Scaling up carbon dioxide removals

Recommendations for navigating opportunities and risks in the EU

European Scientific
Advisory Board on
Climate Change

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About the European Scientific Advisory Board on Climate Change

The European Scientific Advisory Board on Climate Change is an independent scientific advisory body providing the EU with scientific knowledge, expertise and advice relating to climate change. The Advisory Board identifies actions and opportunities to achieve the EU's climate neutrality target by 2050. The Advisory Board was established by the European Climate Law of 2021 with a mandate to serve as a point of reference for the EU on scientific knowledge relating to climate change by virtue of its independence and scientific and technical expertise.

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Recommendations

With global warming accelerating, the long-term goal to keep warming below 1.5°C set out in the Paris Agreement is increasingly at risk of being breached. Limiting this risk and stabilising the climate requires urgent and coordinated global efforts. The EU is legally committed to achieving climate neutrality at the latest by 2050 and to pursuing net-negative emissions thereafter. To meet these goals, the EU must both drastically reduce emissions and counterbalance residual emissions from activities with currently no or limited mitigation alternatives with carbon dioxide removals. Removals are essential for achieving net-negative greenhouse gas emissions and helping stabilise the global climate.

The European Scientific Advisory Board on Climate Change hereby makes **nine recommendations to policy makers for rapidly scaling up removals, in ways that enhance EU's industrial competitiveness while addressing associated opportunities and risks.** These recommendations address both temporary removals, resulting from activities such as afforestation, reforestation and soil carbon sequestration, and permanent removals, including technologies such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

Recommendation 1: set separate targets

To signal commitment, guide investments, drive innovation and ensure that both temporary and permanent removals contribute effectively to climate goals without deterring emission reductions, the Advisory Board recommends that the EU **set separate legally-binding targets for gross emission reductions, permanent removals and temporary removals.**

Action points for EU policies

- → Set separate near-, medium- and long-term targets for minimum removals, and maximum contributions of removals towards net emissions' goals, when revising the **European Climate Law** or developing the **post-2030 climate policy framework**.
- → Enshrine a long-term commitment to protect and enhance the EU's land sinks when revising the **land use, land-use change and forestry regulation.**
- → Set **removal-specific targets for carbon capture and storage** for the near, medium and long term.

Recommendation 2: ensure the quality of removals

To build trust, ensure accountability and drive investments while addressing associated reversals and impacts on ecosystems and communities, **the Advisory Board recommends that the EU develop robust monitoring, reporting and verification (MRV) systems at both activity and national levels. The EU must also ensure transparency regarding the contribution of removals to achieving its policy objectives.**

Action points for EU policies

- → Embed measurable and binding sustainability safeguards under **the carbon removals and carbon farming certification (CRCF) regulation**, including on climate adaptation.
- → Develop and regularly update the CRCF methodologies in line with better regulation guidelines.
- → Differentiate the use of **CRCF** certificates, based on whether they pertain to temporary removals, permanent removals, or emission reductions.
- → Use **CRCF data** to enhance the accuracy of national greenhouse gas inventories reported under the Governance Regulation and ensure the visibility of removals' contribution to climate objectives.
- → Rapidly adopt the **Forest Monitoring Law** and **the Soil Monitoring and Resilience Law** to improve land monitoring data collection and use, with advanced remote sensing and digital tools.

Recommendation 3: reverse the decline of the land sink

To enhance removals based on land resources, **the EU must urgently halt and reverse the ongoing decline of its land sink, and ensure a sustainable sourcing and use of biomass. The Advisory Board recommends that the EU integrate its land-related policies into a coherent framework that requires sectoral measures to enhance EU land sinks and foster climate adaptation.**

Action points for EU policies

- → Mainstream climate adaptation **across policies** and adopt the **Forest Monitoring Law** and **Soil Monitoring Law.**
- → Create synergies between removals and ecosystem restoration through the implementation of the **Nature Restoration Law.**
- → Align the reform of the **common agricultural policy** with the net-zero emissions goal, with further incentives for climate adaptation, soil carbon sequestration, emission reductions and sustainable land management.
- → Reinforce the coherence of EU policies that put pressure on land and biomass resources and ensure sustainable bioenergy feedstocks via the **renewable energy directive, FuelEU Maritime, REFuelEU Aviation,** and the EU **CRCF Regulation**.
- → Price emissions and removals in the land sector (see recommendation 7).

Recommendation 4: accelerate innovation

To accelerate the development and deployment of diverse removal methods and enhance EU's industrial competitiveness, **the Advisory Board recommends that the EU strengthen regulatory signals, expand funding across all stages of the innovation cycle, prioritise CCS for permanent removals, and enhance public awareness on removals.**

Action points for EU policies

- → Increase funding from **Horizon Europe** and **LIFE programme** to support a diverse range of removals methods, alongside fostering innovation for deep emission reductions.
- → Prioritise **Innovation Fund** support for CCS towards permanent removals (including BECCS and DACCS) and CCS in activities with no or limited mitigation alternatives.
- → Consider extending the **Recovery and Resilience Facility** beyond 2026 to ensure continued support for long-term removal projects.
- → Strengthen collaboration between the **European Innovation Council** and the European Investment Bank's **European Investment Fund** to address gaps in venture capital and de-risk private investments.
- → Create market incentives for the early adoption of removals through **demand-pull instruments**, such as public procurement, to foster learning-by-doing and economies of scale, and to learn about side effects.

Recommendation 5: secure sufficient CO_2 infrastructure

To develop sufficient CO_2 transport and storage infrastructure, critical to scaling up permanent removals, **the Advisory Board recommends that the EU increase coordination, boost investment and enhance strategic planning for the development of EU's CO_2 transport and storage infrastructure, while ensuring equitable access, a just transition and climate resilience.**

Action points for EU policies

- → Coordinate efforts to secure sufficient infrastructure for removals and to restrict fossil-CCS infrastructure access to activities with no or limited mitigation alternatives, for example under the **Trans-European Networks for Energy Regulation.**
- → Leverage investment through the **Net-Zero Industry Act, Connecting Europe Facility**, and the **Innovation Fund** to make BECCS and DACCS infrastructure accessible where needed.

→ Address regulatory gaps across CO_2 value chains to identify infrastructure needs and to ensure the efficiency, integrity, and climate resilience of the CO_2 infrastructure.

Recommendation 6: price permanent removals

To incentivise the deployment of removals in a fiscally sustainable and cost-effective way, **the Advisory Board recommends that the EU consider a progressive integration of permanent removals into the EU ETS, under strict conditions to prevent mitigation deterrence, address environmental risks, support distributional fairness and enhance dynamic cost-effectiveness.**

Action points for EU policies

→ Use the upcoming revision of the **EU ETS directive** to secure its viability after 2040 and prepare for net-zero and net-negative emissions.

→ Gradually integrate permanent removals in the **EU ETS**, subject to quantitative and qualitative limits to ensure consistency with separate targets (see recommendation 1) and avoid adverse environmental impacts.

→ Ensure robust certification of removals before any market integration (see recommendation 2).

→ Establish an institutional framework to manage the integration process of permanent removals into the **EU ETS** and support early-stage deployment (see recommendations 4, 5 and 9).

Recommendation 7: price temporary removals

To balance the competing demands for land and biomass resources, and to incentivise the conservation and enhancement of the land sink while accounting for reversal, **the Advisory Board recommends that the EU introduce new instruments to price emissions and reward removals in the LULUCF sector, and to ensure coherence with the broader climate policy framework.**

Action points for EU policies

→ Develop a **separate system to price emissions and reward removals** in the land sector, and consider a future integration with other greenhouse gas pricing systems under specific conditions.

→ Reinforce the **pricing and long-term monitoring of LULUCF removals** through other policies for the land sector (see recommendation 3) to ensure sufficient funding for land sink maintenance and enhancement activities, support ecosystem restoration efforts, and increase adaptive practices.

Recommendation 8: recognise the extended emitter responsibility

To enhance removals and reduce the financial burden on future generations in achieving net-negative emissions, **the Advisory Board recommends that the EU recognise an extended emitter responsibility requiring today's emitters to contribute to the future removal of the greenhouse gases they emit.**

Action points for EU policies

→ Assess options and governance requirements, and prepare a strategy to operationalise an **extended emitter responsibility** to contribute to the EU's net-negative emissions.

→ Implement such principle in a way that avoids an increase of the greenhouse gas budget in the short term, and that increases ambition over time.

→ Consider **different approaches** to this end, such as allowing emitters to counterbalance their emissions with future removals while the regulator ensures the overall short-term greenhouse gas budget does not increase, or requiring emitters to pay for both their greenhouse gas emissions and the cost of their subsequent removal.

Recommendation 9: strengthen governance

To ensure efficient policy implementation, accountability, and global cooperation to achieve long-term climate goals, **the Advisory Board recommends that the EU expand its climate governance and institutional capacities. EU diplomacy and policies should support this effort by reducing carbon leakage and enhancing global climate ambition.**

Action points for EU policies

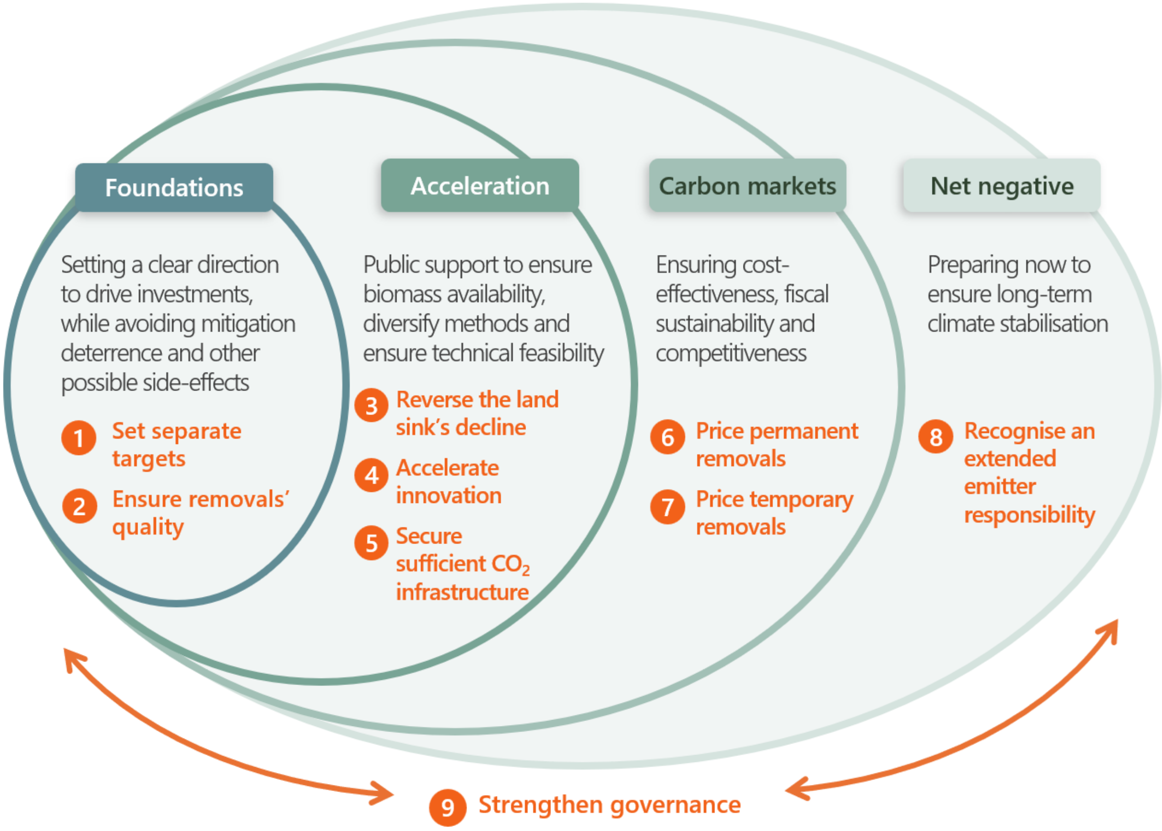
→ Reinforce the integration of removals in the **governance regulation** and the **European Climate Law**, ensuring strong commitment to net-negative emissions.

→ Build capacity within existing institutions and consider creating new ones as needed.

→ Reduce carbon leakage and enhance global climate ambition through **climate diplomacy and policies** fostering financial and technological transfer.

The Advisory Board's nine recommendations are grouped into four categories: foundations, acceleration, carbon markets and net negative, as described below.

Recommendations for a rapid and sustainable scale-up of carbon dioxide removals in the EU



Source: Advisory Board

Summary

The critical role of carbon dioxide removals in limiting climate impacts

The damages caused by climate change are already being felt globally and across Europe, and the risk of crossing tipping points is growing. As the fastest-warming continent, Europe faces increasingly severe climate impacts such as heatwaves, droughts, wildfires and floods. These events not only threaten Europeans' health, water resources and ecosystems, but also food and energy security, infrastructure and financial stability. 2024 was the warmest year on record, with a global average temperature of 1.6°C above the pre-industrial level. This first exceedance of the 1.5°C warming threshold set by the Paris Agreement underscores the urgency of taking action to stop global warming and keep long-term warming under 1.5°C, to reduce the likelihood of extreme weather events and avoid the most severe impacts of climate change.

Concretely, global greenhouse gas emissions must be kept within a finite greenhouse gas budget, which represents the maximum cumulative emissions that can be released while still limiting temperature rise. Exceeding this budget would significantly increase the risk of severe and irreversible climate impacts. As the remaining budget is shrinking rapidly, global efforts must focus on drastically cutting greenhouse gases while simultaneously removing carbon dioxide (CO_2) from the atmosphere through capture and durable storage. Balancing emissions and removals to reach net zero – and eventually net-negative emissions, where removals exceed emissions – is essential to halting global warming and ultimately decreasing temperatures. Although net-negative emissions cannot reverse past climate impacts or undo the crossing of tipping points, they would restore atmospheric greenhouse gas levels to within safer limits and help to manage temperature overshoots.

To support global efforts in the fight against climate change, the EU is committed to achieving net-zero greenhouse gas emissions domestically within the EU by 2050 at the latest, and pursuing net-negative greenhouse gas emissions thereafter. This requires deep emission reductions, as well as a rapid and sustainable scale-up of removals to counterbalance residual emissions from activities that currently have no or limited mitigation alternatives (for example, heavy industry, long-distance air and maritime transport, and agriculture). Emission reductions and carbon dioxide removals should be pursued in parallel, and one cannot substitute for the other: efforts to scale up removals should not deter the EU from accelerating investments to support drastic emission reductions.

Various removal methods can be deployed in the EU. These fall essentially into two categories:

- temporary removals, which refer to the capture of CO_2 from the atmosphere and its storage in carbon pools such as forests, soils or wood products, where the storage duration is inherently limited and can range from several years to centuries;
- permanent removals, which refer to the capture and long-term storage of CO_2 in reservoirs such as geological formations or mineralised carbon, where the storage is designed to be stable and secure for thousands of years. This can be achieved through novel methods such as direct air carbon capture and storage (DACCS) or bioenergy with carbon capture and storage (BECCS).

Currently, the EU relies almost solely on its forests and land sector to provide temporary removals. It has set an ambitious target for the land use, land use change, and forestry (LULUCF) sector, aiming for an increase of approximately 15% in net removals compared to current level. However, the EU's land carbon sink has declined by around one third over the last decade. Reversing the ongoing decline will take time, as ecosystems need years to recover their carbon sequestration capacity. In parallel, the current capacity of the EU to remove carbon permanently through novel methods, such as BECCS and DACCS, remains limited. Developing these methods at an industrial scale also takes time. It is therefore timely for policy makers in the EU to act now towards an accelerated scale-up of carbon dioxide removals in the EU, carefully navigating their associated opportunities and risks.

Leadership in removal technologies will contribute to the EU's competitiveness, a key EU strategic priority for 2024-2029. The 2024 report by Mario Draghi on the future of European competitiveness highlights the strong links between climate technologies and competitiveness, asserting that leadership in clean technologies provides the EU with an opportunity to capitalise on the surging global demand in this domain. Following this idea, the European Commission's Competitiveness Compass for the EU reinforces the crucial role of clean technologies in driving both decarbonisation and competitiveness and announces the development of incentives to build a business case for permanent carbon dioxide removals. Deploying carbon dioxide removals offers considerable potential for high-skilled employment as well as opportunities for income diversification, in particular in the agriculture sector. Furthermore, removals present other environmental benefits and opportunities, such as the maintenance and restoration of natural ecosystems and biodiversity.

Seizing such opportunities to their full potential requires overcoming current limitations and managing risks associated with various removal methods. Most available methods rely on the availability of land and biomass resources, which are under the pressure of multiple competing interests. The potential to protect, restore and enhance the existing land sink is limited by increasingly severe climate impacts such as wildfires, droughts, pests and storms. Protecting and enhancing the land sink requires changes in land use and management practices, as well as enhancing resilience to climate change impacts. In parallel, the development of permanent removal methods is hindered by insufficient technological or commercial readiness, significant investment needs for new capacity (and associated financial risks), lack of market incentives, as well as governance challenges.

In a context of constrained financial capacities, the EU needs to mobilise funds cost-effectively. Achieving the necessary scale will require mobilising both public and private funding to avoid excessive financial burdens on certain sectors or society as a whole. Strong institutional governance and cross-border coordination will be needed to manage these investments in a way that achieves the necessary scale of carbon dioxide removals without compromising other environmental and social goals.

Several initiatives have recently been launched to establish an EU policy framework for carbon dioxide removals. For example, the Commission's industrial carbon management strategy promotes the development of technologies to capture, utilise and store CO_2 in industrial sectors and foresees new mechanisms to account for removals in the upcoming revision of the EU emission trading system (EU ETS) directive. Additionally, the carbon removal and carbon farming certification (CRCF) regulation is establishing a voluntary certification framework for removals.

While these initiatives are steps in the right direction, further action is needed to strengthen certain aspects of a comprehensive policy framework for carbon dioxide removals. This includes developing adequate incentives for high-cost removals, aligning land policies, supporting innovation and infrastructure development, and ensuring robust governance to achieve net-zero and net-negative emissions.

