et al., 2018; Brand et al., 2021). First, it focuses on fairness and justice (Bal et al., 2023; Otto, 2023), radicalizing insights from 'just transitions' (Büchs and Koch, 2019; Koch, 2020; Armutskonferenz et al., 2021; Koch and Buch-Hansen, 2021; Hirvilammi et al., 2023; Schneider, 2023). By addressing distributive (e.g., consumption corridors) and relational forms of justice, a 'system change' pathway can ensure an equitable transition to climate-friendly living. It can integrate procedural justice (e.g., in forms of participatory governance), recognitive justice (concerned in particular with groups at risk of falling behind) and, finally, international justice (related to respectful treatment) (Bal et al., 2023). Second, it promotes place-based development initiatives, often focusing on transformative adaptation. This can facilitate equal access to infrastructures and can foster social cohesion through communal cooperation and bottom-up solidarity (Moulaert and MacCallum, 2019; De Castro Mazarro et al., 2023; Kaika et al., 2023). Successful examples include the commons (Edelmann et al., 2020; Villamayor-Tomas and García-López, 2021), the foundational economy (Bärnthaler, 2023; Calafati et al., 2023), the social and solidarity economy (Exner and Kratzwald, 2021) the doughnut economy (Raworth, 2017; Wahlund and Hansen, 2022) and the economy for the common good (Goydke and Koch, 2020). In urban development, improvements in social services, accessible retailing, existing public spaces, urban renaturation, building retrofitting and shared housing can benefit everyday life. The city of Vienna is discussed as a – contested – best practice model for inclusive transformation (Mocca et al., 2020; Bärnthaler et al., 2023; Haderer, 2023; Novy et al., 2024b). In regional development, experiments include revitalizing village centers (Madner and Grob, 2019), integrated land-use planning to safeguard ecosystem services, increasing land taxes, and urban and regional contractual development agreements to fund multi-story (social) housing and urban infrastructures (Madner and Grob, 2019; Getzner and Kadi, 2020; Schirpke et al., 2023).

The key weakness of this pathway resides in limited political support, as it challenges the advantages of the status quo, be it incumbent interests of residents, business, or politicians. Restricted political support requires even stronger societal support to pressure for climate-friendly measures. Today, however, effective climate policies are primarily supported by parts of the socio-cultural milieus of Post-Materialists and Progressive Realists, who together represent less than 20 % of the population (Barth and Molina, 2023; Borgstedt, 2023; Schleer et al., 2024). Although these groups are willing to reduce their individual footprint, voluntary efforts alone – without comprehensive and democratically decided rules – do not impact on the practices of other socio-cultural milieus. At the same time, large sections of society feel insecure and unprotected due to labor market flexibilization and eroding social security systems (Schneider, 2023). Fears of economic decline and not having 'enough' tend to overshadow concerns about climate change (Mau et al., 2023) (Section 8.5.4). Lower-class milieus, such as the Traditional milieu, tend to be skeptical about social changes and oppose transformative measures, due to a perceived lack of fairness in policymaking (Barth and Molina, 2023; Fritz and Eversberg, 2023).

A lever for advancing towards climate-friendly living lies in fostering unconventional multi-milieu and multi-class alliances based on fairness, justice and common interests, including short- and long-term benefits for everyday life (Fritz and Eversberg, 2023, 2024). Prioritizing spatial planning measures that reduce risk exposure, can score on societal support for widely popular nature-based solutions and ecosystem-based adaptation in both rural contexts (e.g., natural retention, groundwater renewal areas, cool air corridors) and cities (e.g., blue, green spaces). The Adaptive-Pragmatic milieu as well as parts of traditional lower-class milieus can be attracted to this alliance by measures that reduce costs of living, e.g., subsidizing renewal energy installation or public transport. Societal support can be further enlarged by improving working conditions, a job guarantee, fair wages (Gough, 2017; Schulze Waltrup, 2023) and by providing foundational social and green infrastructures (Foundational Economy Collective, 2018; Millward-Hopkins et al., 2020; De Castro Mazarro et al., 2023; Kaika et al., 2023). Targeting middle- and lower-income groups with explicit eco-social policies to reduce inequalities and enhance well-being (Hirvilammi and Koch, 2020; Koch, 2022) can also help countering skepticism towards democratic institutions in these milieus (Zandonella, 2022). Raising confidence in public institutions in uncertain times by maintaining secure and affordable public provisioning can reduce resentments towards democracy, science, and climate policies (Ter Mors et al., 2012; Bal et al., 2023).

