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Need for speed: Co-creating scenarios for climate neutral energy systems in Austria in 2040

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A B S T R A C T

The Austrian government has pledged to achieve climate neutrality by 2040, but so far, there is a lack of consistent net-zero scenarios. Therefore, we integrate a comprehensive stakeholder with a techno-economic modelling process, coupling an energy and a power system model, to co-create qualitative scenario narratives and quantitative model-based scenarios for Austria's energy system, assuming all non-energetic emissions are eliminated. All four scenarios reach climate neutrality by 2040, but differ in terms of energy demand and trade in energy carriers. In the scenario narratives, variations in the local acceptance of renewables and of sufficiency lifestyles explain these differences. All scenario narratives emphasize that commitment of all societal actors is required to reach climate neutrality by 2040. We find that the quantitative model-based scenarios consistently point at far-ranging electrification of transport and heat supply, the buildup of renewables, and a switch in steel producing technology until 2030. Long-term developments are more diverse and show either elevated imports of synthetic fuels or a more pronounced expansion of domestic renewables. Consistently across scenarios, significant fossil fuel infrastructure must be retired before end of life and the required speed of change in energy infrastructure is unprecedented in the history of the Austrian energy system.

1. Introduction

Limiting global warming to well below 2 °C requires rapid reductions in global greenhouse gas (GHG) emissions (IPCC, 2023). At the global level, GHG emissions must reach net-zero around the middle of the century to have a reasonable chance of achieving the goals of the Paris Agreement. Accordingly, Austria, which has historically large cumulative per capita emissions compared to other countries, has committed to achieving "climate neutrality" by 2040 (Bundeskanzleramt Österreich, 2020), implying that all anthropogenic GHG emissions balance to net-zero, i.e. that any anthropogenic GHG emissions are balanced by respective anthropogenic sinks.

While the IPCC's Assessment Report 6 (IPCC, 2023) provides a large variety of global and regional scenarios towards this goal, national scenarios for Austria are scarce. In fact, only three alternative (almost) net-zero scenarios by 2040 have been developed: the "Transitions" scenario by the Environment Agency Austria (Krutzler et al., 2023) and the two "Mother Earth scenarios" by (Steininger et al., 2024). For the "Transitions" scenario, the scenario design and development lack full transparency, as no alternatives are explored and as the scenario did not undergo peer-review. Similarly, the "Mother Earth scenarios" have not been peer-reviewed and are partially based on the "Transitions" scenario. Despite these limitations, all three scenarios serve as important references for comparison in our discussion. None of these existing scenarios provide a detailed assessment of pathways to net-zero emissions for non-energetic emissions. Likewise, our focus remains on the energy sector, assuming that non-energetic emissions are also eliminated without specifying an explicit pathway.

Other existing climate and energy scenarios for Austria largely aim to evaluate current or proposed policies (Bundesministerium Nachhaltigkeit und Tourismus, 2019; Krutzler, 2017), represent narrow stakeholder interests (Krutzler et al., 2016; Veigl, 2017; Windsperger et al., 2018), focus on specific sectors (Fallahnejad et al., 2022; Geyer et al., 2019; Nagovnak et al., 2024; Rahnama Mobarakeh and Kienberger, 2022; Windsperger et al., 2018), and mostly achieve climate neutrality by 2050, if at all. Therefore, these scenarios do not provide the comprehensive, balanced picture that is necessary to assess potential alternatives towards climate neutrality in Austria. Furthermore, the existing scenarios have methodological limitations: first, most of them lack a detailed representation of the power sector which is crucial for

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evaluating the techno-economic feasibility of net-zero scenarios, especially given their reliance on very high shares of intermittent renewable energy sources. Second, they were developed by a relatively small panel of experts without broader stakeholder engagement, heightening the risk of misalignment between model-generated pathways and stakeholder demands (Andersen et al., 2021; Prehofer et al., 2021; Xexakis et al., 2020). Third, they typically do not incorporate detailed scenario narratives, which are essential for effectively communicating scenario outcomes (Trutnevyte et al., 2014). Consequently, they are only of limited relevance for supporting the current policy ambition.

At the same time, results of international scenarios cannot be directly transferred to the Austrian context. While general trends, such as the build-out of renewables (IPCC, 2023), will be fundamental in Austrian decarbonization scenarios, technological specifics will differ from those of other regions, due to the unique configuration of Austria's energy system. For instance, Austria's energy system has a high share of hydropower storage, which simplifies the integration of intermittent renewables compared to other countries (Hirth, 2016; Höltinger et al., 2019). Also, Austria's large industrial sector requires tailored decarbonization approaches (Nagovnak et al., 2024; Rahnama Mobarakeh and Kienberger, 2022). Thus, conducting in-depth, country-specific analyses is essential for effectively steering the transformation process. This also relates to engaging national stakeholders, which can contribute important local knowledge.

The engagement of heterogenous stakeholder groups in co-creating net-zero scenarios offers manifold benefits (Chambers et al., 2021), in particular for enhancing modelling processes (Bataille et al., 2018). Depending on the purpose of a modelling exercise, stakeholders can actively participate in the different model development stages and with varying degrees ranging from information to consultation, dialogue and co-creation (Barreteau et al., 2017). They can offer context-specific, experiential and phenomenological knowledge (Enengel et al., 2012) based on their different value sets and mental models (Jungermann and Thüring, 1987). Furthermore, they can provide sector-specific input to parameter choices in the model development process, strategic advice during scenario development from a pragmatic and practice-oriented perspective (Bailie et al., 2023; Galende-Sánchez and Sorman, 2021; Wachsmuth et al., 2023)), provide policy and planning alternatives and act as knowledge brokers (Dilling and Lemos, 2011; Rothman et al., 2009; Voinov and Bousquet, 2010). Hence, scenarios that have emerged from knowledge exchange and collaboration between researchers and stakeholders can lead to a more holistic vision of the required energy system transformation, which can consequently impact decision-making and face less obstacles in implementation (Bots and van Daalen, 2008; Voinov and Bousquet, 2010).

However, existing model-based scenario processes for attaining net-zero pathways do lack co-creation efforts between researchers, stakeholders, and policymakers (Bataille et al., 2016; Dafnomilis et al., 2023; Dixon et al., 2022; Duan et al., 2021; Glynn et al., 2019; Jacobson et al., 2015; Johnson et al., 2023; Oshiro et al., 2018; Raycheva et al., 2023; Schreyer et al., 2020; Williams et al., 2021), with the exception of Wachsmuth et al. (2023) who expose quantitative modelling results to an extensive stakeholder process to identify bottlenecks for the feasibility of socio-technical net-zero scenarios ex-post and to overcome them through developing tailored policy mixes. In other contexts, beyond the development of net-zero pathways, a dialogue between quantitative model based scenario development and stakeholder-oriented pathway processes were established, for example, in re-industrialization policy scenarios with iterative cycles of stakeholder consultations (Lechtenböhmer et al., 2015) or in transport scenario planning by integrating qualitative narratives (Venturini et al., 2019). While forecasting based on currently available data inputs dominates in scenario-driven modelling exercises, alternative methodologies such as participatory backcasting without relying on past trends remain niche (Godínez-Zamora et al., 2020; Quist and Vergragt, 2006; Sharmina, 2017).

Our contribution is therefore twofold: first, we close the gap in the availability of comprehensive Austrian net-zero scenarios by providing an internally consistent and openly accessible set of scenarios attaining full decarbonization of the energy system. We limit our analysis to the whole energy system, including all energetic emissions, which cover about 80% of all Austrian GHG emissions (Anderl, 2023), and examine decarbonization requirements given non-energetic emission reduction scenarios. Second, we build on an existing scenario protocol (Mitter et al., 2019) which actively engages stakeholders in scenario development, allowing deriving consistent qualitative scenario narratives and quantitative model-based scenarios to reach climate neutrality.

In the following, we first present our scenario development process. It addresses the integration of multiple perspectives in a mutual learning process between the team of researchers and stakeholders to increase legitimacy, facilitate acceptance, and support the co-dissemination of the final scenarios. At the same time, it ensures techno-economic consistency by the application of an integrated modelling framework for the energy system, with a particular focus on power systems. And second, we outline the core elements of the resulting scenarios as a guideline to (a) inform policy makers and other stakeholders about how to proceed with decarbonization efforts in Austria, and (b) identify core uncertainties that should be tackled in future research.

2. Data and methods

We follow a structured stakeholder engagement and participation process for developing and evaluating scenarios in a transparent and reproducible way. Building on a protocol initially designed for creating exploratory, or descriptive, scenarios—those that start from the present and explore plausible future developments driven by key factors (Mitter et al., 2019)—we extend this framework to include steps aligned with achieving specific societal or policy goals. This extension introduces anticipatory, or normative/prescriptive, scenarios that begin with a defined future vision and work backward to the present (Alcamo and Henrichs, 2008). Hence, we systematically combine a forward-looking approach with a backcasting method or "backwards logic" (Ashina et al., 2012; Quist and Vergragt, 2006; Robinson, 1982; Wright et al., 2013). In the protocol, in particular, working steps related to specifying a long-term vision and policy goal, exploring technology and policy options to achieve the climate neutrality, modelling the system of interest, and checking the desired outcomes are added to the original nine-step protocol (see Fig. 1).

In a first step, four qualitative net-zero scenario narratives have been developed with stakeholders by identifying and clustering drivers of the energy system and their development directions (see section 2.1). Selected drivers of the energy system have subsequently been quantified by stakeholders in an online survey and have been translated to model parameters (see section 2.2). Additionally, a GHG emission pathway has been defined based on stakeholder inputs. We used the whole energy system model TIMES and the power system model MEDEA in the quantitative model-based scenario process and developed model interfaces between them to derive quantitative pathways for the evolution of technologies (see section 2.3). Furthermore, a range of model parameters not quantified by stakeholders was parametrized based on recent literature (see section 2.4). The scenario narratives and the quantitative model-based scenarios have been checked for their consistency, and the reconciled scenarios were presented and evaluated in a final stakeholder workshop (see section 2.1).

2.1. Stakeholder engagement process

The primary objective of the stakeholder engagement and participation process was to derive scenarios for climate neutrality in Austria through the sharing of knowledge and joint decision taking during scenario development by researchers and stakeholders. The societal and national policy goal of climate neutrality by 2040 served as the starting

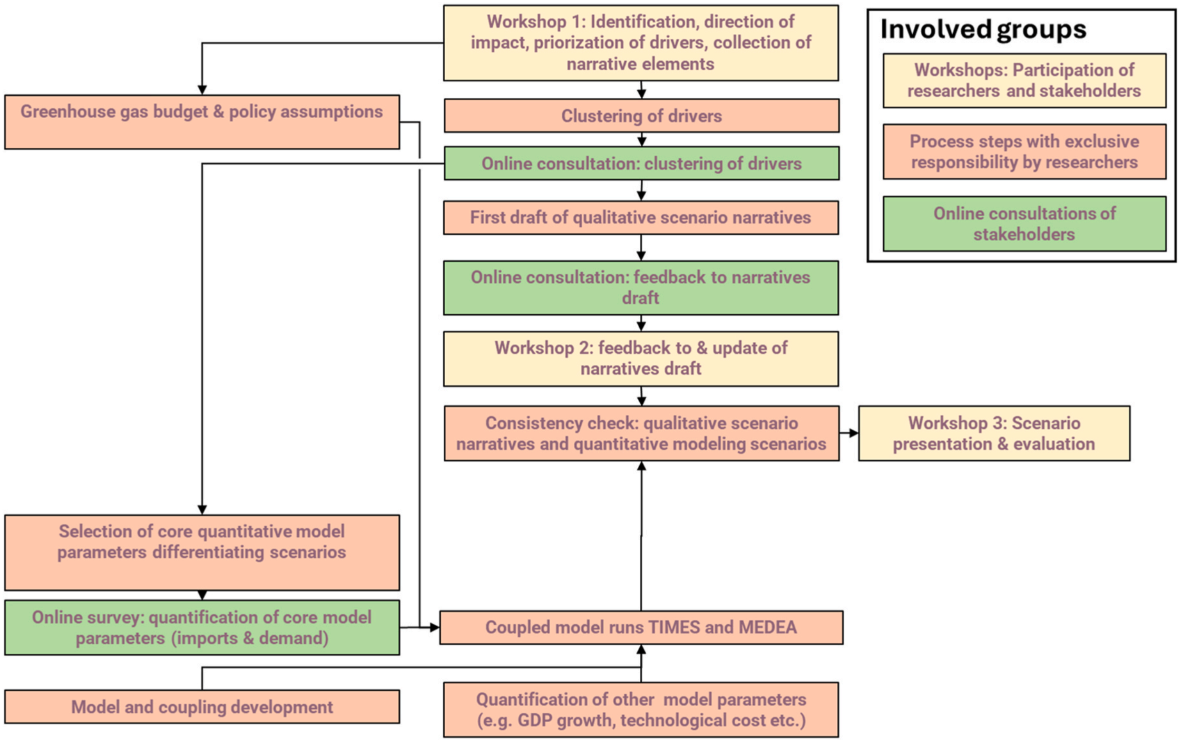

Fig. 1. Scenario co-creation process.