With this report, the European Scientific Advisory Board on Climate Change (hereafter the 'Advisory Board') aims to provide scientific advice to support the elaboration of a robust EU policy framework on carbon dioxide removals, as part of the upcoming post-2030 climate policy framework.

Identifying needs and policy options for a robust governance of carbon dioxide removals in the EU

To develop its policy recommendations on carbon dioxide removals, the Advisory Board identified and analysed the key steps and policy functions needed to scale up carbon dioxide removals rapidly, while ensuring that such scale up complements greenhouse gas emission reductions and is socially, economically, and environmentally sustainable.

The Advisory Board assessed the potential and costs of different carbon dioxide removal methods in the EU and outlined key environmental, social, and economic opportunities and risks associated with scaling up each method. Based on these opportunities and risks, the Advisory Board identified the following seven key functions necessary to manage and scale up removals in a way that aligns with the EU's climate goals and sustainable development objectives:

1. Managing the greenhouse gas budget
2. Maintaining fiscal sustainability and enhancing distributional fairness
3. Ensuring the quality of removals
4. Reversing the decline of the land sink in a changing climate
5. Accelerating innovation and raising public awareness
6. Securing the CO_2 infrastructure's availability and resilience
7. Enhancing institutional governance

The Advisory Board then conducted a gap analysis to evaluate the current state of EU policies on removals, focusing on how well these policies fulfil the seven identified functions. The policies assessed include the LULUCF regulation, the CRCF regulation, the carbon capture and storage (CCS) directive and carbon pricing mechanisms.

The analysis identified key policy gaps where current frameworks fall short in delivering on the necessary scale-up of removals. These include the absence of clear targets for permanent and temporary removals, shortcomings in existing monitoring and verification systems to ensure transparency and environmental integrity, declining land sinks due to poorly aligned land policies, fragmented funding for technological innovation, inadequate CO_2 transport and storage infrastructure, and the lack of adequate incentives to reward both permanent and temporary removals. As strategic, evidence-based and innovative removal policies depend on robust and integrated governance systems across sectors and levels, the Advisory Board also identified the need to build, develop, test and enforce institutional capacity to ensure the effective governance of removals.

To address the identified gaps, the Advisory Board analysed policy options to improve and further expand the existing policy framework. The Advisory Board evaluated how policy options may perform in fulfilling the seven governance functions, ensuring the environmental, social and economic dimensions were thoroughly considered. This evaluation covered notably a mix of incentive instruments such as:

- carbon pricing via EU ETS integration,
- mandates and takeback obligations for high-emitting sectors,
- public procurement as well as financial incentives to encourage investment in removals.

Recognising that the deployment of removals is a dynamic process, the Advisory Board explored how different policies could be introduced and adapted over time to maximise benefits, reduce costs, and mitigate risks as the scale-up of removals progresses. This approach considers the evolving readiness of technologies, infrastructure and market conditions.

Recommendations and action points to navigate opportunities and risks for a rapid and sustainable scale-up of carbon dioxide removals

Based on its analysis, the Advisory Board identified policy recommendations and corresponding action points for EU policies to help establish a comprehensive and credible removal policy framework that addresses the seven identified governance functions. As the role of these governance functions, and the right mix of policy instruments to address these are expected to evolve over time, the Advisory Board recommends a dynamic and adaptive policy approach, balancing environmental integrity, fairness, and dynamic cost-effectiveness over time to ensure the feasibility and credibility of ambitious removal policy objectives.

The Advisory Board formulated the following nine recommendations for the EU to embed carbon dioxide removals in its policy architecture and support EU's efforts towards achieving and sustaining net-zero greenhouse gas emissions domestically within the EU by 2050 and net-negative greenhouse gas emissions thereafter.

1. Set separate legally-binding targets for gross emission reductions, permanent removals and temporary removals.
2. Develop robust monitoring, reporting, and verification systems at both activity and national levels, and ensure transparency regarding the contribution of removals to achieving EU's policy objectives.
3. Urgently halt and reverse the ongoing decline of EU's land sink, ensure sustainable sourcing and use of biomass, and integrate EU's land-related policies into a coherent framework that requires sectoral measures to enhance EU land sinks and foster climate adaptation.
4. Strengthen regulatory signals, expand funding across all stages of the innovation cycle, prioritise CCS for permanent removals, and enhance public awareness on removals.
5. Increase coordination, boost investment and enhance strategic planning for the development of EU's CO_2 transport and storage infrastructure, while ensuring equitable access, a just transition and climate resilience.
6. Consider a progressive integration of permanent removals into the EU ETS, under strict conditions to prevent mitigation deterrence, address environmental risks, support distributional fairness and enhance dynamic cost-effectiveness.
7. Introduce new instruments to price emissions and reward removals in the LULUCF sector, and to ensure coherence with the broader climate policy framework.
8. Recognise an extended emitter responsibility requiring today's emitters to contribute to the future removal of the greenhouse gases they emit.
9. Expand EU's climate governance and institutional capacities. EU diplomacy and policies should support this effort by reducing carbon leakage and enhancing global climate ambition.

These recommendations are elaborated below, along with their rationale and corresponding action points for EU policies.

Recommendation 1: set separate targets

To signal commitment, guide investments, drive innovation and ensure that both temporary and permanent removals contribute effectively to climate goals without deterring emission reductions, **the Advisory Board recommends that the EU set separate legally-binding targets for gross emission reductions, permanent removals and temporary removals.**

Achieving sufficient volumes of removals at the necessary speed requires providing a clear direction for investments and technological developments. At the same time, investments in emission reductions should continue in parallel, as substantial efforts are required to minimise residual emissions. To ensure that emission reductions and removals progress in parallel, emission targets should be structured to drive both objectives simultaneously. Although the EU has established short- and long-term climate targets, the Advisory Board has identified gaps in the current target framework that could hinder achieving this dual-purpose.

- The EU has a 2030 target for temporary removals in the LULUCF sector and for CO_2 storage, but it does not differentiate CCS based removals – where CO_2 is removed from the atmosphere either directly (via DACCS) or through plant growth (via BECCS) – from fossil-CCS, which captures CO_2 from fossil fuel use, preventing emissions but not achieving the net removal of CO_2.
- Separating targets for gross emissions and removals can help prevent mitigation deterrence, avoiding delays in either emission reduction or removal efforts, or the diversion of investments from emission reductions. The EU has set a maximum contribution from net removals towards the 2030 net emissions target. However, beyond 2030, there are no targets to guide the contribution of removals towards achieving net-zero and net-negative emissions. Furthermore, the EU lacks short-, medium- and long-term targets for permanent and medium- and long-term targets for temporary removals. Temporary removals can, in particular, support short-term climate mitigation efforts, whereas permanent removals play a necessary role in long-term climate stabilisation.
- Setting targets for both minimum levels of removals and maximum contributions from removals towards net emissions goals can provide the flexibility needed to pursue cost-effective solutions, while safeguarding against market failures and mitigation deterrence.

Action points for EU policies

→ Set separate near-, medium- and long-term targets for minimum removals, and maximum contributions of removals towards net emissions' goals, when revising the **European Climate Law** or developing the **post-2030 climate policy framework**.

→ Enshrine a long-term commitment to protect and enhance the EU's land sinks when revising the **land use, land-use change and forestry regulation.**

→ Set **removal-specific targets for carbon capture and storage** for the near, medium and long term.

Recommendation 2: ensure the quality of removals

To build trust, ensure accountability and drive investments while addressing associated reversals and impacts on ecosystems and communities, **the Advisory Board recommends that the EU develop robust monitoring, reporting and verification (MRV) systems at both activity and national levels. The EU must also ensure transparency regarding the contribution of removals to achieving its policy objectives.**

Removals offer significant opportunities to mitigate climate change but also present potential side effects. Robust monitoring is essential to ensure the delivery of removal's intended climate benefits, manage reversals and liability, maintain environmental integrity, and address social impacts. The Advisory Board identified opportunities to ensure a sustainable and credible deployment of removals.

- The quantification of net carbon dioxide removals through the certification of removal activities requires robust MRV. Robust certification is essential to ensure transparency and accountability, provide a reliable basis for incentives, and build public trust as well as confidence in carbon markets.
- The governance and LULUCF regulations support inventory-level accounting of carbon dioxide removals, but they are not yet sufficient to reflect the greenhouse gas effects of all removal methods and lack the granularity needed to quantify specific removal activities. The IPCC is developing guidelines to better reflect removals in national greenhouse gas inventories, and the future availability of certified removal data presents an opportunity to improve the transparency and accuracy of these inventories.
- The quality of land monitoring data collected under the LULUCF regulation is currently inadequate to fully support the MRV of carbon dioxide removals and the resilience of EU land sinks. The European Commission has proposed two legislative measures to address this gap, but these have not been adopted yet.
- The EU has adopted of the CRCF regulation, a first step towards a framework for the certification of removals. The CRCF regulation is expected to support the integration of removals into EU corporate compliance schemes and carbon markets.
- Certification methodologies should clearly distinguish between permanent and temporary removals, as well as emission reductions, to support the different uses of certificates. They should be based on credible and up-to-date baselines and ensure robust monitoring with sufficiently frequent verification, especially for temporary removals.
- It remains unclear how the CRCF framework will address sustainability risks and opportunities, including impacts on communities, biomass and land resources. The certification methodologies should include mandatory sustainability safeguards supported by measurable indicators. The development of these methodologies should be transparent and participatory.

Action points for EU policies

→ Embed measurable and binding sustainability safeguards under **the carbon removals and carbon farming certification (CRCF) regulation**, including on climate adaptation.
→ Develop and regularly update the CRCF methodologies in line with better regulation guidelines.
→ Differentiate the use of **CRCF** certificates, based on whether they pertain to temporary removals, permanent removals, or emission reductions.
→ Use **CRCF data** to enhance the accuracy of national greenhouse gas inventories reported under the Governance Regulation and ensure the visibility of removals' contribution to climate objectives.
→ Rapidly adopt the **Forest Monitoring Law** and **the Soil Monitoring and Resilience Law** to improve land monitoring data collection and use, with advanced remote sensing and digital tools.

Recommendation 3: reverse the decline of the land sink

To enhance removals based on land resources, **the EU must urgently halt and reverse the ongoing decline of its land sink, and ensure a sustainable sourcing and use of biomass. The Advisory Board recommends that the EU integrate its land-related policies into a coherent framework that requires sectoral measures to enhance EU land sinks and foster climate adaptation.**

Among the environmental opportunities and risks associated with removals, the availability of land and biomass resources is a central issue that can limit the scale-up of both temporary removals (e.g., from forests, wetlands, or agricultural soils) and permanent removals (e.g., from BECCS). The EU's land sink is declining rapidly, driven by climate impacts and competing demands for land use, such as food production, bioenergy production or ecosystem restoration. Although the EU has set an ambitious target to enhance the land sink by 2030, the Advisory Board has identified gaps and inconsistencies in the policy framework related to land and biomass management.

- The EU's land sink declined by 30% between 2012 and 2022 due to factors such as ageing forests, higher harvesting rates and climate change-induced hazards, including wildfires, droughts, pests and storms. Land use change and agricultural practices have contributed to this decline by affecting soil carbon levels. Scaling up adaptation measures to protect, restore, and enhance the sink, while strengthening resilience within the land sector, is essential for expanding both temporary and permanent removals.
- Biomass resources face pressure from competing land uses, including food and fibre production, rural and urban development, bioenergy, biodiversity conservation and carbon sequestration. EU policies governing land use, the agri-food system and the bioeconomy are not sufficiently aligned with climate and environmental objectives, and face significant obstacles to implementation. Better integration is needed to further incentivise removals and other environmental goals (see recommendation 7 on land sector pricing).
- A scale up of BECCS leading to increased biomass demand risks exacerbating land-use conflicts and leading to unsustainable biomass extraction. The EU should adjust its bioenergy policies to prioritise the most efficient uses of biomass, consistent with the cascading use principle, while minimising environmental impacts.

Action points for EU policies

→ Mainstream climate adaptation **across policies** and adopt the **Forest Monitoring Law** and **Soil Monitoring Law.**

→ Create synergies between removals and ecosystem restoration through the implementation of the **Nature Restoration Law.**

→ Align the reform of the **common agricultural policy** with the net-zero emissions goal, with further incentives for climate adaptation, soil carbon sequestration, emission reductions and sustainable land management.

→ Reinforce the coherence of EU policies that put pressure on land and biomass resources and ensure sustainable bioenergy feedstocks via the **renewable energy directive, FuelEU Maritime, REFuelEU Aviation,** and the EU **CRCF Regulation**.

→ Price emissions and removals in the land sector (see recommendation 7).

Recommendation 4: accelerate innovation

To accelerate the development and deployment of diverse removal methods and enhance EU's industrial competitiveness, **the Advisory Board recommends that the EU strengthen regulatory signals, expand funding across all stages of the innovation cycle, prioritise CCS for permanent removals, and enhance public awareness on removals.**

Diversifying the EU's portfolio of CO_2 removal methods can help achieve scale quickly while mitigating the risk of over relying on one removal method and managing trade-offs, such as biomass availability and other environmental and social impacts. Some novel methods, such as enhanced rock weathering and ocean-based removals, are at low readiness levels and require further research to assess their potential and associated risks. Other methods, including DACCS and BECCS, are at medium readiness levels and need support to reach commercialisation. Although the EU has been investing in research and development, further public support is needed to increase readiness, reduce costs and build public awareness.

- To scale up removals rapidly and sustainably, the EU must build a diverse portfolio of methods by accelerating the uptake of existing solutions, streamlining costs and diffusing knowledge, while increasing the readiness of early-stage methods.
- Advancing different removal methods from low readiness levels towards maturity requires targeted policy mixes that address the four main stages of the innovation process: emergence, early adoption, diffusion and stabilisation. The EU and Member States should make use of subsidies, state procurement (e.g. reverse auctions) and tailored financing instruments, such as targeted loans and support from the European Investment Bank.
- Current EU innovation funding for removals, mainly through Horizon Europe and the Innovation Fund, remains fragmented and insufficient to achieve the necessary scale. A targeted approach is necessary to prioritise funding for CCS-removals over fossil-CCS. Clarity on the future governance of removals is needed to provide long-term signals on the profitability of investments into CCS-removals.
- Broader societal engagement and knowledge diffusion are necessary to build public awareness and ensure the sustainable uptake of carbon dioxide removals.

Action points for EU policies

→ Increase funding from **Horizon Europe** and **LIFE programme** to support a diverse range of removals methods, alongside fostering innovation for deep emission reductions.
→ Prioritise **Innovation Fund** support for CCS towards permanent removals (including BECCS and DACCS) and CCS in activities with no or limited mitigation alternatives.
→ Consider extending the **Recovery and Resilience Facility** beyond 2026 to ensure continued support for long-term removal projects.
→ Strengthen collaboration between the **European Innovation Council** and the European Investment Bank's **European Investment Fund** to address gaps in venture capital and de-risk private investments.
→ Create market incentives for the early adoption of removals through **demand-pull instruments**, such as public procurement, to foster learning-by-doing and economies of scale, and to learn about side effects.

Recommendation 5: secure sufficient CO_2 infrastructure

To develop sufficient CO_2 transport and storage infrastructure, critical to scaling up permanent removals, **the Advisory Board recommends that the EU increase coordination, boost investment and enhance strategic planning for the development of EU's CO_2 transport and storage infrastructure, while ensuring equitable access, a just transition and climate resilience.**

In addition to technological readiness, the deployment of certain permanent removal methods face early-stage challenges, particularly related to the availability of infrastructure. Permanently storing CO_2 in geological formations, after it is captured either directly from the atmosphere or from bioenergy plants, requires the development of CO_2 transport networks, including pipelines and shipping, as well as suitable geological storage sites. While EU legislation, such as the CCS directive or the Trans-European Networks for Energy, has supported initial development, further public funding and coordinated efforts are needed to scale up infrastructure.

- The EU's CO_2 transport and storage infrastructure is insufficient to support the scale of removals required to meet its climate goals. By 2030, an estimated EUR 18 billion is needed to meet the EU's geological storage goal of 50 $MtCO_2$ per year, with additional investments needed for long-term expansion. Current incentives are inadequate for large-scale roll-out.
- EU policies do not set binding targets for prioritising access to CO_2 infrastructure for CCS-removals and fossil-CCS from activities with no or limited alternatives. Enhanced mapping, cross-border planning and progress tracking are needed to deploy BECCS and DACCS at scale, while ensuring equitable access to storage infrastructure where needed.
- The EU must establish a predictable regulatory framework that ensures efficiency, environmental integrity, climate resilience and safety for CO_2 infrastructure, while accelerating permitting processes and addressing public concerns.

Action points for EU policies

→ Coordinate efforts to secure sufficient infrastructure for removals and to restrict fossil-CCS infrastructure access to activities with no or limited mitigation alternatives, for example under the **Trans-European Networks for Energy Regulation.**

→ Leverage investment through the **Net-Zero Industry Act, Connecting Europe Facility**, and the **Innovation Fund** to make BECCS and DACCS infrastructure accessible where needed.

→ Address regulatory gaps across CO_2 value chains to identify infrastructure needs and to ensure the efficiency, integrity, and climate resilience of the CO_2 infrastructure.

Recommendation 6: price permanent removals

To incentivise the deployment of removals in a fiscally sustainable and cost-effective way, **the Advisory Board recommends that the EU consider a progressive integration of permanent removals into the EU ETS, under strict conditions to prevent mitigation deterrence, address environmental risks, support distributional fairness and enhance dynamic cost-effectiveness.**

Investing in removals will help limit long-term costs of climate impacts, but requires new instruments to leverage substantial investments, with annual needs in the EU estimated between EUR 30 billion and EUR 80 billion by 2050. Managing these costs and scaling up removals effectively will require a dynamic mix of instruments to enhance cost-effectiveness, avoid mitigation deterrence and maintain fiscal sustainability.