## Cross-Chapter Box 8. Green Finance

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### What is green finance?

Broadly, green finance is seen as a channel that can allow economies to achieve climate goals such as net zero emissions as defined by IPCC targets and Nationally Determined Contributions (NDCs). This transition away from carbon-intensive sectors into 'green' sectors requires redirecting investments while also ensuring growth, sustainable jobs, and competitiveness. Thus, green finance encompasses a broad range of financial activities, policies, and climate objectives, which can vary significantly across institutions, regions, and stakeholders. This can range from financing low-carbon transitions through infrastructure projects such as renewable energy to climate adaptation through support for vulnerable communities. Furthermore, the question whether financing itself should come from the private or public sectors or enabled through market (e.g., carbon taxes) or non-market instruments (e.g., regulations) is widely debated. In practice, a mix of public and private financing, or 'blended finance', and a combination of policies is typically implemented. Otto et al. (2020) highlight that finance is one of the key pillars that can induce positive social tipping dynamics to enable a global transformation to carbon neutrality. This could be achieved by employing different instruments such as green bonds, loans, and climate investment funds. Governments also play a crucial role in this process by creating enabling policies, offering incentives, and providing public funding to attract and de-risk private investments. Given that public spending constitutes a significant share of GDP in EU countries, including Austria, the role of the state in driving green finance and fostering systemic change is substantial.

Climate change also poses significant risks to economies and financial systems, broadly categorized into physical risks, which arise from the direct impacts of extreme weather events and long-term environmental shifts, and transition risks, which stem from the economic and financial adjustments required to shift to a low-carbon economy. While on the one hand, there is ample evidence that the Costs of Inaction (COIN) (see Section 6.7.2) will result in higher damages, on the other hand, rushed policies and rapid structural transitions can result in a costly disorderly' transition (Battiston et al., 2017; Campiglio et al., 2018; Dunz et al., 2021) and are also a rising concern for financial supervisors as they can exacerbate economic and financial risks (Battiston et al., 2017; Mercure et al., 2018). In the context of Austria, rising physical risks, such as increasing flood events, heatwaves, and damages to critical infrastructure, add significant financial challenges as more resources need to be allocated towards adaptation and mitigation measures. While insurance, whether private or public, can help improve resilience of households and businesses, this sector is also likely to face additional challenges as rising physical risks might reduce its capacity to absorb losses, providing additional challenges to policymakers if sectors of the population or sets of economic activities become uninsurable.

Climate policies also need to factor in lock-ins and path dependencies of firms as regulatory risks arising from changing policies may be substantial (van der Ploeg and Rezai, 2020) and may have negative consequences on financial markets (Daumas, 2023). Thus, a stringent regulatory framework for sound climate policies is needed that also ensures financial market stability (Roncoroni et al., 2021), and accounts for forward-looking financial planning to ensure that investments move away from industries that are incompatible with decarbonization targets and the broader socio-ecological transformation (Jones, 2015; Polzin, 2017; Steininger et al., 2022). Recent Euro area financial climate stress test studies show (Alogoskoufis et al., 2021; Gourdel et al., 2022) that an orderly transition to a carbon-neutral economy can achieve early co-benefits by reducing carbon emissions (12 % less in 2040 than in 2020) while a disorderly transition worsens the economic performance and financial stability of the euro area and with physical risks leading to real GDP decreases of 12.5 % in 2050 relative to an orderly transition. A disorderly transition can also introduce new risks for the Austrian economy that is deeply integrated along finance and physical value chains within Europe (Battiston, 2019; Guth et al., 2021; Monasterolo et al., 2022a) yet a recent survey of Austrian finance stakeholders concludes that the integration of green finance in climate policies is not yet sufficient (Kletzan-Slamanig and Köppl, 2021).