point for scenario development. The stakeholder process was initiated by the researchers, first identifying and selecting stakeholders (see section A1 for details). Subsequently, the stakeholders were continuously involved in a goal-oriented and interactive research process. The four scenarios were categorized with the widely used matrix approach (Ramirez and Wilkinson, 2014; Rounsevell and Metzger, 2010) and differentiated by the variations in energy demand within Austria and the extent of energy carrier imports. The researchers initially defined these dimensions of the matrix to ensure that the stakeholder process operates effectively along dimensions that can be represented in the models.

The stakeholder engagement and participation process comprised three workshops, separate online consultations, and an online survey (see Fig. 1). The three workshops served to (1) identify and prioritize drivers of the Austrian energy system, discuss plausible development directions of these drivers, and collect narrative components for the four scenarios, (2) gather feedback on the scenario narratives and their further development from stakeholders, and (3) finally evaluate the scenarios. Online consultations were used to gather feedback on scenario-related products between the workshops, and an online survey was used to quantify selected drivers for its application in modelling.

A total of 30 invitations to stakeholder institutions were sent out for the first workshop. 26 stakeholders participated. 14 (19) of the 27 (28) invited stakeholders joined the second (and third) workshop, respectively (see Table A1 for stakeholder engagement information). Due to COVID-19 restrictions, the first and second workshop had to be conducted online via Zoom-video conferences, whereas the third workshop took place in person in Vienna. The digital whiteboard tool ‘Mural’ was integrated in the online workshops to enhance teamwork and collaborative exchange of ideas. All plenary and group workshop sessions were recorded and transcribed for qualitative content analysis.

In total, the participating stakeholders identified 207 drivers of the Austrian energy system in the first workshop, which are expected to influence future (1) Energy demand for residential and commercial buildings, (2) Energy demand for industry, (3) Energy demand for transportation, and (4) Energy imports. A team of four researchers clustered these drivers, which resulted in a list of 44 drivers that was shared with the stakeholders for review. Examples of drivers are climate friendly living styles and consumption behaviour, climate friendly spatial planning, risks of geo-political energy and resource dependency, and speed of technological progress. For a full list see the online appendix (Schmidt, 2024). Of these 44 clustered drivers, the research team selected six drivers for quantification by stakeholders (see section 3.2). We limited ourselves to six drivers, to keep the respective surveys sent out to stakeholders at a manageable length. Criteria for the selection of these six drivers were data availability, the technical possibility to translate them to model parameters, and the expected relevance along the two scenario dimensions demand and imports, pre-defined by the researchers.

Based on the collaborative identification and description of scenario characteristics in the first workshop, initial titles for the four scenarios were chosen by researchers and a first version of the scenario narratives using the list of drivers and narrative components collected in the first workshop was developed by them. Feedback on the list of drivers and the qualitative scenario narratives was obtained in two online consultations, as well as during the second workshop, from stakeholders and the team of researchers. Subsequently, the narratives were adapted accordingly. During the third workshop, the researchers presented both qualitative scenario narratives and quantitative scenario results to the stakeholders, using presentations, posters, and in person discussions. Stakeholders were engaged in group reflections about factors facilitating or impeding the achievement of the climate neutrality goal referring to three categories: social justice, potential demand reductions, and imports of synthetic fuels. They furthermore gave feedback on scenario narratives and scenario titles, which led to minor adaptations. Additionally, reviewers of this paper commented on titles, which caused final modifications.

2.2. *Stakeholder quantification of model input parameters*

After finalizing the first draft of scenario narratives, stakeholders were asked to quantify drivers of the energy system in an online survey which were subsequently translated to model input parameters. We asked the stakeholders to quantify four selected drivers related to energy demand and furthermore assess import shares for electricity and total energy carriers, using an online survey which we sent out twice to the 35 selected stakeholders. The first survey wave took place before the second stakeholder workshop, the second one afterwards. The drivers assessed by stakeholders are listed in Table A2. For each one of these drivers, the questionnaire showed a timeseries for a historical period, mostly 2004–2021, depending on data availability. The stakeholders were asked to indicate their expected value in 2040 for the respective driver in the high import or high demand and in the low import or low demand scenario, respectively, while always keeping the climate neutrality goal in mind. Furthermore, we posted the survey on social media, i.e. on the X account @NetZero2040 and we sent it internally to energy experts at the Austrian Energy Agency and researchers in the energy cluster at BOKU University Vienna. Table A3 shows the number of participants in the respective survey rounds. We only used responses from external stakeholders when we translated drivers into definite model input parameters, while we used the responses from other groups for validation purposes.

2.3. Model descriptions & coupling

For the development of the scenarios for the Austrian energy system, we used an energy system model that has been implemented using the TIMES model generator which has been developed by the IEA-ETSAP group (IEA-ETSAP, 2024a, 2024b). It allows the development of a detailed energy system representation as a linear program, automatically generating all structural equations from model input files. The generated model is used to minimize total costs of energy supply with perfect foresight under given technical constraints and policy targets. The model exogenously assumes driver variables (e.g. GDP or population development), technical parameters (e.g. conversion efficiencies), upper and lower limits to relevant parameters (e.g. import shares, technology shares, potential for the expansion of renewables, etc.), availability of predefined technologies (e.g. hydrogen, carbon storage etc.), prices of technologies or fuels and dynamic constraints such as limits to maximum or minimum annual growth rates of technologies.

The TIMES model for Austria (Krutzler, 2017) constructed using the TIMES model generator, is calibrated to be aligned with the official Austrian energy balance (Statistik Austria, 2023). This alignment refers to the sectoral structure of the model by disaggregating the energy system into five final energy demand sectors, i.e. households, services, industry, agriculture and transport, as well as several subsectors for energy supply: production of electricity and district heat, synthetic fuels, biogenic fuels and fossil fuels, fuel imports and domestic production. All energy carriers covered by the energy balance are explicitly accounted for. For a more detailed description of the technologies included, see section A3.1.

The *medea* power system model (Wehrle et al., 2021) co-optimizes investment, de-commissioning and hourly operation within an integrated Austrian and German power system by 2040. *Medea* minimizes total system cost, encompassing fuel, emissions operations, and investment expenditures across energy generation, storage, and interconnectors. The model reflects a perfectly competitive energy-only market with fully price-inelastic demand, ensuring the model meets exogenous hourly demand for electricity, district heat, and synthetic gases. Although *medea* does not represent internal transmission and distribution grids, it accounts for cross-border electricity trade between Austria and Germany, constrained by interconnector capacities. The model is implemented in GAMS, with data processing in python. The model code is published on Github (Wehrle, 2024) under an open-source MIT license. A more detailed description of the implementation of the technologies in the model can be found in section A3.2. Wehrle et al. (2021) gives a detailed description of a previous model version.

We couple TIMES and *medea* to enhance energy system analysis by integrating TIMES' long-term, multi-sector optimization with *medea's* detailed hourly dispatch and investment. TIMES provides consistent long-term investment decisions, while *medea* validates their operational feasibility under real-time conditions, which is particularly important in our scenarios with high renewable penetration. The model coupling improves the assessment of flexibility and storage options by ensuring that the capacity expansion proposed in TIMES is operationally viable and not excessive. Additionally, *medea's* cross-border electricity flows between Austria and Germany ensure consistency with TIMES long-term scenarios even when electricity exchange with neighboring countries is integrated. Thus, coupling TIMES with *medea* results in a comprehensive analysis that balances long-term planning ensuring that model results can meet the practical operational challenges in energy transitions. The coupling is described in detail in section A3.3.

2.4. Scenario assumptions

A crucial scenario input is the assumption on the emission pathway, which was specified as a predefined model parameter. Following stakeholder input from the initial workshop, we adopted a greenhouse gas emission budget approach consistent with the Paris agreement goals. The total Austrian budget up to 2040, based on Steininger and Kirchengast (2021), accounts for total emissions including historical emissions up to 2020. To establish the remaining budget for the 2023–2040 scenario horizon, we deducted 2021 and 2022 emissions from this total. The emissions budget refers to net-emissions, accounting for carbon sinks. We split emissions in two categories: (1) those from sectors explicitly represented in the models – primarily energy-related emissions, which constitute about 80% of total emissions; and (2), emissions from sectors not modeled, including agricultural non-energetic emissions, land-use and land-use change, cement industry, f-gases, solvents, and fugitive emissions from waste. For sectors not covered by the models, emission reductions followed a linear pathway to zero emissions from 2023 to 2040.

This approach implies that we do not balance positive residual emissions in the energy sector with potential negative emissions from e.g. forestry or land-use and land-use change, nor do we offset positive emissions from agriculture with potential negative emissions in the energy sector. Emissions from non-modeled sectors were subtracted from the carbon budget. Subsequently, we defined an emissions pathway for the energy sector with larger annual reductions in earlier years, tapering over time. Any residual emissions in 2039 were set to reach zero by 2040.

This emission pathway served as an upper limit on model emissions. Although 2021is shown in the results as reference, it was not modeled, relying instead on historical data. It does not contribute to the emissions budget. We modeled the time steps 2023, 2030, 2035, and 2040. Emissions between these years are linearly interpolated and remain below the emission cap in all years.

All scenarios share the same emissions pathway, but are differentiated by variations in demand and import shares of energy carriers. These have been qualitatively described by stakeholders and quantified in terms of key parameters (see Section 2.2). They are discussed in more detail in the results section. Technically, the variables determined by stakeholders were used to exogenously alter energy demand, while the import shares quantified by stakeholders were set as upper import share constraints in the models. To achieve relevant quantities of imports in the high import scenarios, we had to additionally assume low import costs for synthetic fuels. In all scenarios, we enforce the Austrian renewable expansion act until 2030.

Furthermore, we have constructed thematically specific sensitivity scenario runs to assess in more detail the effect of important single model choices on model results. These runs are not embedded in the logic of the scenarios, and are not assumed to be feasible, but are used to show the magnitude of impact of very significant changes in assumptions. We based these on our scenario C (see results), as it is the most demanding of the four scenarios, due to the low availability of imports of energy carriers at high energy demand levels. In particular, we assessed the consequences (I) of a much lower uptake rate for electric cars, (II) of reducing maximum imports of low-carbon energy carriers further to 5% of gross domestic energy consumption, and of (III) disabling thermal renovation of buildings (see Table 1).