- Given a lack of strong incentives in the current policy framework, the Advisory Board examined several options for new mechanisms to manage the costs and quantities of removals. Public support will be crucial in overcoming early-stage challenges (see recommendation 4), but constraints on public budgets mean innovative financing models will be necessary to ensure rapid deployment and economic viability. A gradual shift towards greenhouse gas pricing mechanisms could enhance cost-effectiveness and fiscal sustainability on the path to climate neutrality. The EU's carbon market – established through the EU ETS in 2005 – has successfully driven cost-effective emission reductions by requiring emitters to pay and generating revenue for the transition. Gradually integrating removals into the EU ETS offers the most practical approach to managing their costs and quantities.
- Initial integration into the EU ETS should be limited to permanent removal methods, while temporary removals should be incentivised through separate pricing instruments in the short term (see recommendation 7).
- Robust certification is a critical precondition for any integration, ensuring durability and additionality (see recommendation 2), along with governance frameworks to guarantee long-term CO_2 storage. The CCS directive provides governance to manage reversal risks from geological storage.
- The integration of individual removal methods should reflect their specific risks and entry conditions. For example, the integration of BECCS credits should be conditional on sustainable biomass sourcing and wider policy developments to reduce pressures on biomass and land resources (see recommendations 2-3). Quantitative limits or restrictions on BECCS applications (e.g., restricting its use to specific processes) may also be necessary to prevent excessive biomass use.
- To prevent mitigation deterrence and environmental risks, an intermediary institution should oversee the supply and demand of removal credits, including conditions, quantities and timing for the integration of different methods into the EU ETS. This institution could also help prepare for future integration of removals by developing capacity, lowering costs through mechanisms like reverse auctions, and developing a diverse portfolio of permanent removal methods in the early stages (see recommendation 4).

Action points for EU policies

→ Use the upcoming revision of the **EU ETS directive** to secure its viability after 2040 and prepare for net-zero and net-negative emissions.
→ Gradually integrate permanent removals in the **EU ETS**, subject to quantitative and qualitative limits to ensure consistency with separate targets (see recommendation 1) and avoid adverse environmental impacts.
→ Ensure robust certification of removals before any market integration (see recommendation 2).
→ Establish an institutional framework to manage the integration process of permanent removals into the **EU ETS** and support early-stage deployment (see recommendations 4, 5 and 9).

Recommendation 7: price temporary removals

To balance the competing demands for land and biomass resources, and to incentivise the conservation and enhancement of the land sink while accounting for reversal, **the Advisory Board recommends that the EU introduce new instruments to price emissions and reward removals in the LULUCF sector, and to ensure coherence with the broader climate policy framework.**

While permanent removals are well-suited for a gradual and conditional integration into the EU's carbon market, temporary removals present distinct challenges. These include a shorter CO_2 storage duration that limits their contribution to long-term climate goals, higher risks of reversal, and challenges in ensuring robust monitoring, reporting and verification. Currently, the EU lacks dedicated pricing mechanisms for emissions and removals within the land sector. The Advisory Board has assessed various options to address this gap.

- Addressing land-use conflicts and enhancing policy synergies are essential first steps to rebalancing incentives for land and biomass use, while promoting practices that maintain and enhance the EU's land sink (see recommendation 5). However, the absence of a price signal for carbon sequestration and storage in the LULUCF sector contributes to unbalanced incentives for land and biomass use, and the ongoing decline of the EU's land sink. The EU should therefore introduce new instruments to price greenhouse gas emissions and reward removals in the LULUCF sector to support its long-term climate objectives.
- Various options exist for pricing emissions and rewarding temporary removals. An upstream pricing approach may be more feasible initially, supported by strong regulatory measures and complementary mechanisms to manage reversals and environmental risks. As MRV systems improve, more comprehensive greenhouse gas pricing mechanisms, such as downstream pricing or stock-based subsidies, should be considered. Until then, additional sectoral policies and funding must be in place to maintain existing sinks and carbon stocks.
- Extending greenhouse gas pricing to the LULUCF sector presents governance challenges and requires a supportive environment to help land managers meet stricter certification needs. Given the growing risks of CO_2 reversal due to climate impacts, mechanisms are necessary to manage these risks and incentivise adaptative land management practices.
- Integrating temporary removals into the existing EU ETS would create significant risks and governance challenges that cannot be effectively managed in the short to medium term. To urgently reverse the decline of the land sink, the EU should develop alternative pricing instruments separately to the current EU ETS. Future integration or linkages could be considered once governance challenges and risks have been resolved.

Action points for EU policies

→ Develop a **separate system to price emissions and reward removals** in the land sector, and consider a future integration with other greenhouse gas pricing systems under specific conditions.

→ Reinforce the **pricing and long-term monitoring of LULUCF removals** through other policies for the land sector (see recommendation 3) to ensure sufficient funding for land sink maintenance and enhancement activities, support ecosystem restoration efforts, and increase adaptive practices.

Recommendation 8: recognise the extended emitter responsibility

To enhance removals and reduce the financial burden on future generations in achieving net-negative emissions, **the Advisory Board recommends that the EU recognise an extended emitter responsibility requiring today's emitters to contribute to the future removal of the greenhouse gases they emit.**

While the EU carbon pricing system is designed to reach net-zero emissions, it lacks mechanisms to prepare for the transition to net-negative emissions. Achieving net-negative emissions is becoming increasingly urgent due to recent temperature overshoots and the need to avoid further climate impacts. Cleaning the atmosphere of "CO_2 waste" will be a collective effort that needs to be planned now. The Advisory Board explored proposals to ensure that emitters take responsibility for removing the CO_2 they release in the atmosphere.

- The EU needs to address its fair share of the global greenhouse gas budget and contribute to managing global temperature overshoots. This requires not only stopping emissions but also recognising the responsibility to clean up pollution, thereby reducing the burden on future generations. Current EU climate policies incentivise emission reductions but do not include mechanisms to ensure emitters take long-term responsibility for removing their greenhouse gas emissions.
- This gap could be addressed by operationalising an extended emitter responsibility through instruments for today's emitters to fund or provide future carbon dioxide removals to "clean up" the greenhouse gases they have emitted. These instruments could help secure additional funding for achieving net-negative emissions, reducing the financial burden being entirely placed on future generations.
- Instruments to enforce an extended emitter responsibility could be designed in different ways, such as an extension of the EU ETS, or as standalone mechanisms. While careful deliberation is needed to assess the advantages and disadvantages of different options, a key consideration for all options is their timing, as early implementation will be critical to their ability to generate net-negative emissions. The EU should therefore start planning for how to address these needs in the coming years.
- Even with an extended emitter responsibility, the global and regional need for net-negative emissions will likely surpass the capacity of these instruments alone. Additional funding mechanisms will be required as part of broader global efforts to manage temperature overshoot.

Action points for EU policies

→ Assess options and governance requirements, and prepare a strategy to operationalise an **extended emitter responsibility** to contribute to the EU's net-negative emissions.

→ Implement such principle in a way that avoids an increase of the greenhouse gas budget in the short term, and that increases ambition over time.

→ Consider **different approaches** to this end, such as allowing emitters to counterbalance their emissions with future removals while the regulator ensures the overall short-term greenhouse gas budget does not increase, or requiring emitters to pay for both their greenhouse gas emissions and the cost of their subsequent removal.

Recommendation 9: strengthen governance

To ensure efficient policy implementation, accountability, and global cooperation to achieve long-term climate goals, **the Advisory Board recommends that the EU expand its climate governance and institutional capacities. EU diplomacy and policies should support this effort by reducing carbon leakage and enhancing global climate ambition.**

Designing and implementing a comprehensive policy framework to govern the progress-to-target tracking, certification, innovation, infrastructure, and pricing of carbon dioxide removals in the EU requires strong institutional oversight and coordination. The Advisory Board highlights the needs for expanded institutional capacity and enhanced international cooperation efforts.

- The EU's current climate governance lacks the capacity to provide the required strategic direction and long-term oversight for carbon dioxide removals to achieve net-zero and net-negative greenhouse gas emissions. Fully integrating carbon dioxide removals into EU's climate policy framework would ensure consistent and efficient planning, policy implementation, and reinforced accountability.
- Governing net-negative emissions will require assigning new tasks to existing bodies and possibly creating new institutional entities dedicated to scaling-up removals sustainably. Institutional governance will play a central role in managing incentives, targets, certification, land management, innovation and infrastructure development. Special attention to equity and justice will be essential to ensure public acceptance and a fair, effective scale-up.
- Enhanced international cooperation is vital to harmonise accounting standards, prevent carbon leakage, ensure fairness in global contributions, and align strategies for managing temperature overshoots and adapting to future climate stabilisation needs.

Action points for EU policies

→ Reinforce the integration of removals in the **governance regulation** and the **European Climate Law**, ensuring strong commitment to net-negative emissions.
→ Build capacity within existing institutions and consider creating new ones as needed.
→ Reduce carbon leakage and enhance global climate ambition through **climate diplomacy and policies** fostering financial and technological transfer.

Part A – Need, potential, opportunities and risks associated with carbon dioxide removals in the EU

1 The need for carbon dioxide removals

- **Removals are urgently needed to achieve the EU's climate objectives.** While they cannot substitute for rapid and deep reductions in gross emissions throughout the EU economy, removals play a key role in achieving the objectives of the European Climate Law.
- **Counterbalancing residual emissions is necessary to reach net zero.** To achieve net-zero greenhouse gas (GHG) emissions by 2050 at the latest, removals will be needed to counterbalance residual emissions from sectors with currently no or limited mitigation alternatives. The exact level and composition of these emissions is uncertain, and a continued emphasis on reductions is necessary to limit them. Assessments of the availability of mitigation alternatives need to consider a full suite of demand- and supply-side mitigation options; and consider the changing technological and socio-economic landscape in which they should be deployed.
- **Further removals are required to achieve net negative.** Removals also allow the EU to achieve net-negative GHG emissions after 2050, which will help avoid or limit a global temperature overshoot by reducing the EU's contribution to warming, help close the gap towards its fair share of the global GHG budget, and potentially reduce overall transition costs.
- **There are challenges in scaling up removals.** Achieving net-zero and net-negative objectives requires a rapid, substantial and sustainable scale-up of removals, by reducing and overcoming significant technological, socioeconomic, sustainability and governance challenges.
- **The EU policy framework needs to be enhanced to overcome challenges.** While removals have been increasingly integrated into the EU's policy framework, these efforts are still at an early stage. The EU will need to continue refining and expanding this framework to enable a rapid and sustainable scale-up of removals, while ensuring coherence with other climate, energy and environmental policies and a just transition.

1.1 Introduction

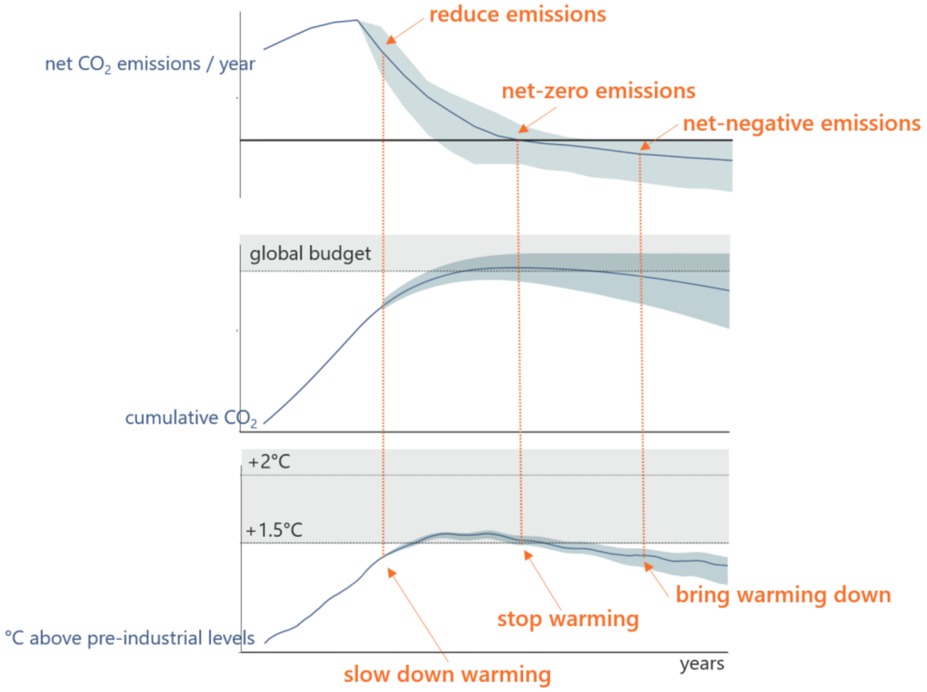
Removals play different roles in mitigating climate change in the near, medium and longer term.

The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report defines carbon dioxide (CO_2) removals (hereafter referred to as 'removals') as anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products (IPCC, 2022i). As further outlined in Chapter 2, there are a wide variety of methods that can provide removals, which can be categorised in different ways. Overall, this report broadly distinguishes between temporary removals, which mostly come from land sector sinks and account for almost all current removals both globally and in the EU; and permanent removals, which are generally comprised of emerging technologies or methods that can reliably store carbon for thousands of years but are currently only deployed at a very small scale.

In the context of mitigation strategies, the IPCC emphasises that whereas removals cannot substitute deep emission reductions, they can fulfil different, complementary roles, at different points in time (IPCC, 2022e, p.12).

1. In the near term[1], they can further reduce net GHG emissions. This would accelerate the transition to net zero and reduce cumulative emissions before reaching, thereby reducing peak warming, the risk of tipping points and irreversible climate impacts.
2. In the medium term, they are needed to counterbalance residual CO_2 emissions to halt CO_2-induced warming. Thereafter, achieving and sustaining net-negative CO_2 emissions to achieve overall net-zero greenhouse GHG emissions would reverse warming in the medium-term.
3. In the longer term, removals might be needed to sustain overall net-negative GHG emissions, to further reduce global temperatures.

Figure 1 Global net emissions pathways, greenhouse gas budget and corresponding warming



Source: Advisory Board based on IPCC C1 global pathways (median and 25th and 75th percentile range, annual/cumulative $MtCO_2$ and °C, 2000-2100)

Removals play a key role in meeting the objectives of the European Climate Law. While they cannot substitute for rapid, deep reductions in gross emissions throughout the EU economy, removals are necessary to reach and sustain net-zero GHG emissions by 2050, and net-negative emissions thereafter.

The EU's commitment to achieving climate neutrality by 2050 and net-negative emissions thereafter, as enshrined in the European Climate Law (EU, 2021b), aligns with the Paris Agreement's goal to pursue efforts to limit global warming to 1.5°C. Removals play a key role in achieving these objectives, as illustrated in Figure 2 and briefly introduced below.

As further described in Section 1.2, removals will be needed in addition to deep reductions to achieve EU climate neutrality, as some residual emissions are expected to remain by 2050, that need to be counterbalanced. However, the level of residual emissions in the EU economy – and therefore the

[1] Under IPCC scenarios compatible with the 1.5°C objective with no or limited overshoot, global CO_2 emissions reach net zero by the 2050s, and global GHG emissions reach net zero by the 2060s. On this basis, and in a global context, near term refers to the period starting this year and up to 2040, the medium term refers to the decades around mid-century (i.e. 2040-2060), and the long term refers to the period thereafter. As the EU has committed to achieving net-zero GHG emissions by 2050 at the latest and net negative thereafter, in the EU context the near term refers to the period up to 2040, the medium term refers to 2040-2050, and the long term refers to the period after 2050.

required volume of removals – is uncertain due to dynamic future technological change, activity levels and diverging ways to define and identify activities with no or limited mitigation alternatives.

Beyond 2050, removals are also necessary to achieve EU net-negative emissions. Net-negative emissions can be used to help stabilise and bring down global temperatures in the event of a temporary overshoot, increase the fairness of the EU's contribution to global climate action, and as a source of intertemporal flexibility, as further described in Section 1.3.

The EU policy framework needs further improvements to support a rapid development and deployment of removals in an environmentally and socially-responsible way, in combination with continued, deep emission reductions across all sectors.

Not only the volume of removals needed to counterbalance residual emissions, but also their potential scale of deployment is uncertain and faces several barriers, as further described in Section 1.4. Given this uncertainty, it is essential to pursue deep reductions across all sectors to avoid over-reliance on removals, but at the same time to urgently support the development and deployment of different removal pathways to overcome these barriers and ensure they can be achieved at the required scale. Whereas the EU has gradually integrated removals into its policy framework, further steps are needed to deploy them at the required scale while ensuring their environmental integrity and addressing potential negative impacts on communities and different stakeholders, as further described in Section 1.5.

1.2 The need for removals towards EU climate neutrality

Achieving EU climate neutrality by 2050 will require both rapid and deep emission reductions across all sectors of the economy, and a rapid scale-up of removals to counterbalance any residual emission that remain by this point.

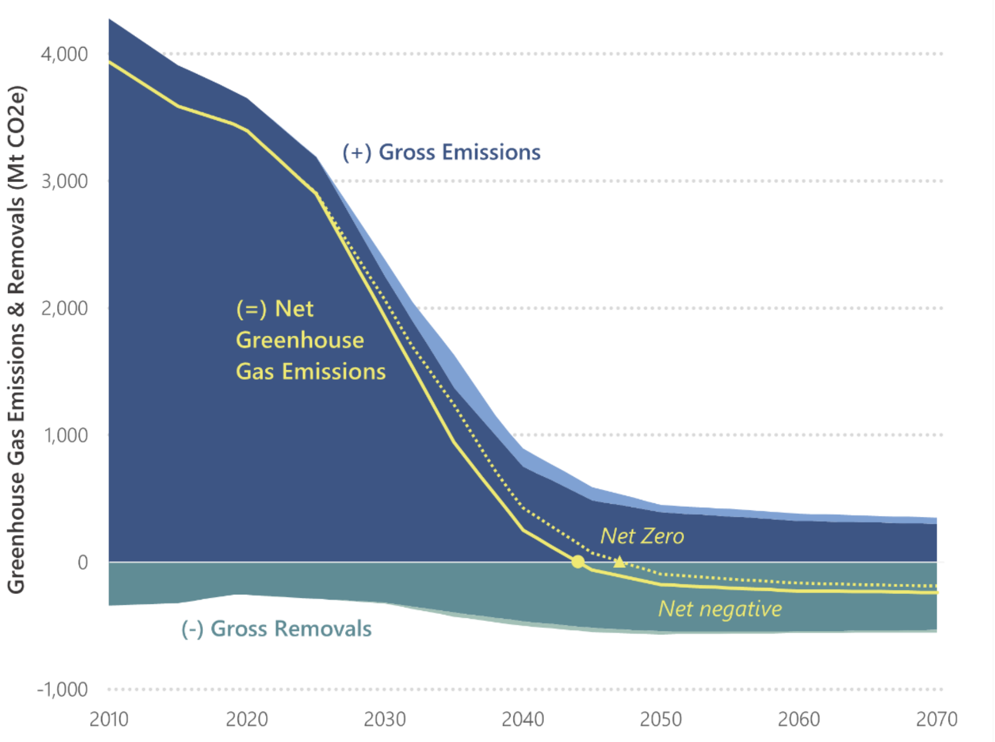
In its analysis of over 1 000 scenarios for the determination of the EU's 2040 climate target, the Advisory Board found two common features (Advisory Board, 2023). Firstly, all scenarios show that reaching EU climate neutrality by 2050 is not possible without rapid, deep reductions in gross emissions across all sectors. Secondly, all scenarios show a certain level of residual emissions remaining by 2050, highlighting the necessity for maintaining and expanding the current land sector sink, and a rapid, substantial and sustainable scale-up of removals to counterbalance these emissions.