## The role of green investments

The development of green financing instruments is closely linked to the investment gap that needs to be bridged in order to reach the climate policy objectives (see 6.7.1). Strategies and instruments are being developed and applied with the aim of redirecting (private or institutional) financial flows towards sustainable and/or climate friendly investments. A precondition for achieving this is developing a regulatory framework for financial markets and the business sector that ensures the proper consideration of climate-related risks (physical, transitional, and regulatory) and the implementation of adequate risk management measures in financial institutions. Beyond finance-specific measures, broad climate-economic strategies also play a critical role in improving the competitiveness of green technologies over incumbent ones. Measures such as removing subsidies to dirty technologies or sectors, carbon pricing, subsidies for green innovation, or similar policies can help level the playing field by shifting the financial flows away from fossil fuel-intensive to renewable technologies. In addition, provisions are required to ensure the environmental and ethical soundness of investments and prevent greenwashing (Kletzan-Slamanig and Köppl, 2022).

Following the Paris Agreement, a series of international initiatives, such as the Central Bank Network for Greening the Financial System (NGFS), have come into effect that also aim to comprehensively disclose climate-related financial risk and to define standards for green finance instruments and products. In the EU, the sustainable finance framework including the Taxonomy on Sustainable Finance, the Green Bond Standard, Corporate Sustainability Reporting Directive, and the European Sustainability Reporting Standards, provide a classification of economic activities that inter alia contribute to climate mitigation and define reporting requirements for companies and financial market participants (Getzner, 2022; Nykvist and Maltais, 2022). These EU Directives are in the process of being transposed into national law and thus will substitute voluntary practices with legally binding requirements, that will also improve data transparency. In Austria, the members of the Green Finance Alliance voluntarily agreed to decarbonize their core business until 2050.

Studies indicate a clear appetite for ESG investments among (retail) investors (Delsen and Lehr, 2019; Seifert et al., 2022; Gutsche et al., 2023). Although 17 % of investment funds held by households are already certified with the Ecolabel (Ćetković and Zhan, 2022), the proportion of all other financial products is still only in the low single-digit percentage range (Breitenfellner et al., 2020). Even though Austrian investors are paying more attention to climate risks, the understanding and perception of climate-related financial risk vary across financial actors (Glas et al., 2020; Breitenfellner and Kariem, 2024). The role of disclosure, of policy coherence and social engagement are perceived as a main driver to decrease market uncertainty (Glas et al., 2020) and indeed financial actors regard the provision of specific ratings or labels for green and high-carbon activities as an effective approach to increase transparency (Kletzan-Slamanig and Köppl, 2021). Climate-financial risk assessment is crucial to inform a revision of investors' risk management and portfolio rebalancing, to reduce the risk of stranded assets for financial stability. It is also relevant for firms' investment decisions in the transition via the interest rates. Since climate change policies are forward looking (Battiston, 2019), they also need to account for climate-related uncertainties such as fat-tailed events (Weitzman, 2009; Ackerman, 2017), non-linearity and tipping points in both climate systems (Steffen et al., 2018; Lenton et al., 2019) and financial networks (Battiston et al., 2021), climate scenarios play a key role for climate financial risk assessment. Nevertheless, the current climate scenarios (NGFS) recommended to regulators to perform climate financial risk assessment have important limitations in terms of granularity, coverage, and financial relevance (Monasterolo et al., 2022b; Ranger et al., 2022).

## Challenges of green finance

Taxonomies and labels for 'green finance' vary considerably across countries, institutions, economic sectors, and products. This range of classifications can result in greenwashing with negative effects on consumer welfare (Fatehi et al., 2023), can create reputational risks for companies (Monasterolo and Volz, 2020), and are a serious concern for financial institutions (De Freitas Netto et al., 2020; Schumacher, 2020; Breitenfellner and Kariem, 2023). For Austria, Seifert et al. (2022) find in a survey that additional information on financial and environmental impacts of investments can stimulate participants' willingness to invest sustainably with higher confidence and also shield consumers from greenwashing.

The perceptions and preferences of financial professionals regarding their attitudes towards climate emergency and climate policy are important aspects of whether and how green finance instruments will be used in practice (Gsottbauer et al., 2024). Investors are aware of climate risks to their assets, but they address those risks mainly through more engagement in ESG-related investment instead of divestment from carbon-intensive industries (Krueger et al., 2020), which might be driven by financial concerns and diversification considerations.