Exogenous price data for Crude Oil, Natural Gas, and Emission Allowances for the modeled years 2023, 2025, 2030, 2035 and 2040 has been compiled. To ensure the plausibility and internal consistency of these time series, we devised a method aimed at providing realistic price projections (For details, see section A4). Population growth assumptions were taken from the main official population projection for Austria by Statistik Austria from the year 2022 (Statistik Austria, 2022). GDP growth assumptions in the high demand scenario are aligned with the Transitions scenario by Umweltbundesamt (Krutzler et al., 2023) at a 1.4% annual growth rate. In the low demand scenario, we lowered industrial output as quantified by the stakeholders, causing overall lower GDP growth rates. All CO_2 emissions in the model are priced uniformly at the same carbon price (See Table 2). Techno-economic assumptions for specific supply technologies were based on the technological catalogue by the Danish Energy Agency (2023) with the exception of carbon capture and storage technologies. Given that carbon storage is currently not permitted in Austria and was considered a last-resort mechanism by stakeholders, CCS was included in the model, but at rather high cost. The respective model parameters are summarized in Tables 2 and 3.

3. Results

In the following, we give an overview of the qualitative scenario narratives, the quantification of model parameters by stakeholders, and quantitative modelling results. The emission pathways as shown in Fig. 2 was a crucial reference throughout the whole scenario development process, as it was used while developing qualitative scenario narratives as well as directly as a quantitative emission limit in the energy and power system models. Note that the kink in the last year is caused by reducing remaining emissions in the year 2039 to 0 in 2040.

3.1. Qualitative scenario narratives

The qualitative scenario narratives are structured along the two dimensions of final energy demand, and imports of energy carriers, as shown in Table 4 (also see Figure A3). The extensive stakeholder input on the scenario narratives was structured into five thematic areas for all four scenario narratives: (i) Social acceptance and lifestyles, (ii) Politics and institutions, (iii) Energy supply and network infrastructure, (iv) Buildings and housing, (v) Transport and mobility, and (vi) Prices and costs. There are important commonalities among the scenarios. All four scenario narratives emphasize the need and urgency of (i) effective multi-level cooperation and (ii) societal change. Multi-level cooperation requires clear political commitment for the climate neutrality goal and refers to the cooperation between federal states, EU member states and economic sectors to reduce trade-offs and use synergies. Cooperation with third countries is, however, viewed critically because of potential dependencies.

Multi-level cooperation shall ensure the implementation of a mix of measures including incentive-oriented instruments, such as instruments for price or quantity control, public investments such as in the renovation of buildings, legal regulations such as the ban on emission-intensive technologies or on the expansion of infrastructure for fossil fuels, the serious consideration of the climate neutrality goal in laws and regulations, the reduction of regulations that inhibit innovations, and the socially just design of the energy transition for instance, through strengthening participation in decision-making processes. Societal change requires broad support from all demographic groups and social classes for the energy transition. In this context, public awareness for the urgency of climate protection, social acceptance for the build-out of renewable energies and the related infrastructure, the willingness to adopt climate-friendly lifestyles, and the sharing of resources are addressed in the four scenario narratives. However, we have also identified key factors which differentiate the scenarios (see Table 4, Figure A3). In detail, the scenario narratives contain more differentiated content regarding the five thematic fields. They can be found in German in our online repository (Schmidt, 2024).

Table 1
Sensitivity runs.

Name	Short name	Description
S1: Low battery electric vehicles	S1: Low BEV	Based on scenario C, restricting penetration of battery electric vehicles to 20%
S2: Autarky	S2: Autarky	Based on scenario C, restricting imports further to 5% of gross domestic consumption
S3: No building renovation	S3: No renov	Based on scenario C, disabling building renovation

3.2. Quantification of input parameters by stakeholders

Stakeholders quantified four core demand drivers and two import limits (see Fig. 3). The survey results affirm that stakeholders grasped the task accurately, as their chosen values align consistently with the respective scenarios (see section A2 for details). A key finding is that stakeholders anticipate demand drivers to increase in high demand scenarios, mirroring recent trends. A notable exception is the annual per capita distance driven in cars. The stakeholders estimated that distance driven by cars will decrease (slightly) in the high demand scenario compared to latest observations, indicating stakeholders' recognition of the transport sector's pivotal role in achieving climate neutrality. Conversely, stakeholders' specifications of the low demand scenarios witness a structural shift across all parameters, marking a departure from long-term trends of escalating demand drivers. For instance, the per capita heated building area is suggested to decline compared to recent observations, implying a reduction in the total heated building stock in 2040. Industrial value added was assumed to remain stable in the low demand scenario which may reflect stakeholders' skepticism regarding the feasibility or social acceptance of larger reductions. The parameters resulting from the 25%/75% quantiles of the distributions of answers have been implemented in the models (see Table A2).

3.3. Quantitative model scenario results

The four scenarios show common trends in almost all indicators, but different magnitudes of change (see Fig. 4). The upper left panel shows gross domestic energy consumption, which is the sum of all primary energy extracted within a country, encompassing both fossil fuels and renewables, along with imports of primary and secondary energy carriers, such as electricity, fossil or synthetic fuels. This metric serves as a standard indicator of overall energy use in a country. All scenarios show a common trend of falling gross domestic energy consumption, projected to reach 54%–66% of the levels observed in 2021 by the year 2040. The primary factor contributing to lower gross domestic energy consumption is the electrification of mobility (see sensitivity analysis in section 3.4), coupled with a lesser but still notable impact from the electrification of heating.

There are differences in the magnitude of the decrease in gross domestic consumption across the scenarios. Scenarios with lower imports exhibit 2%–7% higher gross domestic consumption, primarily due to the need to produce synthetic fuels within Austria, which introduces efficiency losses inherent in the production process to manifest in the Austrian energy balance. In contrast, in higher import scenarios, these efficiency losses occur in exporting regions. Additionally, demand-side measures - such as reduced mobility, decreased heated area, and diminished industrial activity - can significantly influence gross domestic consumption, potentially leading to differences of 12%–17%

Table 2
Model input parameters – dynamic.

Parameter	Unit	2025	2030	2035	2040	Source
GDP Growth high demand	% p.a.	1.4	1.4	1.4	1.4	Krutzler et al. (2023)
GDP Growth low demand	% p.a.	0.8	0.8	0.8	0.8	Adjusted for lower industrial output as parametrized by stakeholders
Population	'000 people	9193	9363	9521	9654	
Gas price	€/MWh	41,37	13,26	12,68	12,11	Table A4
Oil price	US$/bbl	68,01	35,00	32,25	29,50	Table A4
CO2-emission allowances	€/tCO2	50	100	150	200	Table A4
Synthetic gas price	€/MWh	30	30	30	30	Calibrated to increase imports in high import scenarios
Synthetic liquid price	€/MWh	45	45	45	45	Calibrated to increase imports in high import scenarios
Direct Air Capture (DAC) cost	€/ton CO2	1000	1000	1000	1000	Young et al. (2023)

Table 3
Model input parameters – static.

Parameter	Unit	Value	Source
Potential wind	TWh/a	71.6	Höltinger et al. (2016)
Potential solar	TWh/a	1600	Mikovits et al. (2021)
Potential expansion biogas	TWh/a	11	Baumann et al. (2021)
Potential expansion hydro	TWh/a	11	Pöyry (2018)

across the scenarios, as demonstrated by the low demand scenarios.

The structure of the energy system in Austria is modified fundamentally (see Fig. 4). A consistent, common technological shift in energy supply until 2030 is observed in all scenarios: a rapid expansion of renewable power generation coupled with the electrification of mobility and heating, and an associated decline in the use of fossil fuels. Differences between scenarios primarily lie in the extent of fossil fuel consumption, which is higher in high-demand scenarios, leading to limited implementation of carbon capture and storage in those scenarios even before 2030. Additionally, variations exist in the amount of electricity imported, with higher levels in high import scenarios.

Beyond 2030, the scenarios diverge in terms of the development of the energy supply structure. Generally, in low-import scenarios, there's a greater reliance on domestic biomass & waste and ambient heat, with reduced usage of synthetic fuels. Moreover, in the high-demand, low-import scenario, additional expansion of domestic renewable energy generation becomes imperative after 2030. This contrasts with other scenarios where further growth in low-carbon energy is met through imports of synthetic fuels. Notably, total imports approach the constraints specified by stakeholders in low-demand scenarios but remain well below the upper constraint in the higher-import scenario. This suggests that even with relatively low-price assumptions for imported fuels, domestic resources are preferred due to their low cost. As an example, in the scenario with the highest usage of synthetic fuels, the quantity of those fuels is 60% less than fossil fuel use in 2021, highlighting the substantial shift towards electrification and domestic low-carbon electricity supply.

Furthermore, the results underscore that the primary alternatives to domestic renewable expansion and electrification are imports of low-carbon fuels or using fossil fuels combined with carbon capture and storage, both technologies which are uncertain to scale to the sufficient level in the short-term. The total cumulative sequestered CO2 in the period 2020–2040 in the scenario with highest sequestration levels amounts to about 10% of current Austrian annual emissions and is therefore low. Interestingly, storage of carbon is necessary in 2030 in one scenario, due to stringent emission restrictions up to 2030, and at the end of the period, when residual emissions are sequestered, but not in 2035. This underlines the challenge of the very rapid decarbonization until 2030, implied by our emission pathway, and furthermore shows that demand reductions, as shown in our low-demand scenarios, can in the short-term lower the need for technologies which are currently not fully market ready, as in the early period carbon is only sequestered in high-demand scenarios.

In all scenarios, the electrification of end-use sectors is essential for achieving climate neutrality targets. Notably, in the realm of mobility, fuel demand undergoes a drastic reduction, plummeting by over half due to the universal electrification of road transport. The electrification of road transport has a significant effect: reductions in mobility services, such as fewer kilometers driven per person, have only a limited impact on final energy demand within the sector in 2040, owing to the efficiency of battery electric vehicles (see Fig. 5). This development is only possible due to an assumed rapid turnover rate of vehicles which ensures that no fossil fuels remain in land transport due to a complete

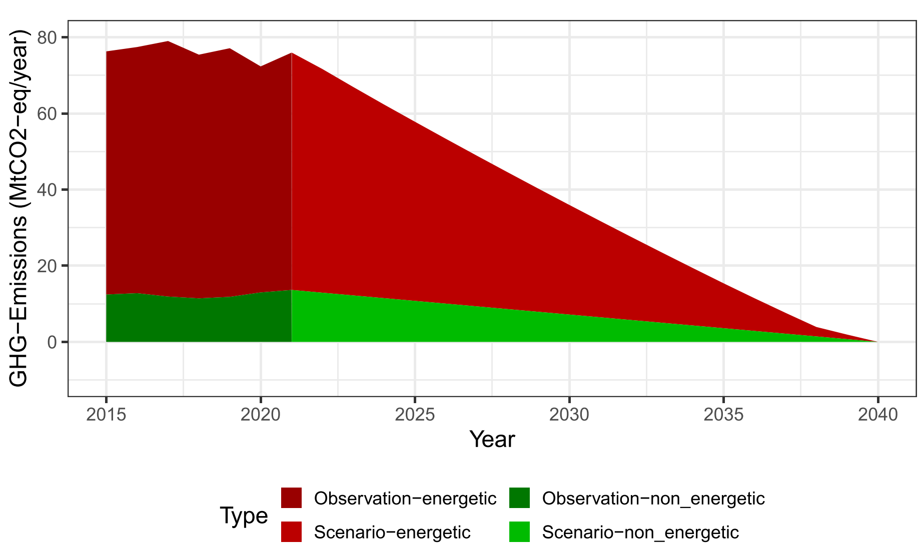

Fig. 2. Emission reduction pathway assumed in Net-zero2040.

Table 4
Key factors demonstrating the qualitative differences between the four Netzero2040 scenario narratives.