Deploying removals alongside deep emission reductions has the potential to reduce the cost of reaching climate neutrality. If some sectors or economic activities continue to face significant technological, economic or social barriers to fully abate their GHG emissions, the economic costs of reaching climate neutrality through GHG reductions alone may become prohibitively expensive (Edenhofer et al., 2024b). If removals can reliably balance residual emissions from these sectors at a lower social cost, integrating removals in the range of possible mitigation options could allow for more cost-effective achievement of EU climate neutrality.

Achieving a reliable scale up of removals will require overcoming several challenges. Their deployment relies on emerging technologies, whose eventual deployment may be constrained by various barriers (see Section 1.4). As described in more detail in Chapter 4, the anticipated but uncertain deployment of removals could increase the risk of delaying other reduction options or leaving them unused. If the expected removals do not materialise on time, this would jeopardise the achievement of the EU's climate neutrality target by 2050. Furthermore, the required scale of net-negative emissions to hedge against future, high-risk climate outcomes (see Section 1.3) might leave little room for the use of removals to counterbalance residual emissions beyond those activities with no or limited mitigation alternatives

(Schleussner et al., 2024). Therefore, the use of removals to counterbalance residual emissions should be limited to activities with no or limited mitigation alternatives, where a full reduction of gross emissions would result in prohibitive abatement costs. This is also in line with the Advisory Board's previous recommendation to better target the deployment of carbon capture and utilisation or storage for efficiency and sustainability reasons (Advisory Board, 2024), as many permanent removal options rely on carbon capture and storage (CCS).

Figure 2 Roles of removals towards EU climate neutrality, as illustrated by scenarios in the Advisory Board's 2040 scenario database



Source: Advisory Board (2025), based on scenario data from the 2040 scenario database (Advisory Board, 2023)

Notes: Emissions and removals data comes from the 5-7 scenarios that are aligned with the Advisory Board's advice on a 90-95% target for 2040, without exceeding any of the identified environmental risk thresholds. The lighter shaded areas, and the solid/dotted line show the variation between scenarios.

Table 1 displays data from the Advisory Board's scenarios underpinning its advice on a 2040 target, along with data from the European Commission's 2040 target impact assessment. In the Advisory Board's scenarios that were aligned with the recommended 90-95% reduction target for 2040, the annual levels of residual GHG emissions[2] in the EU economy were 772-915 $MtCO_2e$ in 2040, and 392-451 $MtCO_2e$ in 2050. The levels of residual emissions in these scenarios are broadly comparable to the values from Scenario S3 in the European Commission's (2024i) impact assessment for the 2040 climate target, where residual emissions were 748 $MtCO_2e$ in 2040, and 411 $MtCO_2e$ in 2050.

The total level of removals deployed in these scenarios were between 465-501 $MtCO_2e$ in 2040, and 544-568 $MtCO_2e$ in 2050. Scenario S3 from the European Commission generally shows a lower deployment of removals than the Advisory Board's scenarios, at 392 $MtCO_2e$ in 2040 and 452 $MtCO_2e$ in 2050. Comparing these scenarios in Figure 3, these differences largely reflect a higher deployment of carbon

[2] In this context, residual emissions are calculated as net GHG emissions released to the atmosphere. This value is *after* carbon capture and storage has been applied to fossil emissions, but *before* removals from BECCS, DACCS and the net LULUCF sink. For comparability with the European Commission's scenarios, the scope of international transport bunkers includes intra-EU aviation and maritime, as well as 50% of extra-EU maritime MRV scope.

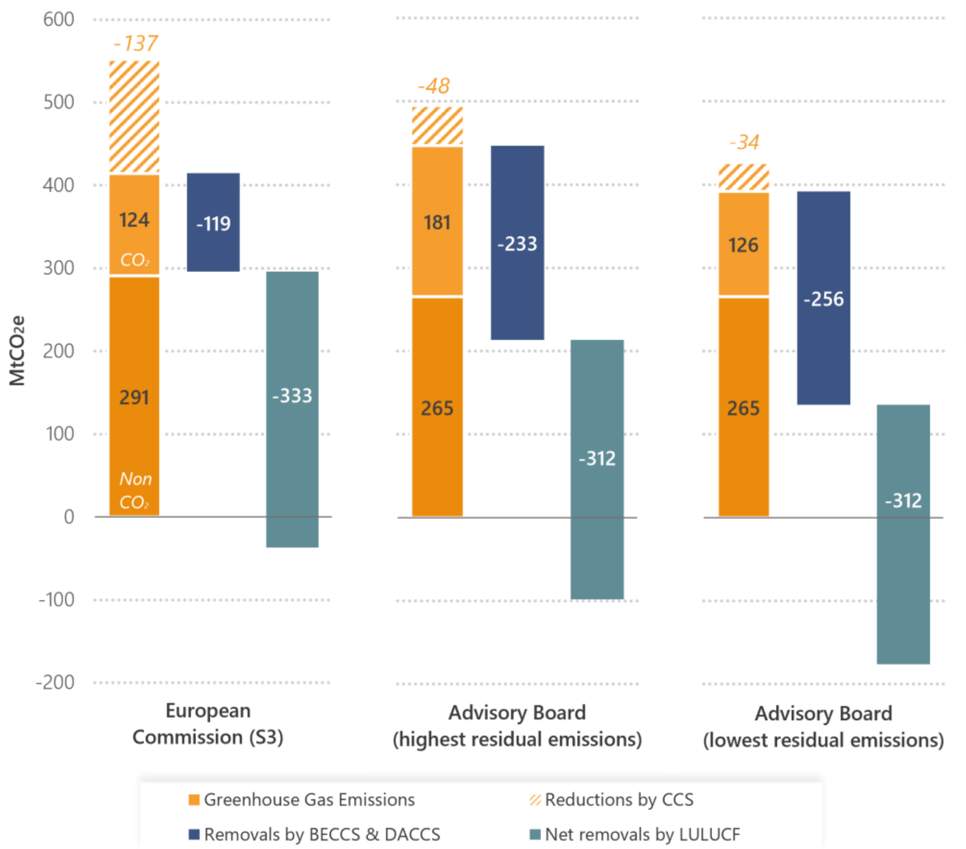
capture and storage on fossil and industrial process emissions in the European Commission scenarios, as well as a more rapid achievement of net-negative emissions in the Advisory Board's scenario (see below). While these levels exceed the level of residual emissions in 2050 in order to achieve net-negative emissions (see section 1.3), medium-term demand for removals is largely driven by assumptions of residual emissions in the EU economy.

Table 1 Range of residual emissions and removals in the scenarios underpinning the Advisory Board's advice for the EU 2040 climate target, million tonnes of CO_2 equivalent

	Scenarios	2030	2040	2050
Total residual emissions	Advisory Board (90-95% range)	**2,294-2,425**	**772-915**	**392-451**
	European Commission (S3)	*2,301*	*748*	*411*
Total removals	Advisory Board (90-95% range)	**317-326**	**465-501**	**544-568**
	European Commission (S3)	*314*	*392*	*452*

Source: Advisory Board analysis based on data from Advisory Board (2023a), European Commission (2024i)

Figure 3 Comparison of residual emissions and removals in Advisory Board and European Commission scenarios in 2050



Source: Advisory Board analysis based on data from Advisory Board (2023a), European Commission (2024i)

Notes: The Advisory Board 90-95% advice range refers to the 5-7 scenarios that do not exceed any environmental risk thresholds, and are fully consistent with the Advisory Board's advice for a 90-95% emission reduction target for 2040, as explained in Advisory Board (2023a). Data for residual emissions in Table 1 and Figure 3 come from scenarios with the lowest and highest residual emissions within this range. Total removals include BECCS, DACCS and the net LULUCF sink. For comparability with the European Commission estimates, and bunkers scope of the Advisory Board includes intra-EU bunkers + 50% maritime MRV.

Despite patterns from scenarios, the level and composition of residual emissions by 2050 is uncertain, due to unknown future technological progress and activity levels, and diverging ways to define and identify sectors with residual emissions due to no or limited mitigation alternatives.

In regional and global integrated assessment models (IAMs), estimates of residual emissions generally stem from two main sources.

1. **Non-CO_2 (methane and nitrous oxide) emissions** from livestock and fertiliser use in agriculture are difficult to fully eliminate. Non-CO_2 emissions generally constitute the largest share of residual emissions in the Advisory Board's (2023a) scenarios (40-90%), mainly methane and nitrous oxide emissions in the agricultural sector. Similarly, the European Commission's (2024i) impact assessment for the 2040 target highlights non-CO_2 emissions, primarily from agriculture, as the largest source of residual emissions.
2. **Fossil CO_2 emissions** are expected from activities with limited mitigation alternatives, such as heavy industry and long-distance transport (e.g. aviation, shipping). These sectors account for the majority of residual fossil CO_2 emissions in the Advisory Board's scenarios, with similar patterns in the European Commission's scenarios (2024i).

Despite common patterns in these models, neither the level nor the composition of residual emissions is fixed. Within cost-optimising IAMs, sectors with residual emissions have higher marginal abatement costs due to the absence of viable technical or affordable substitution options, and are therefore less responsive to an increasing carbon price than others (Lamb, 2024). However, residual emissions are a dynamic concept, and these figures can change significantly depending on assumptions of technological progress, infrastructure constraints, social change, and future activity levels. The evolution of abatement costs over the coming decades is uncertain, as is the pace of technological innovation (Anadón et al., 2017; Meng et al., 2021). Sectors considered difficult to decarbonise today might find new solutions through increased investment or breakthroughs in technology, while other sectors may struggle due to unanticipated challenges, such as deployment failures of key technologies such as (fossil) carbon capture (Burke and Gambhir, 2022) or in energy-intensive industries like steel and cement (Watari et al., 2023).

In addition, demand-side changes, such as shifts to more sustainable diets, reduced air travel and efficient material use, are often underexplored in models or policy discussions. For example, the predominance of agricultural emissions in residual emissions largely assumes *technical* difficulties in reducing livestock emissions, without fully considering the potential for dietary changes to reduce agriculture-related emissions (Lund et al., 2023). Yet, scenarios that explicitly model such behavioural changes often show the potential for reducing residual emissions at lower costs than those that rely solely on technological solutions, pointing to a need to more systematically incorporate both technological and demand-side changes into models and policy discussions when planning for future reductions in residual emissions (Lamb, 2024; IPCC, 2022l; Advisory Board, 2023; EC, 2024i). The Advisory Board's recommendations for the EU's 2040 target also point at some potentially underexplored mitigation options, for example in the industry and agricultural sectors (Advisory Board, 2023).

Underlying this challenge is the lack of a universal definition of what constitutes an activity with no or limited mitigation alternatives. The terms 'residual' or 'hard-to-abate' emissions are inconsistently defined across national strategies, leading to significant variations in how countries approach this issue depending on their political, economic and social contexts (Buck et al., 2023). Studies like those by Lund et al. (2023) and Brad and Schneider (2023) point out that these definitions often emerge from political processes, framing residual emissions as activities deemed socially necessary yet impossible to fully abate. However, defining this 'social necessity' can raise similarly challenging ethical questions about the distribution of benefits and harms. Lund et al. (2023) highlight the example of aviation as one such challenge: although it commonly appears as one of the main sources of residual emissions in national strategies and models, they note that activity levels and emissions are largely driven by the wealthiest households, and call into question such framing of all of these emissions as a 'social necessity'.

These questions underscore the challenge of conclusively identifying the appropriate balance between residual emissions and removals on the pathway to climate neutrality, although a policy framework for removals will need to find ways to identify and shape this balance. Section 4.2 further addresses these questions in the context of managing the EU's GHG budget.

1.3 The need for net-negative emissions

Global net-negative emissions might be required in the long term to reverse global warming in case the 1.5°C goal is exceeded. In the short term, both accelerated emission reductions and a rapid scale-up of removals remain crucial to keep the level of global warming as limited as possible.

The latest IPCC scenarios (IPCC, 2022e, p. 12) show that global warming can be limited to 1.5°C with no or limited overshoot[3] until 2100, if the world reaches net-zero global CO_2 emissions by 2050-2055, and net-zero GHG emissions by 2095-2100. The latter would already have a decreasing impact on global temperatures and might thus be sufficient to reverse a limited exceedance of the 1.5°C goal. However, due to limited global progress on mitigation in recent years, an exceedance of the 1.5°C goal is becoming increasingly likely, and the question might no longer be if it will be exceeded but rather how much and for how long (Reisinger and Geden, 2023). In event of a more substantial exceedance of the 1.5°C goal, earlier global net-zero GHG emissions (by 2070-2075) and a greater deployment of net-negative CO_2 emissions would be required to bring the global temperature increase back under 1.5°C by 2100 (IPCC, 2022d; Rogelj et al., 2021).

A large-scale, global deployment of removals would thus not only help to limit the global temperature peak, but also to deliver global net-negative emissions to reverse global warming in case the 1.5°C goal is exceeded. Considering uncertainties in the climate's response to emissions, the required global removal capacity to effectively hedge against high-risk future outcomes could become substantial, in the order of hundreds of gigatonnes of CO_2 (Schleussner et al., 2024). Long-term global net-negative emissions thus play a vital role in reversing any exceedance of the 1.5°C goal and managing long-term climate risks (Edenhofer et al., 2024b).

Preparing for net negative in the longer term should go hand in hand with short-term climate action, consisting of parallel efforts to both accelerate emission reductions and to rapidly scale up removals. Such immediate action is necessary to limit both the magnitude and duration of a temperature overshoot, given the risks of irreversible damages caused by climate impacts and of triggering tipping points resulting from any warming (even temporary) beyond 1.5°C (Möller et al., 2024; Schleussner et al., 2024).

Net-negative emissions in the EU can improve the fairness of its contribution to global climate action and help avoid, limit and reverse a global temperature increase beyond the 1.5°C temperature goal.

By achieving net-negative emissions after 2050, the EU can further contribute to achieving global net-zero CO_2 (and later net-zero and potentially net-negative GHG) emissions to stabilise global warming,

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[3] The IPCC defines a temperature overshoot as 'the temporary exceedance of a specified level of global warming, such as 1.5°C. Overshoot implies a peak followed by a decline in global warming, achieved through anthropogenic removal of CO_2 exceeding remaining CO_2 emissions globally.'

and to address a global temperature overshoot if it occurs. This would also enhance the fairness of the EU's contribution to global climate action. In its advice on the EU's 2040 climate target, the Advisory Board estimated the EU's fair share of global emissions for 2020-2050 under different legal, ethical and practical considerations, including historic responsibility and ability to pay. The analysis concluded that for the EU to contribute to the Paris Agreement goal in a fair and feasible way, it must pursue ambitious emission reductions and enhance removals domestically, support additional reductions and removals outside the EU and achieve net-negative emissions to close the remaining gap (Advisory Board, 2023). Achieving net-negative emissions within the EU after 2050 – thereby gradually reducing the EU's cumulative net GHG emissions over time – thus forms an essential part of the recommended approach to bridge the gap between the EU's contribution to global climate action in terms of domestic reduction efforts up to 2050, and its estimated fair share of the global GHG budget. By doing so, the EU will help to avoid, limit and reverse a global temperature increase beyond the 1.5°C temperature goal.

Net-negative emissions could also enhance intertemporal flexibility and decrease overall transition costs, provided that the cost of removals decreases substantially in the future.

Intertemporal flexibility refers to the flexibility to shift or reallocate mitigation efforts throughout time. In climate scenarios, removals provide a source of intertemporal flexibility that can be used to reduce the cumulative net GHG emissions over time (by actively removing historic emissions through net-negative emissions). They also offer a potential opportunity to reduce overall transition costs over time, assuming that the future cost of removals decreases substantially through technological experienced-based learning (Edenhofer et al., 2024b). If such cost decreases occur, the intertemporal flexibility provided by net-negative emissions could make it possible to either reduce the overall cumulative net GHG emissions at equal costs, or to achieve a similar level of cumulative net GHG emissions at a lower cost, compared to a counterfactual where net-negative emissions are not achieved. For example, if marginal reduction costs for certain sectors become very high but removal costs are expected to decline substantially, those sectors could be given the possibility to counterbalance their residual emissions with future net-negative emissions. However, such an approach would need to be designed carefully to manage liabilities and ensure consistency with the EU climate objectives, as further described in Section 4.5.1.

1.4 Barriers to the scale-up of removals

The scenarios that underpinned the Advisory Board's 2040 advice included both temporary removals and certain permanent removal options to achieve net GHG emission reductions. This section discusses the modelled potential of these different removal types under these scenarios, and the main barriers to their scale-up. Chapters 2 and 3 provide a more detailed description of a wider range of removal options, including their potentials, risks and opportunities.

The potential of removals in the land use, land use change and forestry (LULUCF) sector is undermined by current and projected climate change impacts.