Another major challenge is that the field of finance might be unable to appropriately take into account ecological tipping points (FAO, 2021; Eberle et al., 2023; Ripple et al., 2023) and that in general the strategy of expanding the financial system to include (parts of) ecosystems as financial assets might be unsuitable to conserve and restore these endangered ecosystems (Kemp-Benedict and Kartha, 2019; Spash and Hache, 2022). How much of nature in the form of biodiversity, land, emissions, water, resources, etc., should be under the management and control of financial markets as financial assets remains unclear (Sullivan, 2018; Miess, 2023).

## 8.7. Synthesis of policy-relevant insights of transformation pathways

Section 8.7 links policy-relevant insights from the scenario assessment (Section 8.4) and the four minimum requirements for climate-friendly transformation pathways (Section 8.6). The minimum requirements (Section 8.6.1) indicate necessary actions to overcome limitations of ideal-typical transformation pathways that are based on restricted perspectives, such as eco-modernization (Section 8.6.2) and system change (Section 8.6.3). By doing so, they can support broader societal alliances by minimizing societal and political resistance to climate actions. Although Chapter 8 does not propose policy-prescriptive pathways, it provides policy-relevant insights that support policymakers in taking informed and democratically legitimized decisions. Section 8.7 illustrates how adopting a multi-perspectivity approach can help democratic policymakers to improve their respective value- and interest-based decisions, which might otherwise rely on a single perspective.

Taking multiple perspectives into account broadens the range of available policy tools and creates more opportunities to secure societal and political support. Section 8.6 demonstrates that **bundles of measures combining insights from different perspectives tend to be more effective than ideal-typical pathways** focusing solely on specific measures, such as demand reductions or efficiency improvements. This insight is reinforced by scenario modelling, especially by the NetZero2040 scenarios.

Two of the four NetZero2040 scenarios align closely with the two ideal-typical transformation pathways (Section 8.6). The NetZero2040 high-import/high-demand scenario resembles an eco-modernist transformation pathway relying mostly on market- and technology-based solutions. This pathway, however, would require dramatic price increases in energy and carbon pricing along with expansions of wind and solar infrastructure, which could erode societal support. The NetZero2040 low-import/low-demand scenario, in contrast, aligns with a degrowth transformation pathway requiring reductions in per capita housing space and new constructions levels – measures unlikely to encounter societal support in the short-run. While these ideal-typical scenarios appeal to specific socio-cultural milieus, they lack broader societal support. The other two NetZero2040 scenarios also fail to garner societal support, as they do not align with either the eco-modernist or system change perspective. This underscores the importance of integrating diverse perspectives to foster societal alliances for climate action.

Based on the analysis of enablers and inhibitors of climate-friendly transformations (Section 8.4), the NetZero2040 high-import/low-demand and the NetZero2040 low-import/high-demand scenarios are **techno-economically feasible but lack socio-cultural and politico-economic viability**. The NetZero2040 high-import/low-demand scenario implausibly assumes that sufficiency-oriented lifestyles can go hand in hand with resistance to renewable energies, while the NetZero2040 low-import/high-demand scenario assumes that non-sustainable lifestyles can coexist with the radical expansion of renewable energies. Furthermore, the assumption of high energy imports at affordable prices in NetZero2040 scenarios appears overly optimistic given the current rise in geopolitical and geoeconomic tensions (Section 8.4.5).

The EAA scenarios, elaborated explicitly to support policymakers, highlight the necessity of compromises in democratic climate policymaking. Being closer to the reality of policymakers, they all combine different types of measures – avoid/shift/improve, push and pull, sufficiency and efficiency-enhancing – thereby going beyond the ideal-typical transformation pathways. Especially the WEM and WAM scenarios reflect current political priorities, subordinating climate targets to cost of living and competitiveness concerns. Consequently, climate targets in WEM and WAM scenarios are missed due to delayed and insufficient measures. The Transition2040, in contrast, is designed to align with Austria's goal of reaching net-zero emissions by 2040 but necessitates the deployment of CCUS for balancing out residual emissions in the agricultural sector and hard-to-abate industries.