Scenario	Key factor 1	Key factor 2
A: Sufficiency and maximum expansion of renewable energies (Low demand – low imports)	Federal state-specific and national energy policies are strongly climate-friendly. Competitive renewable energy supply and the expansion of energy infrastructure, including pipelines and storage facilities, are promoted at national level, significantly reducing the dependency on foreign energy suppliers.	The sharp rise in environmental and climate awareness among the population is leading to (i) energy-sufficient lifestyles (with emphasis on mobility and housing behaviour), and (ii) a high level of social acceptance for the mix of policy measures required to implement the energy transition.
B: High resource consumption and international energy agreements (High demand – high imports)	The relatively conservative environmental and energy awareness of the population and the lack of progressive policy strategies and instruments lead to a slow national expansion of renewable energy and minor changes in energy-intensive activities.	The high energy demand is covered through the trade of CO_2-neutral electricity and fuels which are available internationally at low cost. Trade is strengthened through trade agreements and international partnerships.
C: Energy-intensive lifestyles and relative energy autonomy (High demand – low imports)	National transformation strategies, regulations and public investments foster relative energy independence and strengthen domestic self-sufficiency, further supported by broad social acceptance of the expansion of renewable energy sources.	The combination of high energy availability, low energy prices, massively decreasing technology costs, and low public awareness of energy sufficiency is leading to rising resource consumption.
D: Restricted expansion of renewables and low resource consumption (Low demand – high imports)	At national level, the reduced efforts to expand renewable energies and their comparatively high production costs, influenced by the low level of social acceptance, lead to rising imports of energy carriers.	Technological innovations are proactively promoted by politicians through regulatory frameworks and investments. Support is also provided by the population through energy-saving behavioural preferences.

substitution of internal combustion engines by electric motors.

Fossil fuel consumption is almost completely phased out in all scenarios. The remaining use of fossil fuels in agriculture, services, and households (see Fig. 5) is explained by lock-in effects of heating systems, which will become carbon-neutral only after 2040, due to legacy effects. Fossil fuels are substituted by electricity, but also by synthetic liquid fuels and gas. These are mainly used in industry, in aviation and in shipping. Power generation uses some synthetic gas in combined heat and power plants, to supply district heating, and to cover periods of low output of variable renewables. Biomass use is shifted from households and electricity and district heating to industrial uses.

The dynamics of sectoral emission reductions are very similar across all sectors (see Figure A4). Emission reductions in transport are the most pronounced ones until 2030 and flatten off afterwards. Industry first rapidly reduces emissions, in particular due to a switch in steel production away from coke, then emissions flatten off, and start gaining traction again in 2035 when more expensive processes are substituted by low-carbon alternatives. The electricity sector only starts to lower emissions in 2030, although the buildup of renewables up to 2030 is most pronounced. The reason is that synthetic fuels and gases that can substitute remaining fossil methane in electricity generation become available after 2030 only. The combined sectors agriculture, households, and services, are on an almost linear reduction pathway until 2040.

The pace of change in the energy system required to meet climate neutrality is unprecedented. Both solar PV and wind power must expand at a faster absolute pace than was historically observed for hydro, wind or gas power (see Fig. 7). Historically, the growth rate of wind power has largely aligned with the expansion of hydropower, failing to meet the necessary acceleration for climate neutrality. For solar PV, the absolute expansion in PV generation in 2023, an outlier year triggered by the energy crisis, would have to be maintained each year until 2030 to meet climate neutrality targets. This translates to a required compound annual growth rate (CAGR) of 21% for solar PV, and of 17% for wind power. In comparison, the historical maximum Austrian CAGRs maintained over a decade are 14% for gas power (1970–1980), 8% for hydro power (1930–1940), 13% for wind power (2010–2020) and 37% for solar PV (2010–2020). On a global scale, the CAGR for solar PV reached 34%, while wind power achieved 15% during the decade from 2010 to 2020 (Energy Institute, 2024).

Taking into account that there is at least historical evidence for growth rates of solar PV being in line with the climate neutrality target, a more rapid expansion of solar PV with slower growing wind power may be feasible. This contrasts with a much higher expansion of wind power than solar PV in our scenarios, as wind power reduces total system cost: while the electricity system can operate on solar PV instead of wind power, the costs increase significantly, as sensitivity runs with the power system model *medea* show (see Figure A5). Notably, expanding wind power capacity to 20 GW (GW), the expansion potential assumed in our models, would decrease power system costs by nearly 20%. Beyond this threshold, further expansion can still yield cost savings, albeit with diminishing marginal returns. The reasons for the cost advantage of wind power are discussed in more detail in section A6.

3.4. Sensitivity analysis

Here we compare the three sensitivity runs to their base scenario, the high demand, low imports scenario C (see Fig. 9). The key insight is the crucial role ofbattery electric vehicle adoption. Without BEVs, total gross domestic consumption rises significantly, carbon sequestration quadruples, and both fossil fuel as well as renewable energy use increases compared to scenario C. The absence of a transition to electric mobility strains the entire energy system, as it is central to reducing overall energy consumption.

Additionally, the inability to import even limited amounts of synthetic fuels would place substantial pressure on renewable energy expansion, requiring nearly double the buildout of renewables compared to scenario C, and pushing biomass use to its maximum feasible levels. A combined scenario with both a limited transition to electric vehicles and restricted synfuel imports would dramatically complicate Austria's pathway to carbon neutrality. In contrast, the impact of not fully renovating buildings, as assumed in sensitivity run S3, has a relatively minor effect on the energy system. Gross domestic energy consumption increases by about 12 TW h, which is offset by a moderate expansion of renewables, and a stronger reliance on domestic biomass resources.

4. Discussion

Our integrated approach enables us to deliver consistent qualitative scenario narratives and quantitative model-based scenarios for achieving climate neutrality in Austria by 2040. The scenarios demonstrate that this transition is feasible from a techno-economic perspective, offering multiple pathways that accommodate varying societal preferences around energy intensity and import dependency.

However, two key limitations remain unaddressed: First, the models do not account for the necessary grid and pipeline infrastructure. While

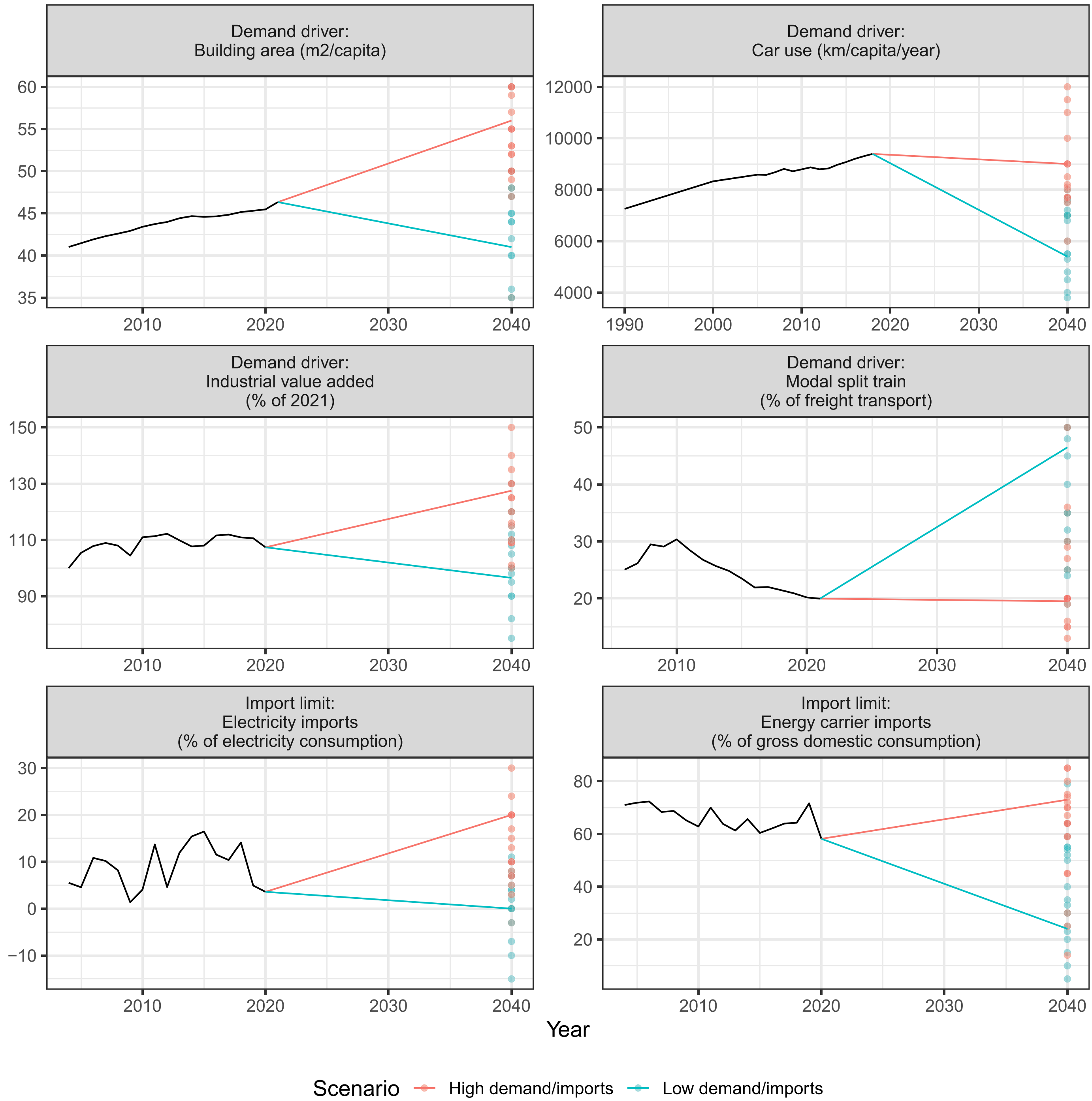

Fig. 3. Quantification of demand drivers by stakeholders (top 2 rows) and of import limits (bottom row). Historical development of drivers (black line), and stakeholder responses for the year 2040 (colored points). The colored lines connect the last observation with the 25% quantile or the 75% percentile of responses, respectively.

the scenario narratives indicate that a significant expansion in power grid infrastructure is essential for enabling climate neutrality, the models do not specify the locations or configurations of grid expansions required by different generation mixes. Second, our power system model only includes interactions with Germany, though Austria is also heavily integrated with other neighboring countries. Enhanced integration with the broader European grid could, in principle, help balance fluctuations in power demand and supply. Consequently, the models may overestimate Austria's internal flexibility needs.

We predefined the emission reduction pathway in line with the Paris agreement, with steeper reductions scheduled earlier in the scenario period. Alternative reduction profiles could slightly alter the scenarios; however, flexibility is limited. Choosing a less aggressive reduction approach early on would rapidly exhaust the emission budget, necessitating extremely steep reductions in the later periods to stay within target.