The LULUCF sector is currently the only one to provide removals in the EU, with the LULUCF sink providing net removals of 236 $MtCO_2$ in 2022 (EEA, 2024e). While some scenarios in the Advisory Board's wider range of filtered scenarios indicated net LULUCF removals of over 600 $MtCO_2$ by 2050, these scenarios do not necessarily consider the growing risks such as wildfires, droughts and pests, which are expected to reduce the effectiveness of the EU's natural carbon sinks (EEA, 2024e). Further analysis carried out by the Advisory Board, drawing on an assessment by (Pilli et al., 2022), suggested that the uncertainties implied by these risks could potentially limit the future potential of the LULUCF sink capacity to anywhere between 100 and 400 $MtCO_2$ by 2050.

After applying this environmental risk threshold, the maximum deployment of LULUCF removals indicated in the Advisory Board scenarios were around 266-406 $MtCO_2$ in 2030, 273-422 $MtCO_2$ in 2040, and 272-398 $MtCO_2$ in 2050, as shown in Table 2 below (Advisory Board, 2023). However, as discussed further in Chapter 2, the EU's LULUCF sink has declined in recent years – jeopardising the achievement of the 2030 EU LULUCF target – and is threatened to decrease further due to climate change impacts (EEA, 2024e). This will make achieving these levels of removals challenging and contingent on increased efforts and funding to maintain the current LULUCF sink. Furthermore, removals in the LULUCF sector have a lower typical storage duration, with the carbon stored at a greater risk of reversal, meaning that these removals may only provide benefits in the near- to medium term (see Section 4.3.1).

The scale-up of emerging permanent removal methods requires overcoming technological, environmental and economic barriers.

The scenarios underpinning the Advisory Board's 2040 advice also considered the potential contribution of some permanent removal methods, namely methods that rely on carbon capture technologies with geological storage: bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). Permanent removals are generally considered essential for achieving and sustaining long-term climate neutrality due to typical storage durations of millennia or more, as well as lower risks of reversal (Allen et al., 2024), as elaborated further in Chapter 2. While these technologies are currently not deployed in the EU, most scenarios indicate a need to rapidly scale up. However, achieving these removals will require overcoming significant technical, environmental and economic barriers. The IPCC and various feasibility studies raise concerns about the scalability of both temporary and permanent removals. For example, limitations in land use and technology readiness suggest that rapid scale-up will require substantial investment, innovation, and policy support (IPCC, 2022g).

BECCS is often considered a key removal method in scenarios, however, its potential is constrained by the availability of sustainable biomass. The carbon sink in EU forests is under pressure from multiple factors, including wood demand (Advisory Board, 2024). Modelling suggests a growing gap between biomass demand and supply, which increases the risk of unintended pressures on biodiversity, ecosystems and other nature-related objectives (EEA, 2023e). If the deployment of BECCS at scale increases biomass demand, there is a risk this could pressure on the LULUCF sink and other nature-related objectives. Furthermore, the scalability of BECCS relies on the availability of large-scale infrastructure for CCS. Temporarily storing biogenic carbon in wood-based products while CCS infrastructure is scaled up might help to address this constraint. DACCS, though promising, faces high costs, high energy intensity, and limited deployment to date. Current demonstration projects are small in scale, and ramping up deployment will require significant breakthroughs in technology and investment (IPCC, 2022e).

While some scenarios in the Advisory Board's wider filtered range indicated higher levels of removals from BECCS and DACCS, the Advisory Board similarly applied additional environmental risk thresholds to account for these challenges in the comparative feasibility analysis. These included a maximum deployment of CCUS technologies of 425 $MtCO_2$ by 2050, as well as a maximum primary energy demand of 9 EJ from biomass (Advisory Board, 2023). After applying these thresholds to the scenarios, the remaining scenarios indicated maximum removal potentials from BECCS and DACCS of about 9-32 $MtCO_2$ by 2030, 48-179 $MtCO_2$ by 2040 and 147-256 $MtCO_2$ by 2050, as shown in Table 2.

Table 2 Maximum volumes of removals from LULUCF and geological removal methods in the Advisory Board's 2040 scenarios, million tonnes of CO_2 equivalent

		2030	2040	2050
LULUCF	Below LULUCF thresholds	266-406	273-422	272-398
Geological (BECCS & DACCS)	Below CCUS and Bioenergy thresholds	9-32	48-179	147-256

Source: Advisory Board scenario database (2023b)

Notes: The environmental risk thresholds were applied for the purposes of comparative feasibility analysis in the analysis underpinning the Advisory Board's 2040 advice. Although each level is based on the available scientific literature, there is no definitive level at which deployment becomes a risk or challenge. The risks and challenges associated with deployment of mitigation options will depend not only on the level of deployment but also on the implementation of well-considered climate policies

The EU must urgently overcome barriers and scale up removals to keep its climate objectives within reach. This needs to be done in a responsible way, taking into account their feasibility and sustainability.

While Table 2 highlights the significant potential to scale up removals, these ranges are informative rather than prescriptive, and represent the upper limits of feasibility given current technology readiness and environmental constraints. They are also subject to uncertainty inherent to the way removals and their potential are estimated in IAMs. Certain models might either overestimate the potential of certain methods, or not include the full range of removals methods. The scenarios analysed by the Advisory Board did not contain estimates for many emerging removal methods, nor detail on the potential offered by specific methods in the LULUCF sector. As introduced above, the volume of removals depends on estimates of residual emissions, which are subject to uncertainties and assumptions that are likely to change over time (Carton et al., 2023; Buck et al., 2022; Schenuit et al., 2023). Therefore, exploring a wider range of removal methods would not necessarily reveal a higher removal potential than the level assumed in these scenarios. The scenario results have therefore been complemented by a more in-depth assessment of the status, potentials, opportunities and risks of different removal methods, as included in Chapters 2 and 3.

Delivering the levels of removals envisaged in the scenarios by 2050 in the EU implies the need for a rapid scale up of both temporary and permanent removal methods from current levels. This will require significant investment, technological innovation, and policy coherence across sectors. While the challenges are substantial, a careful balance of solutions – integrating emission reductions with a diverse portfolio of removal methods – will be key to avoiding the worst climate outcomes. While there are important questions and uncertainties regarding the scale and use of removals, as described in this report, it is clear that delaying the necessary scale-up of removals would significantly reduce the EU's ability to meet its climate neutrality and net-negative emissions goals on time, increasing the risk of temperature overshoot. Therefore, urgent and decisive action is needed while ensuring that removals are scaled responsibly, supported by robust evidence supporting their feasibility and sustainability.

1.5 The EU policy framework on removals

Removals and related objectives have been increasingly integrated in the EU climate policy framework.

The EU has gradually developed a policy framework to support removals, reflecting the growing recognition of their essential role in climate change mitigation. This framework has evolved over several decades, encompassing both temporary and permanent removals. However, despite these efforts, the framework is still at an early stage, particularly for permanent removals, and the overall deployment of removals remains far below the level required to meet the EU's climate objectives.

EU policy on removals has been shaped by various legislative instruments, beginning with international commitments under the Kyoto Protocol and continuing through initiatives, notably as part of the fit for 55 package. These include the development of monitoring, reporting, and verification (MRV) frameworks, the setting of LULUCF targets, and the establishment of funding mechanisms to support research, development and deployment of removal methods.

- **Inventories and reporting**. The EU's commitment to removals began with the 1997 Kyoto Protocol, which introduced requirements for monitoring land use change and forestry activities. This was followed by the 2013 monitoring mechanism regulation and the 2018 governance regulation, which formalized reporting requirements for removals under the LULUCF regulation. The 2023 revision of the LULUCF regulation, as part of the fit for 55 package, further strengthened MRV requirements, aiming to improve the transparency and accuracy of removal data in the LULUCF sector.
- **Targets**. The European Climate Law enshrines the EU's commitment to reduce net GHG emissions by at least 55% by 2030 compared to 1990 levels, and to achieve climate neutrality by 2050. In order to ensure that sufficient mitigation efforts are deployed up to 2030, the law limits the contribution of net removals to the EU 2030 climate target to 225 million tonnes of CO_2e. The law also sets the foundation for achieving net-negative emissions after 2050, which will require significant contributions from removals. The revised LULUCF regulation establishes a binding target of 310 $MtCO_2$ of net removals by 2030 and incorporates the no-debit rule, which requires Member States to ensure that any emissions from land use and forestry are fully compensated by removals in these sectors. This rule is designed to maintain a balance between emissions and removals in the LULUCF sector, ensuring that LULUCF activities contribute to the EU's overall climate neutrality goals. Finally, under the effort sharing regulation, the EU allocates specific emission reduction targets to individual Member States for sectors not covered by the EU emissions trading system (EU ETS), such as transport, buildings, and agriculture. While the effort sharing regulation primarily focuses on emission reductions, it complements the role of removals by indirectly driving the need to balance residual emissions with enhanced removal efforts.
- **Funding**. Several EU funding instruments, such as the common agricultural policy (CAP), the Innovation Fund, Horizon Europe and LIFE programs, support the development and scaling of different removal methods. The NER300 and Connecting Europe Facility programs also contribute to funding infrastructure for CCS.
- **Bioenergy**. This remains an important part of the EU's renewable energy mix, but it is now subject to stricter GHG and sustainability criteria under the revised renewable energy directive (RED III), adopted in 2023 as part of the fit for 55 package, to ensure among others that it contributes to removals without undermining natural ecosystems. RED III includes measures to limit the use of biofuels at high risk of indirect land use change, which can negatively impact carbon-rich ecosystems like forests, by phasing them out by 2030 unless they are certified as low indirect land use change-risk. This shift is aimed to ensure that bioenergy is sourced sustainably and supports the EU's overall climate goals.
- **Nature restoration.** The Nature Restoration Law requires Member States to put in place effective nature restoration measures on an increasing share of EU land, with specific requirements for enhancing the stock of organic carbon in agricultural land (including the rewetting of drained peatlands), restoring forest ecosystems and contributing to the EU commitment to plant at least

three billion additional trees by 2030. Such measures are expected to enhance removals in the EU by increasing carbon sequestration and making existing carbon pools more resilient to future reversal risks.

- **Forests**. The 2021 EU forest strategy and the 2023 forest monitoring framework are designed to enhance the role of forests as carbon sinks. Given the recent decline in the EU's land sector removals due to deforestation, land use changes, and climate hazards, these policies aim to strengthen the preservation and restoration of forests. The forest strategy also aligns with the EU's sustainable carbon cycles communication, which emphasises the need for improved forest management practices to increase carbon sequestration in natural ecosystems. These initiatives are key to reversing the shrinking capacity of natural carbon sinks, ensuring that they play a crucial role in the EU's climate policy alongside other removal methods.
- **CCS infrastructure and certification**. The 2009 CCS directive and the trans-European networks for energy (TEN-E) regulation have laid the groundwork for CCS infrastructure development, and the publication of the Industrial Carbon Management Strategy in February 2024 marks a significant step forward (EC, 2024z). The industrial carbon management strategy outlines a comprehensive framework for scaling CCS technologies across industrial sectors, providing targeted support to industries with high residual emissions and driving further deployment of removals reliant on CCS technologies. The carbon removal and carbon farming certification (CRCF) regulation (EU, 2024g) establishes a standardised certification system for both temporary and permanent removals to ensure their social and environmental integrity and to boost investor confidence. The CRCF regulation aims to drive the market for certified removals, making it a key element of the EU's climate policy framework.

Further improvements to the EU policy framework are needed to deploy removals at the scale and speed required for meeting the EU climate objectives.

Despite these important developments, the current EU policy framework is insufficient to deploy removals at the scale and speed necessary to meet the EU's climate objectives. Numerous challenges need to be overcome through additional or reinforced policies.

The EU's land sector carbon sinks, such as forests and soils, have been shrinking due to deforestation, land use changes, and climate impacts. This decline has been particularly concerning in recent years, undermining the ability of the EU's LULUCF to act as a reliable source of carbon sequestration. Current policies have not yet been sufficient to reverse this trend and restore the capacity of these natural sinks, indicating the EU is not on track to meet the 2030 target for the LULUCF sector (EEA, 2023b).

The deployment of permanent removals remains limited due to high costs, low to moderate levels of technological readiness and the need for substantial infrastructure development, with the extent of these barriers differing across removal methods. While the policy framework for CCS infrastructure is evolving, which is critical for BECCS and DACCS, permanent removals are still far from being deployed at the scale necessary to make a significant impact on emissions.

The risks and opportunities associated with removals are diverse and will be analysed in greater detail in Chapter 3. These include environmental, social, and economic impacts, such as the risk of over-reliance on temporary removals, the rebound effect of maintaining fossil fuel value chains and the need for robust governance to manage these challenges.

While the EU's policy framework for removals is evolving, it remains at an early stage, particularly for permanent removals. To meet the climate neutrality and net-negative emissions targets, the EU will need to continue refining and expanding this framework. This includes maintaining and enhancing the capacity of natural carbon sinks and increasing investment in removal methods. The success of the CO_2

removal policy framework will also depend on its coherence with other EU policies, particularly those related to agriculture, industry, energy and biodiversity. This will be crucial to ensure removals are deployed sustainable and contribute to the EU's broader goals without creating conflicts, such as competition for land or negative biodiversity impacts.

A more detailed assessment of the status and gaps in the EU's removal policies will be presented in Part B of this report, where we will evaluate the specific legislative and regulatory measures in place, the opportunities for improvement, and the steps required to ensure that the EU can meet its ambitious climate goals.

2 Removal methods and their status, potential and costs

- **CO_2 can be stored in geological, terrestrial, or ocean reservoirs, or products.** CO_2 removal methods can be categorised according to the process by which CO_2 is captured, storage medium and storage duration.

- **The EU's land sink is shrinking.** The LULUCF sink is currently the only large of removals in the EU, although its overall size has decreased by around one third in the past decade. The observed decrease has largely been driven by a reduction in the forest sink, particularly through ageing and harvesting, although soil carbon stocks have also declined due to management of agricultural lands and peatlands. The LULUCF sink is affected by natural hazards and, increasingly, by the impacts of climate change.

- **Land management can enhance the sink in the short-term.** A range of land management practices could contribute to reversing these trends and strengthening the EU's land sink; both by preserving and enhancing existing sinks; and by restoring or creating new sinks. The literature highlights improved forest management practices, wetland and peatland restoration, and soil carbon sequestration techniques among those with the highest short-term potential to contribute to the EU's 2030 LULUCF target, while practices such as afforestation may take several decades to provide significant removals.

- **LULUCF removals are temporary.** While removals by the LULUCF sink could potentially be delivered at relatively low costs, their long-term potential and costs are constrained by saturation, lower typical storage durations and competing land uses. These removals also generally have a higher risk of intentional and unintentional reversal, and are therefore categorised as 'temporary' removals, with typical carbon storage durations of decades to centuries.

- **Several permanent removal methods exist.** A range of emerging removal methods have been developed or proposed to provide permanent removals, with the removal and storage processes creating the conditions for carbon to remain stored for thousands of years in minerals or geological formations.

- **The potential of permanent removals presents several uncertainties.** Methods such as BECCS, DACCS, biochar and enhanced weathering have not yet been deployed at large scale, and current costs are estimated at hundreds to thousands of euros per tonne of CO_2 removed. Estimates from climate models suggest high potentials, and costs that may decrease further through supportive policies, learning and scale effects. However, costs, technological readiness and environmental side-effects will need to be addressed to enable their development and deployment.

- **Future EU removal potential relies on trade-offs.** Overall, estimates largely consider technical or economic potential, with less focus on other feasibility dimensions. The realistic future potential of both temporary and permanent removal methods may be further constrained by other feasibility and sustainability dimensions, such as the availability of, and conflicts over, land and biomass feedstocks, technological progress and infrastructure, which are explored in greater depth in Chapter 3.

2.1 Defining carbon dioxide removals and methods

CO_2 removals are defined as human or anthropogenic activities that remove CO_2 from the atmosphere and store it durably. Removals should be clearly distinguished from other carbon management practices, especially CCS and CCU.

The IPCC's Sixth Assessment Report defines CO_2 removals as anthropogenic activities removing CO_2 (IPCC, 2022c) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. Where this definition is broadened to also include the removal of non-CO_2 GHGs, this is referred to as GHG removals.

To clearly identify removals within the carbon cycle and to distinguish them from other processes or carbon management activities, Smith et al. (2024) define three key principles that must be fulfilled for an activity to count as a removal. These are shown in Figure 4 below: the activity must capture CO_2 or other GHGs from the atmosphere (principle 1), durably store it with a characteristic storage duration of at least decades or more[4] (principle 2), and must also be the result of a human intervention, i.e. additional to the Earth's natural processes (principle 3). One example is DACCS, where CO_2 is captured directly from the ambient air, stored durably for thousands of years or longer in geological storage reservoirs, and occurs with processes or technologies that are the direct result of human intervention. Other examples are also illustrated in Figure 6 below, and a more comprehensive overview of removal methods is provided in Section 2.2.