Although the assessed emission scenarios for Austria demonstrate potential mitigation pathways in line with emission reduction targets, they neglect or only indirectly consider other environmental and social indicators (e.g., land-use impacts of expected bioenergy requirements to meet future energy demand) (Section 8.2.1). These scenarios generally aim at optimizing emission reductions from a techno-economic perspective, thereby overlooking other requirements for climate-friendly living, such as climate adaptation (Section 8.5.5), respecting planetary boundaries (Section 8.2.1) or meeting the SDGs (Section 8.3.1). This narrow focus can result in neglecting potential synergies and trade-offs with other objectives. The expansion of renewables, for instance, may intensify land-use competition and challenges associated with social acceptance, while sharply increasing $CO_2$-prices can exacerbate inequalities and trigger distributional conflicts. A more systemic approach is thus needed to assess scenario effectiveness, incorporating multiple objectives for climate-friendly living moving beyond optimization and single-goal (e.g., net-zero) oriented approaches. Demand reduction strategies, for instance, can maximize synergy potentials with the SDGs (Figure 8.3). Likewise, limiting new constructions (e.g., buildings, roads, etc.) not only lowers emissions but also decreases soil sealing, thereby minimizing biodiversity impacts. Likewise, reducing meat production can cut emissions while improving public health and lowering health care costs, while reducing car dependency can enhance neighborhoods' quality of life (Sections 8.3.1, 8.6.3). However, excessive emphasis on demand reduction may provoke resistance from certain societal groups and stakeholders.

All scenarios share the same path dependencies, reducing the scope for deviation from current trends at least until 2030 and, in many sectors, beyond. This is due to existing lock-ins and already taken or planned investments in the energy and infrastructure system. Achieving the 2040 and 2050 climate targets, however, requires transformation pathways that overcome current path-dependencies, such as the reliance on fossil infrastructures and unsustainable modes of living. This shift is particularly crucial in the mobility sector, where shifting to EV and public transport is essential. While such a transformation towards net-zero is technically and economically feasible, recent policy reactions on geopolitical conflicts still appear biased towards safeguarding fossil-fuel supply. Urgent decisions and related investments taken in this respect, for example the replacement of natural gas from Russia by LNG, and, later on, hydrogen, may create technology-biases and lock-ins that can make necessary emission reductions after 2030 far more challenging and costly (Section 8.5.1).

Additionally, strict fiscal rules may pose an obstacle to meeting climate targets by restraining public investment. (Section 8.5.3). While problematizing these fiscal rules and proposing alternatives (e.g., a 'Green Investment Golden Rule') is one possible political strategy, fiscal austerity also presents opportunities for shifting the focus towards regulatory instruments (e.g., laws, provisions, bans, product liability). The advantage of regulatory instruments, be it speed limits or product provisions, is that these measures can be very effective if correctly implemented (Section 6.5.1). In the current situation, a key advantage is that they can contribute to keep public expenditures at a low level and also reduce transaction costs for market participants, potentially leading to immediate results and increasing the fiscal room of maneuver. In Austrian climate policymaking, pull measures (e.g., grants, incentives, etc.) tend to be privileged, even though they may not align with fiscal discipline.

In rule-of-law-based societies, many specific decisions regarding the choice of means to tackle climate change are left to democratic decisions makers (Section 8.5.2). Based on the assessed minimum requirements (Section 8.6) the implications for democratic policy makers are therefore straightforward yet consequential: they can ignore the minimum requirements, accept given societal preferences, reduce public investments and avoid regulations, thereby implicitly accepting the likelihood of unmet climate targets. Alternatively, they can try to respect the minimum requirements for climate-friendly transformations and implement bundles of measures including policies that may initially lack societal and political support (e.g., tax increases or speed limits) but increase the probability of meeting long-term climate targets. Such a comprehensive and ambitious strategy may indeed be feasible in a democratic setting, if burden sharing is considered as fair and disadvantages for private actors (e.g., bureaucratic costs and inconveniences) are minimized, especially since acceptance of climate measures tends to increase after implementation – thus legitimizing effective climate-actions ex-post.

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