We have identified inconsistencies between scenario narratives and model outputs, which have been iteratively removed. First, in the scenario narratives, the low energy use scenarios would foster energy efficiency more than the high energy use scenarios. However, in the

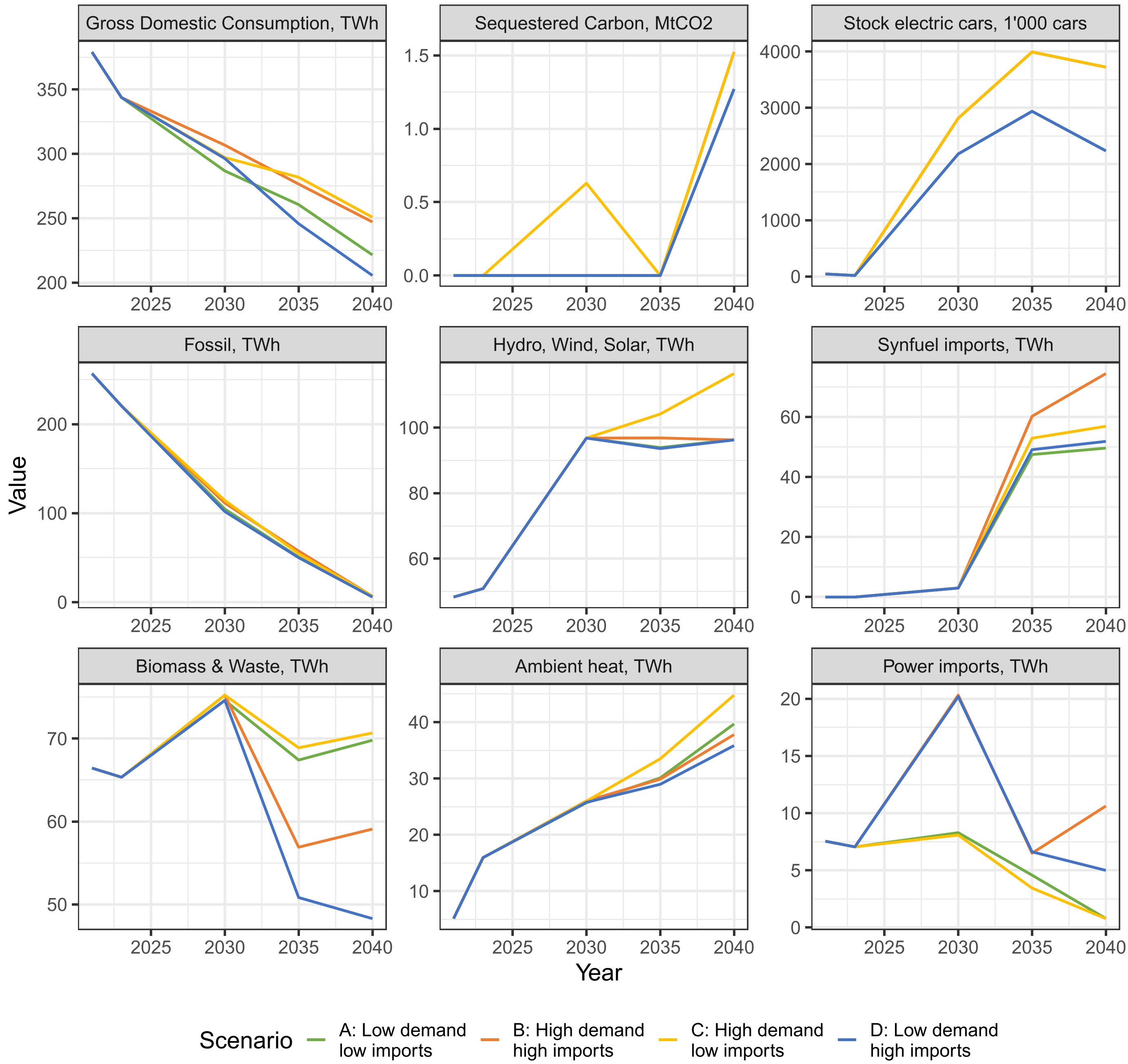

Fig. 4. Overview of energy system configuration for all scenarios. Top row: General indicators, i.e. total gross domestic energy consumption, sequestered carbon, stock of electric cars. Middle and bottom row: Domestic extraction and imports of energy carriers.

quantitative model runs, energy efficiency measures were always deployed to the largest possible extent. Therefore, this differentiation did not materialize in the model runs and we removed it from the scenario narratives. Second, import quantities for energy carriers quantitatively determined by stakeholders in the online survey were close to current import levels in the high scenario. This would imply a substitution of current fossil fuel imports by synthetic fuels, without major changes required in the Austrian energy system. We therefore decided to use stakeholder inputs as upper limits in model constraints instead of fixing them at the levels quantified by stakeholders. Nevertheless, we had to assume aggressively low prices for imported synthetic fuels to push models to import substantial amounts of synthetic fuels in the high import scenario, making these scenarios feasible only under a very rapid development of synthetic fuel production technology. Third, private mobility is assumed to stay high in the scenario narratives, but quantitatively, stakeholders assume a slight reduction in distances driven by private cars also in the high energy use scenario, emphasizing the crucial role of the mobility sector in decarbonization. Final model results, however, indicate that once private mobility is fully electrified, the overall impact of changes in car use on the energy system is minor.

The stakeholder engagement and participation process proved particularly effective for co-creating scenario narratives, which in addition supported cross-sector dialogue and stakeholder networking. However, we experienced two main challenges. First, the interest in the first stakeholder workshop was high but the number of participants in the second stakeholder workshop was substantially lower – even though we regularly exchanged with the stakeholders between the workshops and announced the workshop well in advance. Reasons for the drop out of stakeholders could be the challenges related to building trust in an online setting, as well as practical issues related to resource constraints,

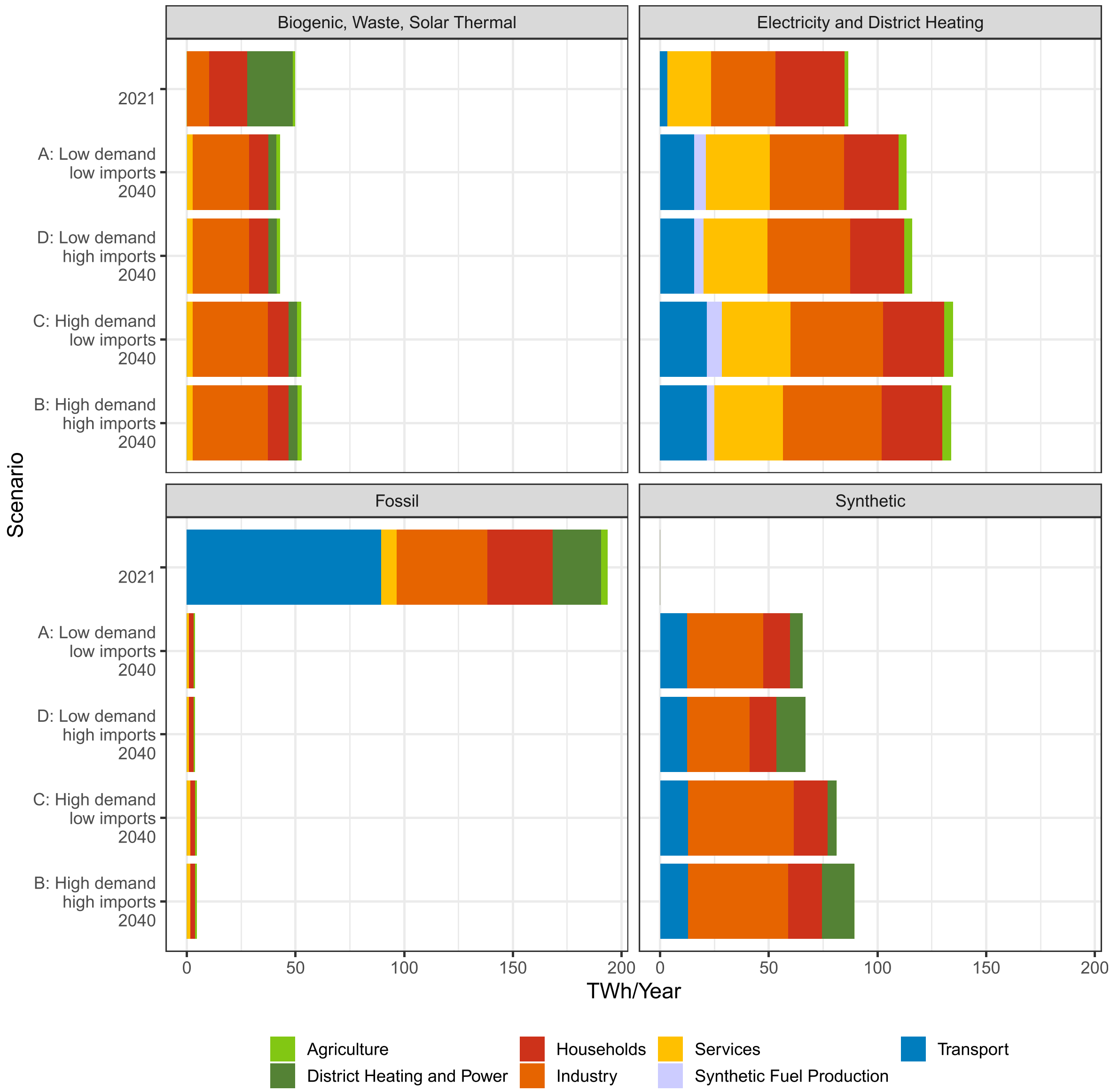

Fig. 5. Final energy use of energy carriers biogenic, waste, and solar thermal energy (upper left), electricity and district heating (upper right), fossil (lower left) and synthetic fuels (lower right) in Austria per sector. Note: coke use for steel production is not included in final energy quantities.

including the choice of the second workshop date (after a public holiday). However, the quality of the discussions and joint reflections was very high in all three stakeholder workshops. Second, aligning the rich inputs of the stakeholders on drivers of the energy system and their desirable developments was a challenging task and required several iterations in the research team to derive the first draft of the qualitative scenario narratives. Similar challenges have been reported from previous scenario development processes (Mitter et al., 2020). However, the stakeholder- and model-based checks of the scenario narratives ensure their consistency, richness and salience (Mitter et al., 2019).

In our survey used to parameterize drivers, we asked stakeholders about the quantitative evolution of drivers, consistently presenting them the historical development of these drivers over time. Based on this information, stakeholders were required to select values for the projected development of drivers in 2040. This method may have introduced bias by anchoring stakeholders to recent trends, and providing a more comprehensive set of information, such as anticipated prices for imported synthetic fuels, might have resulted in different stakeholder choices. Nonetheless, this approach ensured consistency across quantification of all drivers. Moreover, stakeholder assessments were used directly without additional feasibility analysis, reflecting the raw, aggregated expectations of stakeholders, which may not always align with feasible developments. In particular, the steep drop in the use of car-based personal transportation may be considered as unrealistic, but it reflects the expectation of stakeholders that attaining net-zero emissions requires substantial reductions in this form of transportation. This limitation should be addressed in future research, particularly by incorporating more iterative feedback loops between stakeholder choices and input from the research team. However, due to resource constraints, a more in-depth exploration of driver quantification was not possible.

Until 2030, the model-based scenarios to climate neutrality are very similar and differences between technology choices and deployment only appear after 2030. Uncertainty about which pathways to follow is high and goes beyond the divergence in our scenarios: e.g. instead of importing synthetic fuels, fossil fuels combined with carbon capture and storage could be used. We did assess carbon capture and storage only to a limited extent due to stakeholder preferences and the current legal situation in Austria. Nevertheless, we recommend considering it in future scenario processes. In general, future research should put a strong

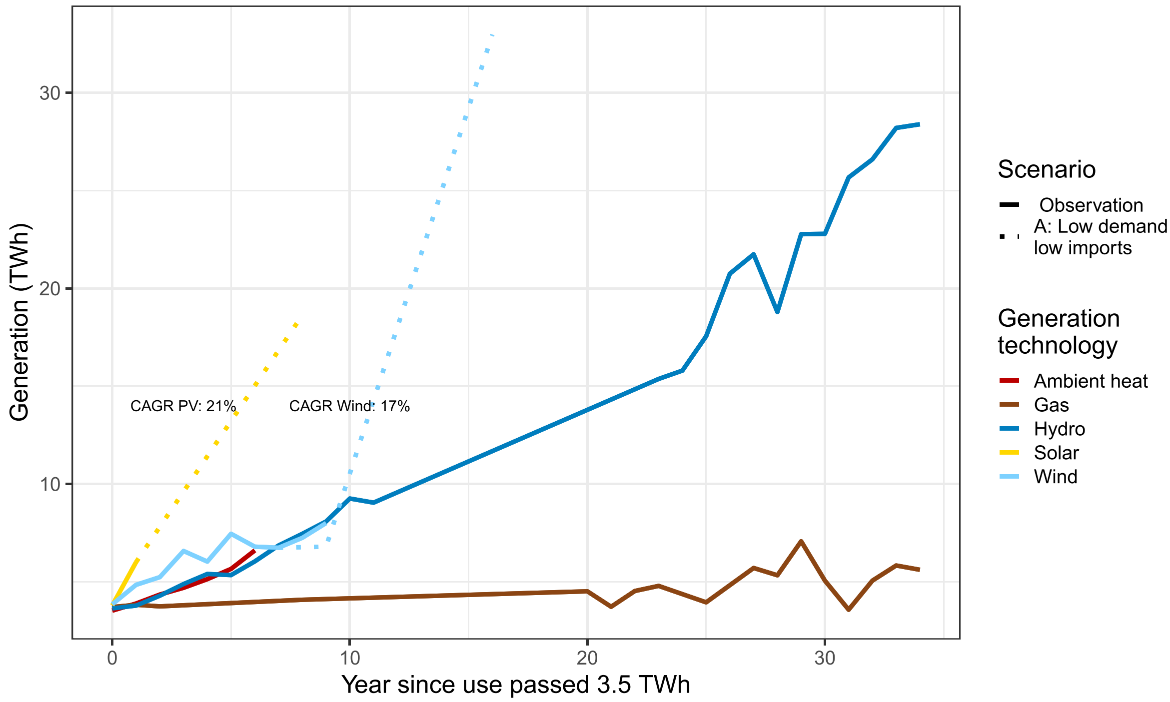

Fig. 7. Speed of expansion of renewable electricity generation technologies in Scenario A compared to the historical expansion of hydro and gas power generation in Austria. CAGR: Compound annual growth rate in the scenario period 2021–2030.

focus on post-2030 scenarios because there are important policy choices in the short-term that will enable or hinder specific pathways in the long-term. Our results are in line with decarbonization studies for other regions, such as from the IEA (International Energy Agency, 2021), which show that the low hanging fruits of electrification and renewable expansion have to be addressed first.