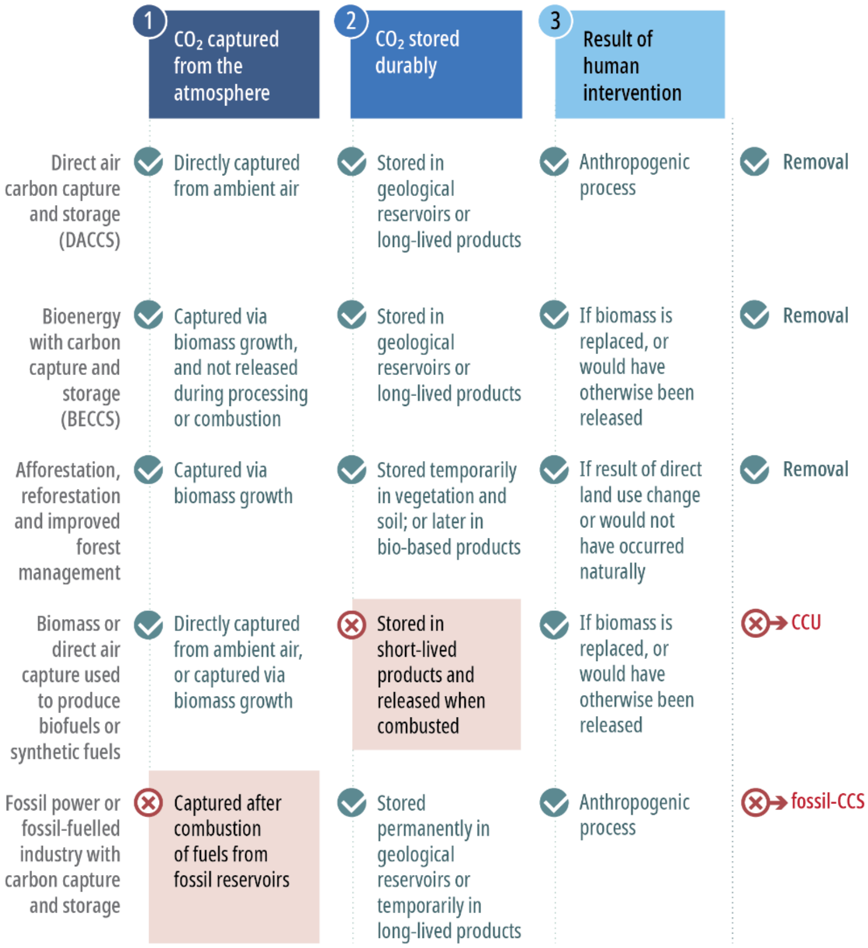
Several related approaches satisfy do not satisfy all of these principles and hence are not CO_2 removals, as also illustrated in Figure 6 below. In particular, principles 1 and 2 are necessary to clearly distinguish CO_2 removals from other carbon management activities, including CCS and carbon capture and utilisation (CCU). For instance:

- CCS is a process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere) (IPCC, 2022c). Whereas some applications of CCS technologies can also result in removals, not all of them do. For example, if CCS is applied to a stream of biogenic CO_2 that is replaced (e.g., planting new trees to replace those cut down) or would have released CO_2 back into the atmosphere naturally (e.g., dead biomass), then it results in removals as the CO_2 is first removed from the atmosphere through photosynthesis as the biomass grows, then captured when that biomass is combusted, and subsequently stored geologically. However, CCS applied to fossil CO_2 emissions ('fossil-CCS') does not meet principle 1, as this results in emission reductions (fewer CO_2 emissions released into the atmosphere), but not in removals (no CO_2 removed from the atmosphere) (IPCC, 2022c)
- CCU is a process in which CO_2 is captured and then used to produce a new product (IPCC, 2022c). Most applications of CCU do not result in a removal, as they mostly use CO_2 from a fossil origin and/or use that CO_2 for products that only store CO_2 for a short period of time (e.g. in fuels, paper). For instance, direct air capture of CO_2 for use in short-lived products such as synthetic fuels does not meet principle 2. CCU can only result in a removal if CO_2 is both actively removed from the

[4] Smith et al (2024) define durable storage as "sufficiently durable if the carbon pool used has a characteristic storage timescale on the order of decades or more", which excludes typically short-lived products like paper and fuels, but note there is no clear consensus on the precise threshold for storage to be considered durable. For activities that meet this threshold of durable storage, they can be further categorised as offering temporary or permanent removals, depending on the typical storage duration, as described further below.

atmosphere (either via direct-air capture or indirectly via biomass combustion with carbon capture), and then stored in a *durable* product for a 'climate-relevant period of time (IPCC, 2022c).

Figure 4 Examples to distinguish CO_2 removals from other carbon management practices

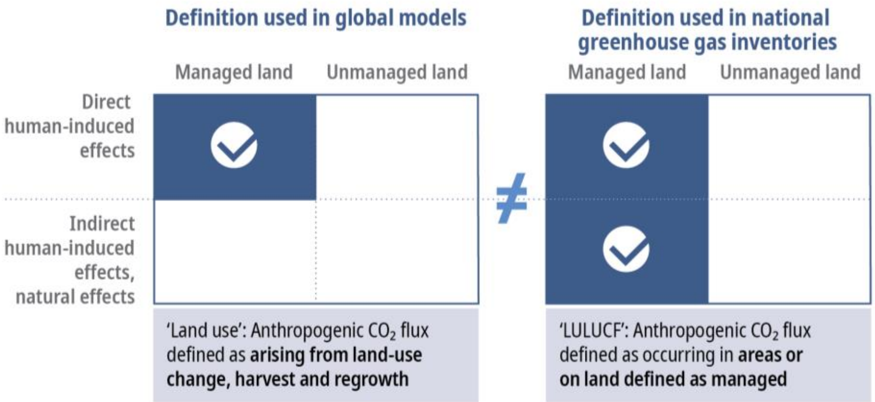


Source: Advisory Board (2025), adapted from Smith et al (2024), Figure 1.3

The principle that the activity must be anthropogenic or result from direct human intervention (principle 3) presents additional complexities in identifying and defining some removal activities, particularly when discussing emissions and removals by the land sink (and to a lesser extent the ocean sink). Under this principle, 'removals' do not include passive CO_2 uptake by the land and the ocean sinks, or other indirect human impacts on CO_2 uptake (e.g. growth due to CO_2 fertilisation). Only direct human activities such as land use change, harvesting and regrowth, or other direct interventions that enhance CO_2 uptake by the land and ocean sinks meet this definition (Smith et al., 2024). Global models and net-zero pathways generally adopt this definition, as this reflects the necessary role of removals within the global GHG budget, where only a balance of *anthropogenic* CO_2 emissions and removals at a global level can halt human-induced warming (Allen et al., 2024). This distinction is also especially important in the context of any markets or certification schemes where removals are intended to counterbalance residual emissions (e.g. in markets, contribution claims), which is discussed further in Chapter 4 in relation to the issue of equivalence.

However, in the compilation of national GHG inventories, a different definition is applied to emissions and removals from the land sink, as illustrated in Figure 5 below. As per the United Nations Framework Convention on Climate Change (UNFCCC) inventory guidelines, land is categorised according to whether it is considered 'managed' or 'unmanaged'. Managed land is defined as land where human interventions and practices have been applied to perform production, ecological or social functions, and when this proxy is used, *all* emissions and removals that occur on managed land are considered to be anthropogenic, even those fluxes that do not result from direct human intervention (IPCC, 2022c). As well as for inventory reporting, most countries also adopt this definition for policies and climate targets (Allen et al., 2024). This includes the EU, where all emissions and removals on managed land contribute to the 2030 target under the revised LULUCF regulation (EEA, 2024d), as well as the overall 2030 and 2050 climate targets (EU, 2021b). This wider scope can be necessary for comparability with inventories and policy targets, as well as assessing the trends and overall health of the LULUCF sector. This also reflects practical difficulties in identifying and disentangling the direct human component of emissions and removals in the LULUCF sector, given that 95% of EU land is labelled as managed, and that there are few areas remaining in the EU that are not affected in some way by human activities (McGrath et al., 2023), as further considered in Chapter 6.

Figure 5 Conceptual inconsistencies in definitions of anthropogenic CO_2 fluxes



Source: Adapted from IPCC, 2022 (IPCC, 2022c)

While both approaches have merits, it becomes important to clearly distinguish between them when discussing 'removals' in different contexts[5], particularly when discussing the role of removals within the GHG budget (Chapter 4), certification and additionality (Chapter 6), and broader efforts to reverse the decline in the EU's land sink (Chapter 7). In this chapter, all emissions and removals in the EU's LULUCF sink are reported when describing the overall status of and trends in LULUCF removal methods.

Various methods can deliver CO_2 removals, which differ across several dimensions, including the process by which carbon is captured, the storage medium, and the duration and risk of reversal of that storage.

There are many ways to categorise CO_2 removal methods, including the capture and storage processes, the storage medium and the typical duration of this storage, the level of technology readiness, or whether the removal occurs on land or in the oceans. Figure 6 represents the taxonomy of removal processes and their duration of storage (IPCC, 2022e, p. 12, 2022c)

CO_2 is naturally captured from the atmosphere through biological processes (i.e., photosynthesis) and stored, as living or dead biomass, in vegetation, soils, and sediments. While much of this sequestration occurs through passive biomass growth, this process can be enhanced through land use change or

[5] For instance, in the Advisory Board's advice on a 2040 target there was a difference in scope between the 'fair share' estimates, where indirect LULUCF emissions and removals were excluded for the purposes of assessing the EU's fair share of the global GHG budget, and the climate neutrality scenarios underpinning the advice on a domestic emissions reduction target, where indirect LULUCF emissions were included within the overall net sink for comparability with GHG inventories and policy targets.

management practices, including afforestation and reforestation, improved forest management, agroforestry, soil carbon sequestration techniques and the restoration of terrestrial wetland and peatlands. However, for land-based ecosystems, this process of carbon sequestration generally cannot continue indefinitely, and most individual sinks will eventually reach a point at which they stop providing net removals due to its maximum natural storage capacity being reached, or becoming 'saturated' (EEA, 2023e).

In principle, good maintenance and management of sinks can allow this level of carbon storage to be maintained indefinitely, with no net-release of CO_2 as vegetation die-off is continually counterbalanced by new sequestration from vegetation regrowth. However, while there are differences between individual methods (see Section 2.2.1), removals with storage in vegetation, soils, and sediments are often categorised as non-permanent or **temporary removal methods**, where typical storage durations can range from decades to centuries depending on the methods and management practices (as shown in Figure 6). This also includes a higher risk of 'reversal', which refers to the release of previously captured and stored CO_2 again into the atmosphere. Reversal can occur through land use change decisions like deforestation or wetland drainage, or changes to or cessation of management practices necessary to maintain carbon stocks (IPCC, 2023b). Closely linked to this is demand for and use of biomass, and various authors have highlighted the pressures from harvesting and bioenergy demand on carbon storage in the land sink, particularly in the short- to medium-term (EEA, 2023e; Jonsson et al., 2021). Natural hazards, such as wildfires, droughts and floods, can also damage sinks and cause reversal. Climate change is likely to increase both the likelihood and severity of these reversal events in the EU (EEA, 2024b, and may also affect the physical ability of some sinks to absorb and store carbon (IPCC, 2022j). For example, weakened and aging forests are also more susceptible to pests and diseases (Forzieri et al., 2021) and their risk of reversal can be contingent on adaptation actions.

The carbon stored in land sector can also be converted or transferred into other storage media, which in some cases, can offer more durable modes of storage over a longer typical storage duration. Biomass can be used to produce harvested wood or other bio-based products, where the storage duration depends on the typical lifetime of the product (Smith et al., 2024). With BECCS, CO_2 generated by biomass combustion is captured, and transferred into geological storage reservoirs. Well-regulated geological storage typically provides the conditions for carbon to remain stored for thousands of years, meaning that BECCS (and DACCS, see below) are generally categorised as **permanent removal methods** (Minx et al., 2018; Brander et al., 2021). Biomass can also be used to produce biochar, a carbon-rich material that is produced by heating organic matter in oxygen-limited environments. Biochar is most commonly proposed as a soil amendment, which current evidence suggests can provide more stable conditions for carbon to remain stored, for decades to potentially millennia depending on the context (see chapter 3). Similarly, biochar can be added to other durable products (e.g., as an aggregate to concrete used in construction), where the storage duration depends on the typical lifetime of the product (Smith et al., 2024).

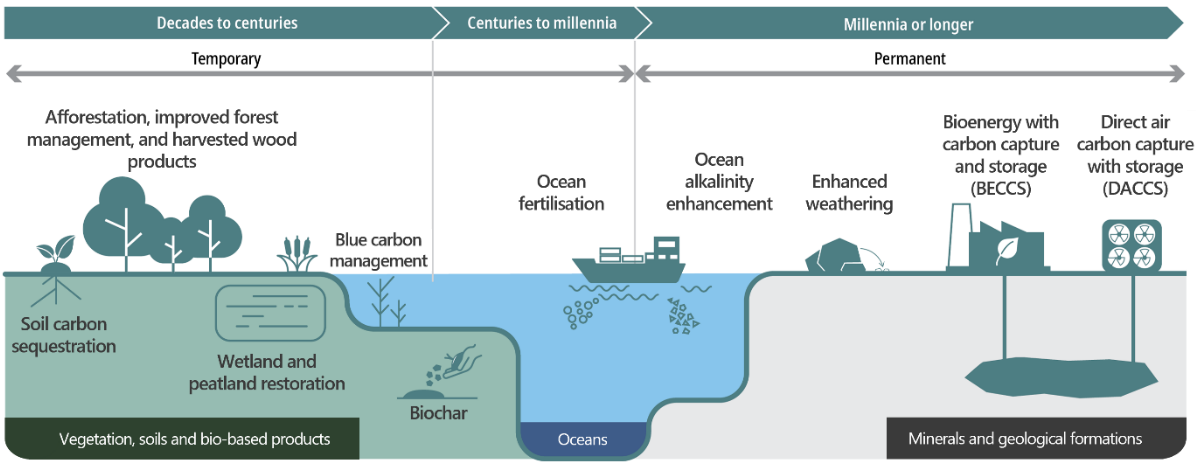
In addition to these terrestrial sinks, oceans also sequester and store carbon, mostly from the ocean carbon cycle, whereby CO_2 is absorbed from the atmosphere through chemical and biological processes, and stored in the form of dissolved organic/inorganic carbon or marine lifeforms or on the sediment floor (Christianson et al., 2022). These core processes are also considered to be non-anthropogenic and not the result of human intervention, meaning they are not accounted in national GHG inventories as removals following the UNFCCC reporting guidelines. However, removal methods exist or have been proposed that aim to directly enhance the rate of carbon uptake by the ocean carbon cycle through human intervention. One example is ocean fertilisation, whereby the growth of phytoplankton would be increased by stimulating biological processes, to increase their absorption of carbon, which is stored durably as these organisms die and sink to the bottom of the ocean. It can also include the restoration and management of certain coastal and marine ecosystems (e.g., tidal marshes, mangroves and seagrasses), often referred to as 'blue carbon management'. Like terrestrial temporary sinks, the capacity of ocean-based removals is also impacted by natural hazards and contingent on increased adaptation actions.

CO_2 can also be captured through a range of non-biological geochemical or chemical processes. Certain minerals naturally react with atmospheric CO_2, removing it from the atmosphere. While these natural processes generally occur only over geologically-relevant timescales, some removal practices aim to accelerate these processes through human intervention. Enhanced rock weathering does this by distributing crushed minerals over land, where the accelerated process of rock decomposition results in increased sequestration of CO_2. Ocean alkalinity enhancement distributes minerals over the ocean to increase alkalinity and its capacity to absorb CO_2. Finally, DACCS is a technological process that captures CO_2 directly from the surrounding atmosphere through chemical processes, so that the CO_2 can then be stored permanently in geological reservoirs, or in durable products where the storage duration depends on the typical lifetime of the product (Smith et al., 2024).

Less well-studied methods are not covered in this report but could provide additional options in the future to meet the EU's climate mitigation objectives.

Other removal methods are largely at a conceptual stage and less well studied, but could provide other options in the future, including to draw non-CO_2 GHGs out of the atmosphere. For instance, several additional ocean- or marine-based methods have been proposed, such as pumping nutrient-rich deep ocean water to fertilise the surface (artificial upwelling), dumping terrestrial biomass into oceans, or sinking marine biomass into the deep ocean. This report also did not examine in depth the full range of products that could offer durable CO_2 storage in future. The removal of non-CO_2 GHGs from the atmosphere might become possible in the future, although there are no demonstrated methods to date (IPCC, 2022e, p. 12). If feasible, these methods would increase the range of removal options, particularly the non-CO_2 removal methods, providing more options to achieve climate mitigation objectives and manage trade-offs (discussed in Chapter 3).

Figure 6 Taxonomy of CO_2 removal methods



Sources: Advisory Board (2025), adapted from on IPCC AR6 WGIII Cross Chapter Box 8, Figure 1 (2022)

Notes: Figure provides an overview of removal methods, grouped by their typical storage duration (top) and storage medium. The forestry category also includes forest management and agroforestry activities, which has similar storage durations and storage media.

2.2 Overview of EU removal potential per method

To complement the Advisory Board's previous analyses, this section provides a more in-depth and EU-focused overview of the status and trends, future potentials and costs of individual CO_2 removal methods.

In its report on a recommended EU climate target for 2040, the Advisory Board provided a first analysis of potential removal volumes by 2040 and 2050 based on a comparison of the scenarios that underpinned that recommendation (Advisory Board, 2023). The analysis below complements this with an assessment of the status, potential and costs of individual removal methods in the EU, focusing on a wider portfolio of methods than were captured in the Advisory Board's scenarios.

Compared to previous global assessments (see for example Fuss et al. (2018); Hepburn et al. (2019)), it focuses on literature containing EU- or European-focused[6] estimates of future removal potentials and costs from individual removal methods. Given the sometimes substantial differences among estimated costs and potentials as detailed below, the analysis provides approximate likely ranges from various sources; prioritising (where possible) results from scientific, peer-reviewed papers in line with the Advisory Board's methodological approach (Advisory Board, 2024, p. 39). For some removal methods, a limited number of studies or wide disparities between available studies limited the confidence in these estimates. Where possible, estimates show annual potential for 2050 (or long-term potential over a similar time horizon), although some studies do not have a particular reference year, or are based on general long-term technical potential. However, explicitly short-term estimates (e.g. earlier than 2040) were excluded from the analysis.

Current cost estimates are largely derived from global estimates and literature reviews, as few EU-wide or EU-specific cost estimates were available. While these global ranges may be appropriate for some methods, they may underestimate or overestimate the costs for others, particularly those in the LULUCF sector where there can be substantial differences in land and labour costs. Therefore, these global cost ranges were supplemented by other studies for comparative purposes, generally marginal abatement cost studies from individual EU or European countries, to assess the applicability of these global estimates. To account for different currencies and time horizons of these estimates, cost estimates were converted into common EUR 2015 values, in line with the methodology used in the IPCC's (2022b) Sixth Assessment Report.

Chapter 2 provides a summary overview, but is accompanied by a more detailed analytical annex (see Annex 1), containing the details of specific studies and scenarios that inform the ranges of potentials and costs contained in the summary overview.

2.2.1 Status and trends

Today, all the EU's reported removals originate from the LULUCF sector, largely from forests. However, ageing forests, increased harvest rates and the impacts of climate change are contributing to an ongoing decline in the forest sink, while poor status and trends in soil carbon stocks have also been highlighted.