There are three alternative scenarios available for Austria. In the Transitions scenario by the Environment Agency Austria (Krutzler et al., 2023), developments are comparable to our model outputs. The gross domestic energy consumption of 260 TW h in 2040 is higher than the range in our four main scenarios of 200–250 TW h. This is mainly explained by lower imports of hydrogen and synthetic fuels from outside of Austria in the Transitions scenario. In our sensitivity scenario “S2: autarky” with slightly lower imports than the Transitions scenario, gross domestic consumption is at 290 TW h, confirming that our overall magnitude of gross domestic consumption is similar to the Transitions scenario. The Transitions scenario also confirms that a major reduction in energy use in the mobility sector is a driver of the overall reduction in gross domestic consumption. In terms of the buildup of renewables, the Transitions scenario finds a significantly higher share of solar PV in the final electricity mix, than wind power. However, the transition scenario is not based on a model with sufficient temporal resolution to adequately reflect renewable electricity generation, and the optimal shares are therefore mere expert judgments. Furthermore, results of the Transitions scenario also depend on lower assumptions for the potential to expand wind power compared to our main scenarios. Furthermore, there are two “Mutter Erde" scenarios (Steininger et al., 2024): “ZeroBasis" and “ZeroTransition." In “ZeroBasis," no additional renewable electricity generation occurs within Austria, as the European power system model used in the development of the scenarios suggests that importing electricity is more cost-efficient, assuming that the necessary transmission expansion is feasible. Consequently, electricity use almost doubles, primarily through increased imports. In contrast, the “ZeroTransition" scenario, which largely builds on assumptions from the UBA “Transitions" scenario, indicates a greater expansion of solar PV compared to wind power. This outcome is likely due to assumed limitations on wind power potential rather than a cost advantage of solar PV, but it is unclear from the documentation. When comparing final sectoral energy use, both scenarios are similar in overall energy consumption, though fully consistent comparisons are hindered by different sectoral definitions. A notable distinction lies in the mobility sector: electricity and fuel consumption in the “ZeroBasis" scenario amount to only 60% of our final energy consumption in a high-demand, high-import scenario, and just 20% in the “ZeroTransition" scenario. This discrepancy suggests the need for a closer examination of potential sectoral mismatches or more radical assumptions within the transport sector in the “Mutter Erde" scenarios.

Our scenarios achieve climate neutrality in 2040 under modest (0.8%–1.4%) economic growth rate assumptions. Under lower growth rates, less supply side measures are required, decreasing in particular imports of synthetic fuels and gas and biomass use, as lower economic growth rates are, in our scenarios, associated with lower industrial output and therefore lower inputs of fuels and gases for high temperature processes. Other demand side measures, potentially linked to economic growth, in particular in mobility and buildings, showed less impacts on overall energy consumption, as due to electrification, these services can be provided at very high efficiency rates.

5. Conclusions and policy implications

We present consistent qualitative scenario narratives and quantitative model-based scenarios towards a climate-neutral Austrian energy sector by 2040. Our co-created energy-system scenarios help defining specific policy goals and developing robust measures at the national level, as well as in the organizations represented by the involved stakeholders. While our scenarios are techno-economically feasible, the necessary speed of change is unprecedented in Austria. Therefore, to ensure continued emission reductions, there is a need for strengthening current policies, and introducing new ones.

In the short term, three main foci of policies should tackle the electricity sector, the mobility sector, and the steel production sector, as these sectors are crucial for attaining short-term emission reductions until 2030. In terms of the electricity sector, the current renewable energy targets until 2030 are too low and should be increased by about

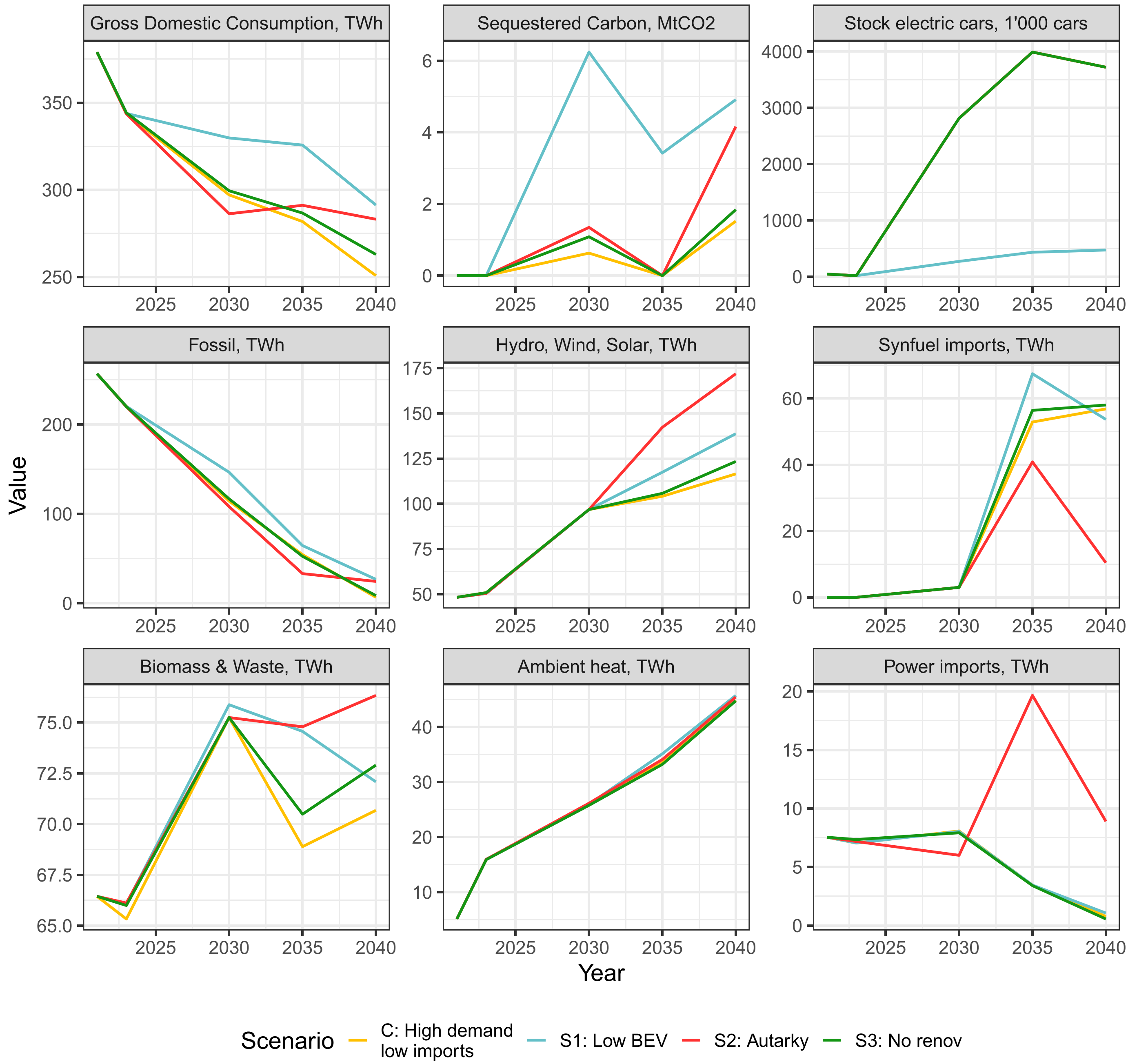

Fig. 9. Overview of energy system configuration in high demand low import scenario C compared to sensitivity runs. Top row: General indicators, i.e. total gross domestic energy consumption, sequestered carbon, stock of electric cars. Middle and bottom row: Domestic extraction and imports of energy carriers. Note: falling import levels of synfuels in 2040 are a result of linearly interpolated import restrictions, which become tighter at the end of the period.

50%. In this context, accompanying policies in terms of spatial planning have been identified to be necessary to increase the renewable uptake in particular of wind power. This may include assigning renewable energy zones by state governments and municipalities. In the mobility sector, current uptake rates of battery-electric vehicles are far too low to enable the necessary electrification of transport. Increasing uptake rates may only be possible, if high subsidies on BEV are granted or sales of combustion engine cars are strongly taxed. The use of significant amounts of synthetic fuels in land transport will require substantially more resources than electrifying transport, policy support for this technology is therefore highly inefficient on the level of total energy systems and is not recommended. Finally, the steel sector has a very high share of total emissions in Austria. A rapid decarbonization of steel production is therefore required to allow for the deep emission reductions necessary until 2030 and needs focused support policies, and infrastructure programs at the respective steel production sites, including increasing the use of scrap steel to lower energy needs in primary resource production. The timing of entry of carbon capture and storage into the system depends on the assumptions of the development of demand and the availability of imports of synthetic fuels, but minor amounts may be already necessary up to 2030. A short-term strategy, beyond the current Austrian carbon management strategy (Bundesministerium für Finanzen, 2024), and associated subsidies for potentially rapidly ramping up limited carbon capture and storage capacities, and associated infrastructure, is therefore recommended.

Starting in 2030, other industries also have to decarbonize, as do households, services, and electricity generation. This is enabled by electrification of heat supply, and by the use of carbon-neutral fuels in particular in industrial applications. The corresponding infrastructure in terms of electricity grids, and the upgrade of existing pipeline infrastructure for the transportation of alternative fuels has to be planned today to allow for investment safety. In this context, a more refined assessment of the decarbonization route, either basing it on CCU or CCS is also required.

A combined effort by the Austrian modelling community in supporting these decisions by providing evidence for stakeholders operating at different scales, in different sectors and in different organizations is therefore of utmost importance. More ambition in modelling sectors which were not included in our and similar scenarios, i.e. non-fossil fuel emissions from agriculture, land use and land use change, and some limited industrial emissions, is necessary in this context.