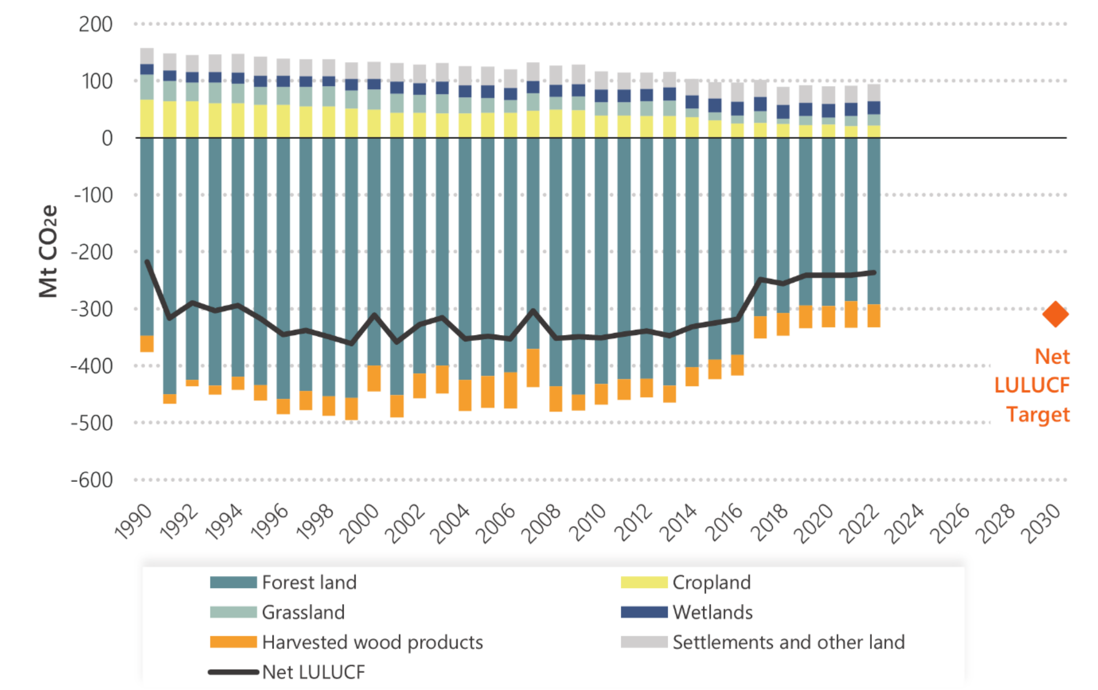
As shown in the latest inventory data for the LULUCF sector (see Figure 7), net LULUCF removals were 236 $MtCO_2$ in 2022. Net sinks in the LULUCF sector came from forest land, where net removals were 292

[6] In some instances, estimates are based on a wider geographic scope than the current EU-27 (for example, older estimates based on EU-28 or estimates including Norway, Switzerland etc.). In these cases, estimates were rescaled to EU-27 level based on an appropriate weighting factor (for example, the EU-27 share of forest or agricultural land). These adjustments are outlined in relation to specific studies in Annex 1.

$MtCO_2$ from existing forest land and land converted to forest land; and a further 40 $MtCO_2$ from harvested wood products. Other land use categories were net sources of emissions, including cropland (22 $MtCO_2$ in 2022), grassland (19 $MtCO_2$), wetland (23 $MtCO_2$) and settlements and other minor categories (30 $MtCO_2$).

The size of the EU's reported LULUCF sink has declined by nearly one third in the past decade (-30% between 2012 and 2022), mainly due to the decline in the forest sink (Korosuo et al., 2023). For most of the 21st century, net CO_2 removals from the LULUCF sector fluctuated between 300-350 $MtCO_2$ per annum, followed by a sharp decline to today's levels visible beginning in the mid-2010s due to lower rates of CO_2 uptake in EU forests. Several underlying and interlinked factors have contributed to this decline, including ageing forests, increased harvesting rates and demand for biomass, and the growing impacts of climate change (Advisory Board, 2024). Climate change is becoming an increasingly prevalent threat to the EU's land sink, and in some countries, the increasing incidence and severity of wildfires, droughts, floods and diseases/pests have made the LULUCF a net source of CO_2 (EEA, 2024b). These trends have significant implications for the EU's LULUCF target, with current projections indicating that EU member states are collectively not on track to achieve the EU-wide target for 2030 (Advisory Board, 2024; EEA, 2023g; Korosuo et al., 2023).

Figure 7 Emissions and removals from land use, land use change and forestry in the EU



Sources: EEA (2023c)

Notes: 'Drainage & rewetting of organic and mineral soils' includes the equivalent sub-category for drainage under each land use category.

Recent research has also highlighted concerns in the state of the EU's soils and soil organic carbon stocks. While net emissions from grasslands, croplands and wetlands are relatively small within the EU's GHG inventories, soil carbon has generally been highlighted as a 'blind spot' in inventories, with the potential for unreported losses and gains due to uncertainties in measurement, methodological differences and unclear implementation of soil management practices (Bellassen et al., 2022) Despite these uncertainties (see Chapter 6), the organic carbon stock in agricultural top soils in Europe is thought to have declined significantly across most of Europe over the past century (Poeplau and Dechow, 2023). Both the natural soil sink and agricultural land continue to be at risk from climate change; for example, temperature increases in high-latitude regions causes permafrost thawing, leading to the release of stored carbon and methane (Arias-Navarro et al., 2024)

Despite these concerning trends, the IPCC describes the land sector as the 'only one in which large-scale CO_2 removal may currently and at short term be possible', providing the potential for 'significant near-term mitigation potential at relatively low cost' (IPCC, 2022a, pp. 750-753). Removal methods in the LULUCF sector have the highest technological readiness levels (TRLs) of all methods, pointing to fewer technological challenges for deployment at scale compared to other emerging technologies (IPCC 2022k). However, technological readiness does not necessarily reflect other barriers to widespread implementation, or sustainability concerns of specific methods, which are outlined further in the sections below and in Chapter 3. Furthermore, biomass growth times means that it may take decades to establish new sinks, meaning that short-term options to address the EU's declining sink and to achieve the 2030 LULUCF target may be more limited (Advisory Board, 2024).

For permanent or other emerging removal methods, which are mostly at demonstration stage or have yet to be deployed at scale, current CO_2 removal volumes are minuscule.

Current global removal volumes from permanent or other emerging removal methods are miniscule, with an estimated 1.3 $MtCO_2$ per year in 2023, albeit with rapid growth compared to previous years (Smith et al., 2024). Of CO_2 removal methods outside of those contained in LULUCF inventories, only biochar appears to be delivering removals in the EU, with (Smith et al., 2024) and industry estimates (European Biochar Industry, 2023) indicating approximately 0.1-0.15 $MtCO_2$ per year coming from biochar. Other methods such as BECCS, DACCS, enhanced weathering or emerging ocean-based methods do not currently provide removals in the EU at scale, although there are projects that are currently at different stages of development.

2.2.2 Potential and costs

Improved management and reduced harvesting of existing EU forests are among the few practices that could deliver significant short-term removals at a relatively low cost. However, the removal potential from afforestation and reforestation is constrained by land availability and long growth times.

Improved forest management		
Annual EU potential	Current costs	TRL
63-80 $MtCO_2$ (19-266)	**0-50 EUR/tCO_2** (0-113)	**8-9**

Source: Average annual EU potential estimated from literature review by Verkerk et al. (2022), costs assessed based on individual studies in Annex I.

Conservation can protect existing land sinks (e.g. avoiding deforestation) from competing land uses, while restoration and **improved forest management** practices can increase sequestration by existing managed forests. This can include practices such as longer rotations, less intensive harvests, continuous-cover forestry, change of species and provenances, and increasing resilience to avoid the risk of hazards (e.g. fires, windthrow, pests and diseases) (IPCC, 2022a) Individual estimates found in the literature show a potentially wide range of future removal or mitigation potentials of 19-266 $MtCO_2$ per year by 2050 in the EU (see Annex 1), with one EU-wide literature review finding average potentials of 53-70 $MtCO_2$ per year from improved forest management practices and a further 10 $MtCO_2$ per year from reduced deforestation Verkerk et al. (2022) (see Annex 1).

The costs of forest management practices are often assumed to be among the lowest of all land management options, as they mainly need to compensate for foregone income from (for example) longer rotation lengths or conservation-based management approaches. Global and EU-wide estimates suggest costs in the range of 0-50 EUR/tCO_2, although estimates from some EU countries could be higher (see Annex 1). While forest biomass growth accounts for most of this carbon sequestration potential, it should be noted that forest soils represent the largest existing carbon stocks in forests, with some of these practices (particularly diverse species selection) offering additional carbon sequestration and storage potential beyond these estimates (Advisory Board, 2024).

Afforestation		
Average annual EU potential	Current costs	TRL
49 MtCO_2 (2-75)	**25-100 EUR/tCO_2** (0-216)	**8-9**

Average annual EU potential estimated from literature review by Verkerk et al. (2022). Costs based on global likely range cited by Fuss et al. (2018), and validated by national-level studies in Annex I.

The future removal potential from increased **afforestation and reforestation** is generally smaller, due to constraints in land availability and longer growth times. Verkerk et al.'s (2022) literature review of afforestation practices also found average EU potentials of 49 MtCO_2 per year by 2050, with a wider range from the literature of 2-75 MtCO_2 per year. Individual estimates are based on author assumptions of available land, with individual studies within this range assuming 1-10% of the EU's agricultural land being turned over to afforestation. Future removal potential also depends on timing of afforestation, and in the short-term (i.e. by 2030), the potential from afforestation is limited as new forests take time to deliver significant removals. There is also considerable uncertainty regarding how the choice and composition of afforested species will affect long-term potential, given their suitability to adapt to future climate and increasing hazards (Jandl et al. 2019). Cost estimates from longer-term global and European studies suggest that removals from afforestation and reforestation could be delivered within a range of approximately 25-100 EUR per tCO_2e, depending on the land type and previous use, although there can be significant variation in costs and outliers (see Annex 1).

There can be temporal trade-offs between some forest management practices (e.g. short-term harvests that might be necessary to replace with more productive or resilient species in the long-term); as well as with the use of biomass in other applications (Verkerk et al., 2022) However, based on the existing scientific literature, the Advisory Board has previously identified that even accounting for substitution effects in the use of harvested wood products, reduced harvesting is generally a more effective climate mitigation strategy in the short to medium term, as wood is currently mainly used to produce short-lived products or for energy. However, a greater emphasis on products with longer storage durations (e.g. for construction materials) could reduce these trade-offs (Advisory Board, 2024).

While terrestrial wetlands and peatlands have become net emitters in the EU, conservation and restoration practices could deliver significant emission reductions in the short-term, with a longer-term potential to become net sinks again over decades.

Terrestrial wetlands and peatland restoration		
Annual EU potential	Current costs	TRL
60-100 MtCO_2 (1-195)	(8-110) EUR per tCO_2 *Based on limited EU estimates*	**8-9**

Source: Annual EU potential estimated based on interquartile range from studies in Annex I, costs from EU studies in Annex I.

Terrestrial wetlands and peatlands are among the most carbon-dense habitats in the EU. However, they sequester carbon very slowly, while drainage, extraction, land use change and prolonged droughts have caused wetlands, peatlands and organic soils to become net emitters in the EU, and it has been estimated that drained peatlands emit about 220 $MtCO_2e$ per year, equivalent to around 5% of EU emissions (JRC, 2024). Rewetting and practices aimed at **restoring wetlands, peatlands and organic soils** to a healthy ecological state can significantly reduce emissions from these habitats in the short-term, with estimates from the literature suggesting significant technical climate mitigation potential of up to 200 $MtCO_2$ per year by 2050, although most estimates are clustered within a range of 60-100 $MtCO_2$ per year (see Annex 1). While there is significant uncertainty and variability in estimates of GHG fluxes across different sites, rewetting is generally highlighted as an important measure to strengthen the LULUCF sink in the short-term, particularly given the small share of agricultural land (1-2%) that would be required. Over decades, restoration and rewetting of degraded wetlands could restore their function as a net-carbon sink, although as before, variability in GHG fluxes make the exact timeframe difficult to predict (Wilson et al., 2016; Humpenöder et al., 2020). EU-wide cost estimates were not found, but limited national-level estimates suggest that wetland and peatland restoration could potentially be a cost-effective mitigation measure in several EU countries. Overall, cost estimates contained in Annex I range from EUR 8-110 per tCO_2 depending on the location, but in most locations, costs came within the lower end of this range (see Annex 1).

Blue carbon management		
Annual EU potential	Current costs	TRL
Insufficient data	*Insufficient data*	2-3

In the scientific literature, the term '**blue carbon management'**[7] usually refers to management and restoration of coastal vegetated ecosystems, particularly mangroves, seagrasses and saltmarshes, distinct from removal methods aimed at enhancing the ocean carbon cycle (IPCC, 2022k; Crooks et al., 2019). While coastal and blue carbon habitats are largely excluded from national GHG inventories, some removals may be included in EU member states' inventory submissions under the wetlands category (primarily salt marshes), although these levels are difficult to estimate explicitly (EEA, 2023a). Blue carbon ecosystems are known to hold high existing *carbon stocks*. However, their potential as a major source of removals is less certain: challenges in carbon accounting, high variability and errors in carbon burial (removal) rates across studies and ecosystem types, combined with a low cost-effectiveness per tCO_2 compared to other removal methods, makes it 'uncertain and unreliable' as an explicit removal method (Williamson and Gattuso, 2022). Few EU-wide estimates of status, potential and costs have been found, with available studies from EU countries or regions indicating a relatively low removal potential (0-5 $MtCO_2$ per year). Despite this, protecting and restoring these habitats remains an important climate mitigation strategy due to their ability to store large amounts of carbon, and to protect this from reversal.

There is also potential to increase CO_2 removals and storage in soils and biomass on existing agricultural lands, such as through soil carbon sequestration practices and agroforestry, with potential opportunities for food production, biodiversity and climate adaptation.

[7] Other removal methods, such as ocean alkalinisation and ocean fertilisation are addressed further in the annex.

Soil carbon sequestration		
Annual EU potential	Current costs	TRL
20-90 $MtCO_2$ (9-122)	**0-90 EUR per tCO_2** (-45-123)	**8-9**

Source: Annual EU potential estimated based on interquartile range from studies in Annex I. Costs based on global likely range cited by Fuss et al. (2018), and validated by national-level studies in Annex I.

Certain agricultural practices can increase carbon sequestration on agricultural lands, both in the soil and in above-ground biomass. Estimates from the literature have found that the adoption of **soil carbon sequestration** practices such as cover cropping, certain crop rotation changes, and enhanced grassland management could deliver additional technical sequestration potential of up to 120 $MtCO_2$ per year, although estimates of economic potential or those based on more realistic deployment scenarios generally suggest potential removals of 20-90 $MtCO_2$ per year by 2050 (see Annex 1). Soil carbon sequestration practices are also among those that can begin to deliver removals immediately (Lugato et al., 2014), particularly against a backdrop of declining soil organic carbon stocks in recent years (De Rosa et al., 2024). However, soils can also become saturated after only a few decades and are at a higher risk of reversal due to cessation of management practices, meaning the long-term potential of soil carbon sequestration practices may be more limited. In addition, soil carbon sequestration potentials can be challenging to estimate due to methodological differences across studies, difficulties in measuring soil organic carbon stocks and fluxes, and uncertainties regarding the future impacts of climate change (Wang et al., 2023; Smith, 2014; Fuss et al., 2018). As soil carbon sequestration encompasses a variety of different practices, the cost can also vary significantly, with global and European estimates generally pointing to a range of between EUR 0-90 per tCO_2e. However, some estimates indicate negative costs (i.e. net savings) due to potential additional benefits from some practices for agricultural production (e.g. improved soil fertility, crop yields etc. – see Chapter 3).

Agroforestry		
Annual EU potential	Current costs	TRL
(10-250) $MtCO_2$ *Based on limited estimates*	(20-90) EUR per tCO_2 *Based on limited estimates*	**8-9**

Source: Annual EU potential shows full range based on limited number of studies in Annex I. Costs based on full range across limited number of national-level studies in Annex I.

Agroforestry, which incorporates trees and woody biomass alongside agricultural production, has been highlighted as a potentially significant mitigation measure that could be deployed on agricultural lands. A limited number of studies have suggested that the widespread deployment of agroforestry practices could provide removals of 10-250 $MtCO_2$ per year, although this is based on a relatively small number of studies of mainly technical potential, and economic or realistic potential is likely to be lower (see Annex 1). No EU-wide cost estimates were found, with a limited number of national-level estimates within Europe indicating that agroforestry costs may lie within a similar range of afforestation and reforestation, with a range of EUR 20-90 per tCO_2. However, the comparability of these estimates can be challenging due to differences in practices assessed, the scope of costs, and local factors, meaning that there is relatively low confidence in these estimates. Agroforestry practices may also compete with soil carbon sequestration practices for the same land, meaning that estimates of potential are likely to overlap to some extent.

As geological storage typically provides conditions for carbon to remain stored for millennia, BECCS and DACCS are the most common permanent removal methods deployed in scenarios. Results from these scenarios suggest high future potential, although in practice, the potential of

BECCS is constrained by sustainability limits and pressure on land and biomass resources, while DACCS faces high costs.

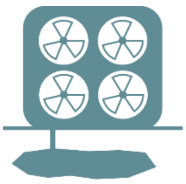
Bioenergy with carbon capture and storage (BECCS)		
Annual EU potential	Current costs	TRL
150-250 $MtCO_2$ (4-360)	**150-250 EUR per tCO_2** (27-360)	**5-6**

Source: Annual EU potential represents approximate range from Advisory Board scenarios that do not exceed CCUS or bioenergy thresholds used for comparative feasibility analysis (Advisory Board, 2023). Costs based on EU studies and early market data in Annex I.

BECCS is the most common permanent removal method included in IAM scenarios, including those used by the Advisory Board to prepare its advice on the 2040 target (Advisory Board, 2023) In the Advisory Board's scenarios that were within the environmental risk thresholds for CCUS technologies and primary bioenergy use, described in section 1.4 previously, BECCS deployment reaches 147-248 $MtCO_2$ per year by 2050, which corresponds to scenarios with 5-7.5 EJ/year of primary energy from biomass.