CRediT authorship contribution statement

J. Schmidt: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **H. Mitter:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **M. Baumann:** Writing – original draft, Software, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **B. Boza-Kiss:** Writing – review & editing, Conceptualization. **D. Huppmann:** Writing – review & editing, Methodology, Data curation, Conceptualization. **S. Wehrle:** Writing – review & editing, Writing – original draft, Validation, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **L. Zwieb:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **M. Klingler:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Disclosure use of large-language model based tools

During the preparation of this work, the authors used Chat-GPT 3.5 to edit the manuscript and improve language. After using the tool, the authors reviewed and edited the content as needed and take full responsibility of the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix. Additional information

A1 Stakeholder selection

Stakeholders (see Table A1) were selected based on consultations with experts from the energy and mobility sectors as well as project-related research on stakeholder engagement and participation in Austria (e.g. Abstiens et al. (2021) abst). The resulting 117 entries for system-relevant representatives were further specified with respect to three characteristics: (i) field of activity (public administration, cooperation network and consulting cluster, energy supplier, industrial supply company, mobility-transport operator, energy network operator (regulated), lobby group, science and research institution, political non-governmental actor or organized civil society actor (non-profit), social movement), (ii) sector (public, private, public-private, club-association, NGO, individual), and (iii) scale (local-regional, state, national). The project team compiled a priority list for invitations in order to ensure a heterogeneous distribution according to these characteristics.

Table A1
Stakeholder engagement information including number of participants per workshop.

Acronym	Name of institution or project	Sector	Work-shop-1	Work-shop-2	Work-shop-3
AEA	AustriaTech, Mobility in Motion	cooperation network and consulting cluster	1		
AGGM	Austria Gas Grid Management	energy network operator (regulated)	1	1	1
AK	Arbeiterkammer Wien	public administration	1		1
APG	Austrian Power Grid	energy network operator (regulated)	2	1	1
BMDW	Bundesministerium für Digitalisierung und Wirtschaftsstandort	public administration			
BMK	Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie	public administration			1
CCCA	Climate Change Center Austria	science and research institution	1	1	
e5	Programm für Energieeffiziente Gemeinden	cooperation network and consulting cluster	1	1	1
EEÖ	Dachverband Erneuerbare Energien Österreich	cooperation network and consulting cluster	1	1	
EIV	Energieinstitut Vorarlberg	cooperation network and consulting cluster	1		
ELECTRO-COUP	ACRP Project	science and research institution			1
Enu	eNu (Energie- und Umweltagentur NÖ)	cooperation network and consulting cluster			1
EWSTMK	Fachabteilung Energie und Wohnbau des Landes Steiermark	public administration	1		

(*continued on next page*)

Table A1 (*continued*)

Acronym	Name of institution or project	Sector	Work-shop-1	Work-shop-2	Work-shop-3
fb	forschung burgenland	science and research institution			1
FGW	Fachverband der Gas- und Wärmeversorgungsunternehmungen	energy network operator (regulated)			
FFF	Fridays for Future	social movement	2		
ÖAMTC	Österreichische Automobil-, Motorrad- und Touringclub	cooperation network and consulting cluster	1		
OE	Oesterreichs Energie	cooperation network and consulting cluster	1	1	1
ÖFSE	Österreichische Forschungsstiftung für Internationale Entwicklung	science and research institution	1	1	1
ÖNB	Österreichische Nationalbank	public administration		1	
ÖStB	Österreichischer Städtebund	public administration	1		1
RIC	Resources Innovation Center Leoben	science and research institution	1	1	
SAG	Salzburg AG	energy network operator (regulated)	2		1
StWi	Stadt Wien	public administration		2	1
TRANSFAIR	ACRP Project	science and research institution	1	1	1
UBA	Umweltbundesamt	cooperation network and consulting cluster	1		1
UniGraz	Universität Graz	science and research institution			2
VCÖ	Mobilität mit Zukunft	cooperation network and consulting cluster	1		
VOEST	Voestalpine AG	industrial supply company	1	1	1
WKO	Wirtschaftskammer Österreich, Abteilung für Umwelt- und Energiepolitik	public administration	1		
WWF	WWF Österreich	non-governmental actor	2	1	1

A2 Online Survey

Here, we assess if the responses to the survey have internal validity and to which extent the answers from our stakeholder groups differ to our other test survey groups. Figure A1 shows if respondents estimated the indicator lower in the "low" or in the "high" scenario. Consistency is high: For the "Modal split train" variable, which determines the share of cargo transported by train, the indicator is higher in the low demand scenario, while it is the other way round for all other scenarios, as expected. Respondents therefore seem to have understood the task.

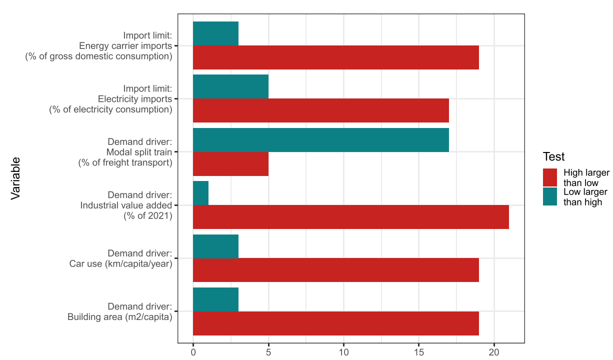

Fig. A1. Consistency check for stakeholder responses

Figure A2 shows the differences between the different survey groups (for number of responses see Table A3). In particular, we show differences between all stakeholder responses (without double responses), the expert responses and the social media responses. In general, the median of the three groups is well aligned, while variability differs between groups (As does the number of observations). This may indicate that our stakeholder group has a similar perception of the development of these parameters, compared to other groups. One exception is industrial energy use in the "low" scenario, where the median of social media respondents results in a decrease of 25% in industrial value added, while the other two groups see virtually no change in industrial value added in the low scenario. Furthermore, variance is quite significant and in many instances either the low or high boundary pre-set in the survey were chosen by at least one respondent.

The largest historically observed value mostly is within the median of the "low" and the "high" scenario, i.e. the median respondent assumes that "high" also means higher than today and "low" lower than today. Interestingly, there are two exceptions: car utilization is proposed to decrease in both the "high" and the "low" scenario, compared to today. Imports of energy also are proposed to decrease in both the "low" and the "high" scenario, when comparing to the median.

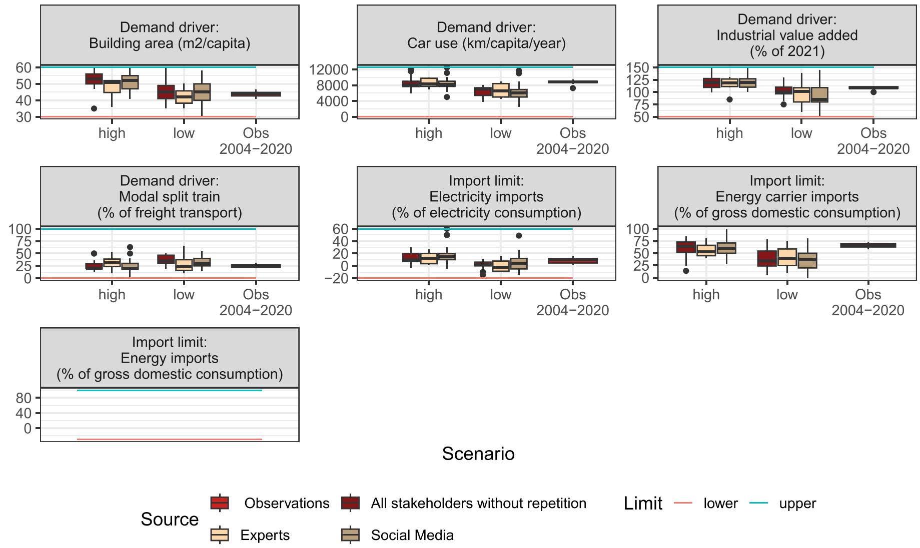

Fig. A2. All responses to the survey differentiated by group of respondents

Table A2
Results of stakeholder survey. In bold, the values used as input parameters in the quantitative model-based scenarios.

Variable	Unit	Scenario	Range in Survey	Last year of observation	Level in last observation	Median	Min	Max	Q (0.25)	Q (0.75)
Heated private building area	m2/capita	high	[30, 60]	2021	46	53	35	60	50	**56**
Heated private building area	m2/capita	low	[30, 60]	2021	46	45	35	60	**41**	49
Car use	Km/capita/year	high	[0, 12,500]	2018	9400	8100	6000	12,000	7650	**9000**
Car use	Km/capita/year	low	[0, 12,500]	2018	9400	7000	3800	8000	**5400**	7350
Industrial value added	% (relative to 2021 energy consumption by industry)	high	[50, 150]	2021	100	120	100	150	109.5	**127.5**
Industrial value added	% (relative to 2021 energy consumption by industry)	low	[50, 150]	2021	100	100	75	130	**96.5**	110
Train share in cargo transport	% (share of train cargo in total cargo transport)	high	[0, 100]	2021	20	20	13	50	**19.5**	29.5
Train share in cargo transport	% (share of train cargo in total cargo transport)	low	[0, 100]	2021	20	35	19	50	30	**46.5**
Energy imports	% (share of primary energy consumption)	high	[-30, 100]	2018	64	64	14	85	52	**73**
Energy imports	% (share of primary energy consumption)	low	[-30, 100]	2018	64	35	5	79	**24**	54.5
Electricity imports	% (share of electricity consumption)	high	[-20, 60]	2019	5	10	−3	30	7	**20**
Electricity imports	% (share of electricity consumption)	low	[-20, 60]	2019	5	2	−15	11	**0**	6

Table A3
Number of respondents in survey

Survey	Number of participants
Stakeholder wave 1	12 (out of 27)
Stakeholder wave 2	10, 3 of them have responded already in survey wave 1 (out of 27)
Stakeholder total	19 out of 27 (+3 double responses)
Social media	25
Internal experts	6

A3 Extended model description

A3.1 Technologies included in TIMES

In terms of mitigation technologies, the model includes renewable electricity generation technologies, hydrogen and synthetic fuels imports and domestic production, the use of biomass, and oxyfuel and amine scrubbing for capturing CO_2 emissions from fossil fuel use in electricity and heat generation and in industrial processes. Additional fossil fuel reduction options include electric mobility, heat pumps, building renovation, changes to more capital-intensive industrial processes, and new steel production technologies. In steel production, the model allows for switching to electric arc furnaces using hot briquetted iron reduced by either hydrogen or methane (see AIT Austrian Institute of Technology GmbH, Österreichische Energieagentur, Montanuniversität Leoben, Montanuniversität Energieinstitut an der Johannes Kepler Universität Linz, 2024 for a description of the processes). The model endogenously decides on the use of these technologies, based on investment costs and constrained by exogenous growth rates.

The efficiency of appliances and machinery in agriculture and services evolve exogenously according to 15-year historical trend, while household appliance efficiency remains constant with the number of households driving total appliance use. Furthermore, the model can opt for direct-air capture as a measure of last resort to reduce residual emissions.

A3.2 medea: technical description

Here, we describe how power system technologies are implemented in *medea*. Cogeneration units convert fuel to heat and power subject to a feasible operating region defined by the unit's electrical efficiency, the electricity loss per unit of heat production, and the backpressure coefficient. Electricity generation from intermittent sources (wind, run-of-river hydro, solar) is subject to spatially diverse, exogenous hourly generation profiles, scaled according to total installed capacities. Electricity from these sources can be curtailed at no additional cost (free disposal).

Electricity can be stored in reservoir and pumped hydro storage, and batteries while heat and synthetic gases can be stored in hot water storages and caverns, respectively. The capacity of hydro storages can not be expanded, as we assume existing potentials to be exhausted. Battery, heat, and synthetic gas storage capacities, on the other hand, can be added endogenously. Generation from storage is constrained by installed capacity and stored energy. Inflows of water into reservoirs add to stored energy. Pumped hydro storages, batteries, heat and synthetic gas storages can actively store energy for later use. To better capture operational differences of hydro storage units, we model short-term, medium-term and seasonal reservoir and pumped storage plants separately. Apart from their ability to pump water, the main difference between these storages is their storage volume. Seasonal storages are modeled with an energy-to-power ratio of more than 1000 h, while medium-term and short-term storages have much lower energy-to-power ratios of about 190 h and 24 h, respectively. To ensure the stable and secure operation of the electricity system, ancillary services (e.g. frequency control, voltage support) are required. We model ancillary service needs as a minimum requirement on spinning reserves operating at any point in time. Thus, we assume that ancillary services can be provided by thermal power plants, run-of-river hydro plants, or any (active) storage technology.

A3.3 Model coupling

The TIMES and *medea* models are coupled in a multi-stage process to ensure consistency between investment, fuel use, and operational costs. The weather year is harmonized to align the capacity factors for renewables, and data exchange is standardized via the IAMC data format using the pyam package (Huppmann et al., 2021). To streamline integration between the two models, a comprehensive, standardized list of variables was developed and sanity checks were implemented to guard against reporting issues.[1] TIMES is first run and the annual consumption of electricity, district heat, and synthetic gases (hydrogen and synthetic methane) for each of the model's sectors, and the installed capacities of energy conversion technologies are being extracted from the results. All aggregate annual time series from the TIMES model are subsequently disaggregated to hourly resolution for use in the *medea* model (see section A3.4 for a detailed description of disaggregation).

The *medea* model is then initialized using the generated hourly profiles and *medea* determines optimal investment starting from actual installed capacities (2020) or capacities from the preceding TIMES-base year (2023 and beyond). Based on these inputs, import prices of hydrogen and synthetic methane are calibrated such that the total annual imported volumes in *medea* match the corresponding values from TIMES. Subsequently, *medea* is run to determine the optimal investment in and operation of all modeled technologies. Finally, technologies are aggregated by fuel and output to make them comparable to the TIMES model. Results are exported to standardized IAMC-format data files complying with the pre-defined list of variables. If optimally installed capacities diverge substantially between *medea* and TIMES, sanity checks on both models are conducted to identify potential causes for the divergence and to implement sufficient fixes if required. This procedure is iterated until optimally installed capacities in TIMES and *medea* converged.

A3.4 Timeseries disaggregation

The TIMES model has an annual resolution and is executed to calculate the primary energy demand and energy imports required to satisfy the useful energy demand for the Austrian energy system, taking into account all necessary intermediary fuels and the technology capacities required for converting or using these fuels under the given scenario assumptions for the years 2025–2040. From this comprehensive set of results, the annual consumption of electricity, district heat, and synthetic gases for each of the model's sectors, and the installed capacities of energy conversion technologies are being extracted. Subsequently, all aggregate annual time series from the TIMES model are disaggregated to hourly resolution for use in the medea model. Hourly consumption profiles were used to generate time series of the electricity demand from electric mobility, including passenger cars, light, and heavy duty vehicles (Fattler, 2021) and from 11 industrial subsectors (Ganz, 2021). To generate a profile of residual electricity consumption from the agricultural, household, and service sectors, we calibrated the synthetic load profiles to the year 2020 and computed the residual hourly load from the difference between observed and synthetic loads. Hourly time series of district heat consumption were generated based on natural gas load profiles for heating by households, and commercial and service (sub)sectors (Almbauer et al., 2021; Almbauer and Eichsleder, 2008). Consumption of hydrogen and synthetic gases in the industry sectors was assumed to be constant.

A4 Price scenarios

For historical data, we relied on actual market data, such as from spot prices. For projecting future prices, we differentiated our approach: for the near future, we used results from future markets where available. For the more distant future, we referred to the "European prices" from the World Energy Outlook 2022 (WEO 2022) Net Zero Emissions scenario (International Energy Agency, 2022) (See Table A4).

[1] The definition of the standardized variables can be found at https://github.com/net-zero2040/net-zero2040

The WEO 2022 offers two forecasts for expected prices in 2030 and 2040 for coal, crude oil, natural gas, and emission allowances, incorporating a blend of historical data, realized future data, and WEO projections. For years without direct data, we employed interpolation to generate a coherent and plausible set of exogenous variables for fossil energy carriers. Currency conversions between the Euro and Dollar were conducted using annual exchange rates, with future conversions fixed at the 2022 rate. We acknowledge that this method overlooks potential price dynamics arising from demand fluctuations. Nevertheless, the WEO's Net Zero Emissions scenario prices are presumed to be in alignment with an Austrian Net Zero Emission Scenario, thus offering a solid foundation for our analysis.

Table A4
Detailed Sources for energy price scenarios

Energy Source	Unit	Historical Data Source	Future Data Source (2023–2030)	Long-term Forecast (2040/2050)
Natural Gas (VTP-CEGH)	*EUR/MWh*	*Yearly mean of spot market prices for central Europe* European Energy Exchange AG (2022a)	*Yearly mean of futures for* Austria, *accessed on February 1, 2023* European Energy Exchange AG (2022b)	*World Energy Outlook 2022 forecasts* (International Energy Agency, 2022)
Crude Oil (Brent)	*US $/bbl*	*Yearly mean of spot market prices for Brent Crude* (US Energy Administration Service, 2022)	*Yearly mean of futures for Brent Crude for 2022, accessed on February 1, 2023* (Intercontinental Exchange Inc, 2022)	*World Energy Outlook 2022 forecasts* (International Energy Agency, 2022)
Emission Allowances	*EUR/tCO2*	*Yearly mean of EU Emission Allowance prices* European Energy Exchange AG (2022c)	*Yearly mean of Emission Allowance futures for 2022, accessed on February 1, 2023* European Energy Exchange AG (2022d)	*World Energy Outlook 2022 forecasts* (International Energy Agency, 2022)

A5 Additional tables and figures

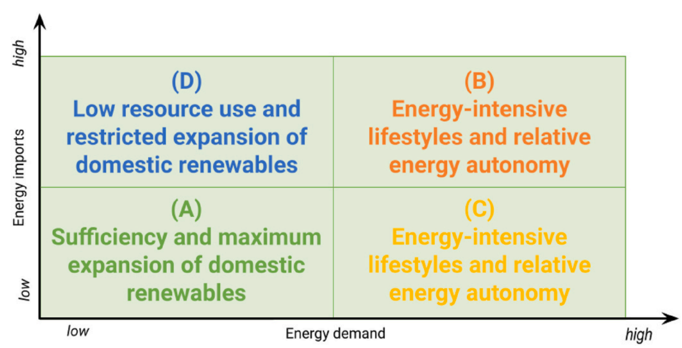

Fig. A3. Net-zero2040 scenario titles organized in a 2 × 2 matrix

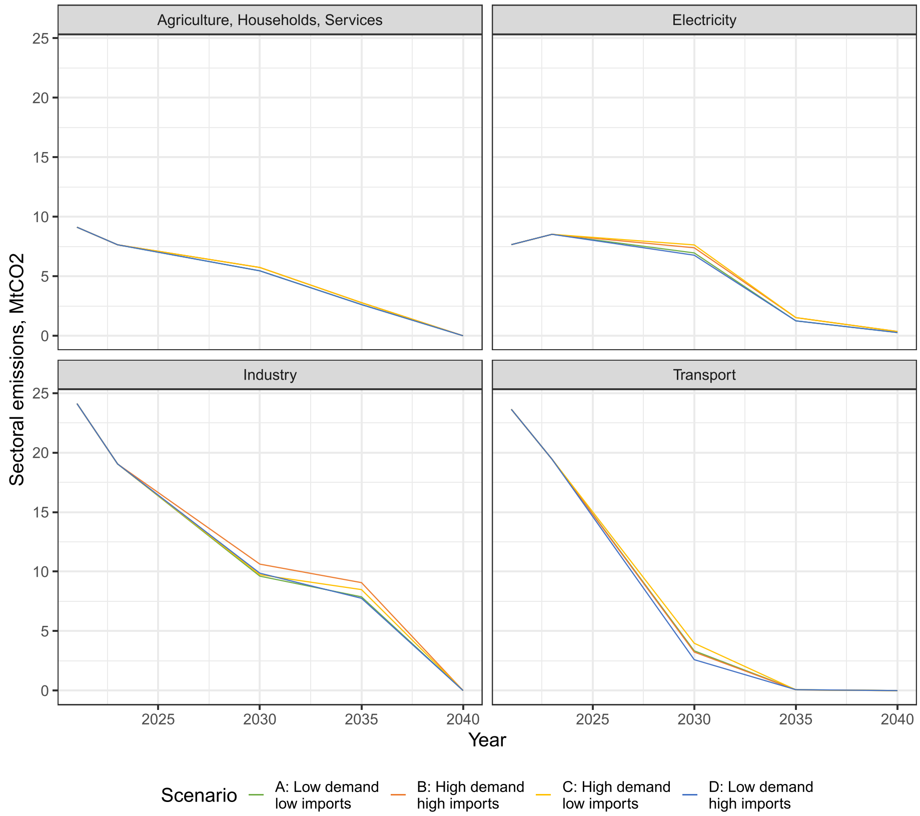

Fig. A4. Emissions by sector.

A6 Cost-advantages of wind power over solar PV

First, wind power offers economic advantages due to its favorable complementarity with existing renewable sources like run-of-river hydropower, which helps mitigate seasonal imbalances inherent in the Austrian electricity system (see Figure A6). Both run-of-river hydropower and solar PV generation peak during the summer when electricity consumption is at a seasonal low. Without additional measures, this seasonal overlap would result in excess summer generation and potential deficits in winter, necessitating costly seasonal balancing strategies. As a result, curtailments increase to 10% of domestic renewable electricity generation in a scenario with no further wind power expansion, compared to only 5% curtailment with additional wind power generation. Conversely, wind power generation peaks during winter when hydropower output is lower and electricity consumption is higher. By integrating wind power, the seasonal imbalances can be alleviated, leading to a reduction in total system costs. Additionally, Austrian wind power generation exhibits a low correlation with wind power generation in neighboring Germany, particularly in its northern, wind power-heavy regions. Consequently, Austrian wind power often generates electricity during periods of favorable market prices, resulting in either high export revenues or the substitution of expensive imports. This further contributes to cost savings and enhances the economic viability of wind power expansion in Austria.

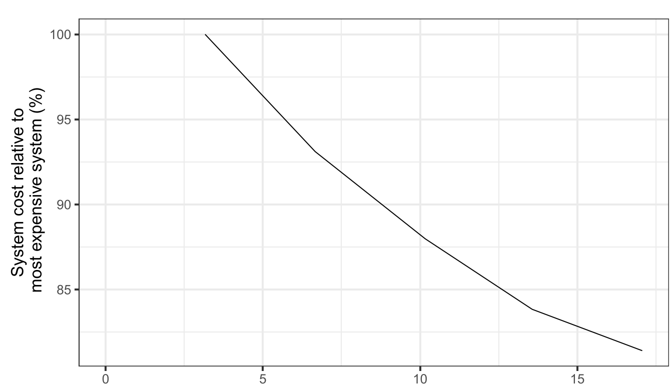

Fig. A5. System cost depending on the expansion of wind power.

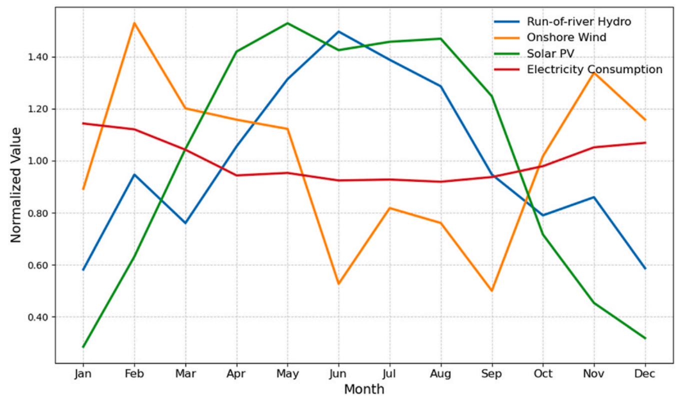

Fig. A6. monthly variation of electricity generation from the renewable sources run-of-river hydro, onshore wind power, and solar photovoltaics and electricity consumption in Austria relative to their annual mean.

Data availability

The final scenario data is shared on zenodo, code on github, as referenced in the manuscript.

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