Other estimates that explicitly limit BECCS to existing installations or residual feedstocks point to a maximum potential within a similar range, with maximum estimates of 200-250 $MtCO_2$ per year in the EU in these scenarios EU (Lehtilä et al., 2023; Rosa et al., 2021a). However, these authors also emphasise potential competition for residual feedstocks between BECCS and other methods (e.g. biochar). Furthermore, the dispersed nature of biomass sources and CO_2 storage sites, combined with cost and infrastructure constraints, may limit the feasibility of reaching these levels with residual feedstocks alone (Lehtilä et al., 2023; Rosa et al., 2021a). In the wider literature, estimates of future BECCS potential in the EU vary widely, ranging from 4 to 360 $MtCO_2$ per year by 2050 (see Annex 1). The primary constraint on BECCS deployment is the availability of land and biomass resources, with estimates heavily dependent on assumptions about feedstock availability and land use. For further discussion on limitations of biomass assumptions in IAM, see Section 7.3.

The cost of removals from BECCS has been estimated at around 100-250 EUR per tCO_2 in the literature and from early voluntary market data, although a lack of large-scale commercial deployment limits the reliability of these estimates. While it is possible that costs may decline further due to experience curve and economy of scale effects, the opportunity for significant future cost reductions is thought to be relatively limited due to the relative maturity of BECCS as a technology (Abegg et al., 2024) and the lack of adequate pricing of land sector emissions (see Figure 8 and Section 7.3).



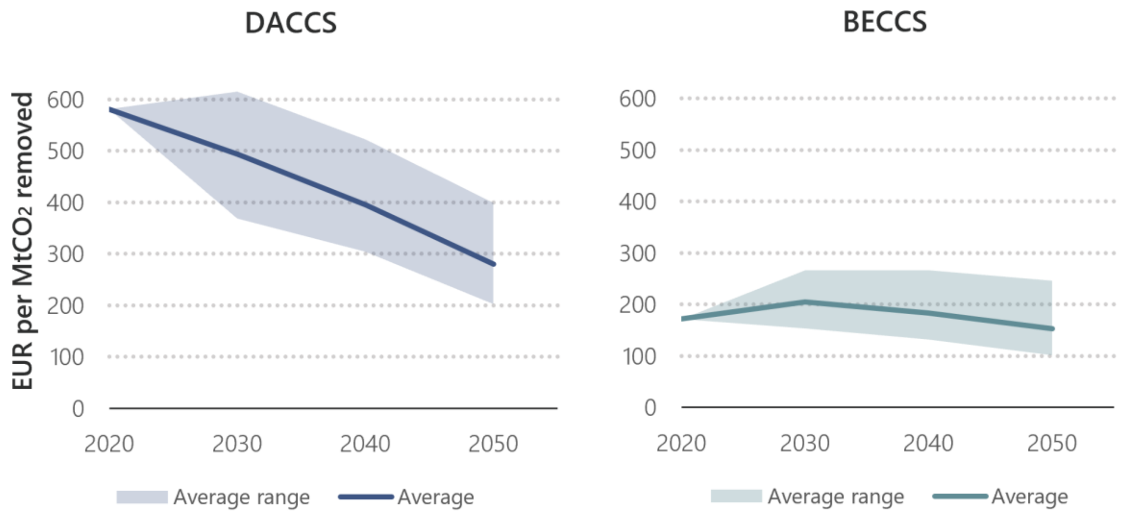
Direct air carbon capture and storage (DACCS)		
Annual EU potential	Current costs	TRL
20-60 $MtCO_2$ (0-400)	**500-1 000 EUR per tCO_2** (450-2 000) *Potential 2050 costs: 200-500 EUR per tCO_2*	**6**

Source: Annual EU potential based on studies contained in Annex I. Costs based on EU studies and early market data in Annex I, future costs based on trajectories from (Abegg et al., 2024; Sievert et al., 2024)

DACCS was not included in all scenarios used in the preparation of the Advisory Board's advice on the 2040 target. In the 6 scenarios aligned with the recommended 90-95% reduction target for 2040, the level of DACCS was relatively low at 0-20 $MtCO_2$ per year. Other estimates from the wider literature have suggested a wide technical potential range of 0-400 $MtCO_2$ per year by 2050, although other modelling estimates of economic potential typically suggest a narrower potential range of 20-60 $MtCO_2$ per year (see Annex I). However, as DACCS is an emerging technology with only a few demonstration plants currently delivering small volumes of removals, the future potential is highly uncertain and ultimately depends on technological performance as well as the evolution of future costs.

Estimates from the literature and from voluntary markets indicate that average costs of DACCS from early-stage plants can range from EUR 500 to over 1 000 per tCO_2, with significant variability and outliers (see Annex 1). Several authors have suggested further potential for costs to decline due to experience curve effects and economies of scale, with some estimates suggesting the potential for costs to decline to 200-500 EUR per tCO_2 by 2050 based on these assumptions (Abegg et al., 2024; Sievert et al., 2024). Figure 8 illustrates potential cost trajectories for DACCS until 2050, based an expert elicitation study by Abegg et al. (2024). Scenario results that show high rates of DACCS deployment also assume significant cost declines, particularly relative to BECCS (Sultani et al., 2024). However, achieving such cost reductions is not guaranteed, and requires not only overcoming significant technological barriers, but a supportive policy environment with mechanisms to encourage a rapid and early deployment to allow for learning effects to take place (see Chapters 4 and 8).

Figure 8 Potential evolution of BECCS and DACCS costs in the EU based on expert elicitation study by Abegg et al. (2024)



Source: Abegg et al. (2024)

Note: The figures illustrate the results of an expert elicitation study conducted by Abegg et al. (2024) to estimate potential future costs of BECCS and DACCS. A 2020 reference cost was provided by the study authors, while experts were asked to provide 'best estimates' of future costs in 2030, 2040 and 2050, as well as minimum-maximum ranges. In each figure, the solid line represents the average of the 'best estimates', and the shaded area shows the range between the average minimum and maximum estimates provided by experts.

Other permanent removal methods were not included in the scenarios collected by the Advisory Board, although the wider literature has highlighted moderate removal potential from methods such as biochar and enhanced weathering, and potentially lower costs compared to BECCS and DACCS.

Biochar		
Annual EU potential	Current costs	TRL
(70-200) $MtCO_2$ *Based on limited estimates*	**100-200 EUR per tCO_2** (27-305)	**6-7**

Source: Annual EU potential based on studies contained in Annex I, costs based on early market data from CDR.FYI (Bednar et al., 2023b) and studies contained in Annex I

A limited number of estimates from the EU indicate technical potential of 70-200 $MtCO_2$ per year from **biochar** in the EU under different scenarios (see Annex 1). Estimates in the literature primarily assume the use of residual feedstocks (e.g. crop and forestry residues, manure, wastewater); with the higher end of these range coming from estimates that assume high residue removal rates. These estimates are therefore likely to conflict with some BECCS potentials described above, especially BECCS that operate on crop and forestry residues. Additional conflicts and overlaps may be possible with the potentials of other land sector methods (e.g. afforestation, SCS, enhanced weathering). The cost of biochar is generally lower than other permanent or emerging removal methods, with estimates from the literature and early market data suggesting costs of approximately EUR 100-200 per tCO_2 (see Annex 1). Data from early-stage biochar projects fall within the higher end of this range, with average market costs of approximately EUR 140-150 per tCO_2 (Bednar et al., 2023b).

Enhanced weathering		
Annual EU potential	Current costs	TRL
(50-200) $MtCO_2$ *Based on limited estimates*	**250-300 EUR per tCO_2** (54-400)	**3-4**

Source: Annual EU potential based on studies contained in Annex I, costs based on early market data from CDR.FYI (Bednar et al., 2023b) and studies contained in Annex I

Modelling and small-scale experiments have been conducted to assess the potential of **enhanced weathering**, but this has not yet been developed or deployed as a removal method at a large scale. Two estimates from the EU suggest moderate potentials of 50-200 $MtCO_2$ per year (see Annex 1), with the upper end of this range corresponding to deployment over 40-60% of the EU's croplands (Beerling et al., 2020). However, it is not clear to which extent enhanced weathering can be deployed alongside other removal practices, particularly soil carbon sequestration or biochar application, which raises the possibility of overlaps in estimates with other removal methods (Lehtilä et al., 2023) Additionally, further research on its technological feasibility, risks and benefits is required to fully understand its potential (IPCC, 2022a) Estimates from the literature generally indicate a cost range of EUR 54 to 400 per tCO_2 which differ according to the mineral types, application rates and real-world sequestration rates. As with biochar, market data from early-stage projects are likely to come in at the higher end of this range, with average costs of around EUR 250 to 300 (Bednar et al., 2023b) (see Annex I).

Global estimates of the potential and costs of ocean fertilisation and ocean alkalinity enhancement are marked by high uncertainty, while EU estimates of the potential were not found.

Ocean fertilisation & and ocean alkalinity enhancement		
Annual EU potential	Current costs	TRL
Insufficient data	OF: (2-400) EUR per tCO_2	**1-2**
	OA: (30-230) EUR per tCO_2	**1-2**

Source: Cost based on estimated from the IPCC

Ocean fertilisation and ocean alkalinity enhancement have the lowest TRLs of the removal methods assessed by the IPCC, and to date have largely been limited to theoretical and modelling assessments, and some field experiments (Lezaun et al., 2021; Hartmann et al., 2023). The global removal potential from ocean fertilisation is estimated at 0.1-5.5 $GtCO_2$/year by 2050, while for ocean alkalinity enhancement, it has been estimated at 0.1-3.5 $GtCO_2$/year by 2050 (see Annex 1). No EU-specific estimates have been found for the potential removals from these methods. Cost estimates in the literature indicate a wide range, marked by high uncertainty. For ocean fertilisation, the IPCC cites a range of around 2-400 EUR/tCO_2, with a median estimate of approximately EUR 200 per tCO_2. Similarly for ocean alkalinity enhancement, global costs were estimated at around EUR 30-230 EUR per tCO_2, although the potential for lower costs were noted with some methods. However, estimates of costs and potential are largely theoretical, and authors have highlighted significant uncertainties, risks, and legal questions associated with the widespread deployment of these technologies (see Chapter 3).

2.2.3 Challenges in assessing and realising future removal potential

In practice, achieving high levels of deployment of any individual removal methods may be challenging, and will depend on overcoming other feasibility, sustainability and cost challenges.

Data availability and extent of research for the different removal methods differs widely, and estimates of the potential can vary significantly across on individual studies and scenarios, and may not be fully comparable due to differing scopes, discount rates and time horizons applied across different studies (Kim, 2008) These estimates generally show 'technical' or (to a lesser extent) 'economic potential'. The sustainable or realistic potential of removal methods is often lower still than estimates of technical and economic potential found in the literature, which do not necessarily consider other dimensions of feasibility (see Box 1 Concepts in estimating the potential of CO2 removals), such as political, social, or institutional factors. These factors and risks (presented in greater depth in Chapter 3) will play a large role in determining to what extent particular removal methods can be realistically deployed, or where significant additional barriers may be anticipated compared to the estimates in this section.

Box 1 Concepts in estimating the potential of CO_2 removals

Technical potential: Most studies on individual CO_2 removal methods in the LULUCF sector estimate their technical potential, which are generally bottom-up estimates of the annual removal potential based on assumptions around land use and sequestration rates. Technical potential gives a theoretical maximum of removal potential but generally cannot be reached due to economic and feasibility constraints.

Economic or cost-effective potential: Estimates of economic potential are derived from IAMs and generally show the optimal quantity of CO_2 removals for which the social benefits exceed social costs at a given carbon price. Economic potential estimates therefore take into account not only competing land uses and methods, but also broader cost-effectiveness considerations; although are less commonly reported for LULUCF-based removals than their technical potential (IPCC, 2022k; Olsson et al., 2019).

Other dimensions of feasibility: The IPCC considers six different dimensions of the feasibility of climate mitigation options, including the geophysical feasibility, environmental feasibility, technological feasibility, economic feasibility, socio/cultural feasibility and institutional feasibility (IPCC, 2022a). Some of these are covered in the considerations above on the technical and economic potential estimates, however some environmental and social limits might not be considered in those two types of potential estimates (see Section 3.4.4 on public acceptance and legal barriers).

Source: (IPCC, 2022a).

As noted, studies on the potential of removals often do not take into account potential competition or trade-offs with other methods and land uses (IPCC, 2022k; Roe et al., 2021). Land is a finite resource, and while it can support multiple uses (and multiple sources of removals), many removal methods imply trade-offs for other methods or uses (see Chapter 7). Most notably, afforestation will reduce the agricultural land available for agroforestry, soil carbon sequestration, or application of biochar and enhanced weathering. There is also a risk that land for bioenergy crops or afforestation projects categorised as "marginal" is in fact used by local communities, hence limiting access to resources (Buck et al. 2020). Methods also potentially compete for the same biomass feedstocks, particularly BECCS and biochar production, which can create trade-offs with forest management practices that aim to increase removals and storage in standing forests. Even when production is limited to residual feedstocks to minimise these sustainability concerns, studies for BECCS and biochar often individually assume the use of the same feedstocks, making it difficult to compare and add potentials (Lehtilä et al., 2023). Therefore, ranges should generally be considered individually to avoid overestimating the future potential, and should be largely considered to reflect the potential scale of specific methods within a broader removals portfolio.

The costs of removal methods can also differ depending on how estimates are constructed by individual studies. Removal costs could include capital and investment costs; operational costs (e.g. staff, energy, materials, etc.); MRV; research and development; and land and opportunity costs among others. In some cases, it could even take into account cost savings or additional benefits, including both private (e.g. timber revenues, crop yields) and public benefits (e.g. the provision of ecosystem services) (Golub et al., 2023). Discount rates and time horizons are also likely to differ between different studies. Finally, estimates are also often based on global assessments which might not accurately reflect costs at an EU level, especially for removal methods that depend heavily on local land and labour costs (Doelman et al., 2020; Fuss et al., 2018). Where possible, additional estimates of costs were therefore collated at an EU- or EU member state level to provide a more targeted cost range. Given the above, while removal costs are generally estimated and compared in a common metric (EUR/tCO_2), it can be difficult to accurately compare cost estimates from the literature.

One aspect that has received increased attention in the literature is the long-term costs of temporary removals, and whether the costs in the literature account for the cost of future reversals. Most studies of the costs of individual methods have been estimated from cost studies over relatively short time horizons (i.e. using reference period of less than 100 years; see Annex 1 for details of individual studies), which do not necessarily account for the future *costs* of reversal or saturation. For instance, if CO_2 captured by an afforestation is assumed to be released from storage again after a number of decades or centuries, this brings with it a 'commitment to perpetual removal of carbon' to maintain the same level of CO_2 removal in the long-term, alongside any future costs associated with these repeated removals (Franks et al., 2022). Similarly with regards to sink saturation, as management practices associated with SCS and forests may still need to be maintained indefinitely in order to prevent stored carbon being re-released, this may result in ongoing costs without any additional removal benefits (Smith et al., 2016b). This 'Sisyphus' task' is often not reflected in shorter-term marginal abatement cost estimates for temporary removal methods, and therefore makes direct comparisons between the costs of temporary and permanent removal methods difficult (Franks et al., 2022; Edenhofer et al., 2023; Prado and Mac Dowell, 2023). These costs have a significant impact on the design of policies and instruments to manage the EU's GHG budget, particularly in the differentiation between temporary and permanent removals (see Section 4.3).

3 Opportunities and risks associated with scaling up removals

- **Removals present economic, environmental and social opportunities and risks.** A rapid scale-up of removals is essential to achieve EU climate objectives, but all removal methods face challenges in scaling up as well as environmental, economic and resource-use related risks and opportunities. These side effects are complex and interlinked, typically depending on the context and scale of deployment.

- **Removals are affected by climate impacts, while contributing themselves to climate adaptation.** There are adaptation gains and losses linked to different removal methods contingent on specific design and implementation. Some, such as those based on nature restoration, have fewer vulnerability and exposure trade-offs and are generally better accepted by the public than geologically based methods.

- **Temporary removals face reversal risks, while presenting economic and environmental opportunities.** Practices that provide temporary removals or reduce emissions in the LULUCF sector can offer synergies with ecosystem restoration and income diversification opportunities, if well managed. However, these face higher reversal risks, and may require large land use changes, with potential implications for food security and resource availability. Environmental risks exist if they are poorly implemented or scaled up unsustainably.

- **BECCS and DACCS offer permanent storage, with limitations on readiness, infrastructure and biomass availability.** Removals based on CCS technologies (BECCS, DACCS) offer permanent carbon storage in geological reservoirs, but will need to address lifecycle emissions, moderate-level technological readiness, infrastructure needs and public acceptance. There are economic opportunities as well as risks relating to high resource use and, in the case of BECCS, significant risks from land use impacts.

- **Biochar can offer long-term storage, but remains uncertain**. The stability of biochar in the soil could offer the potential for long-term carbon storage, although this is still uncertain due to a lack of large scale, long duration studies. Biochar could also create potential opportunities for environmental and food productivity in certain contexts.

- **More research is needed on enhanced weathering and ocean-based removals.** Enhanced weathering could provide removals with environmental and food productivity benefits but is at a low level of readiness and net removals could be affected by energy and transport demands. Ocean fertilisation and ocean alkalinity enhancement methods are at a low-level of readiness, face legal barriers to deployment, and impacts of deployment at scale are highly uncertain. More research is needed on these novel methods.

3.1 Overview of opportunities and risks

To sustainably scale up removals, policies need to address opportunities, risks and challenges associated with removals, including both side-effects associated with removals in general, and those that are specific to individual removal methods.

While there is a need for removals to achieve EU and global climate objectives as presented in Chapter 1, different removal methods present a range of environmental, societal, economic, technological and implementation risks (IPCC, 2022e; Smith et al., 2024; Schäfer et al., 2015; Williamson, 2016), which may have impacts on societal well-being and can become barriers to implementation if not addressed. However, some removal methods – particularly those associated with the land sector and ecosystems – present opportunities and can deliver cross-cutting benefits if well implemented and managed. This chapter broadens the overview of removal methods presented in Chapter 2 with an overview of these wider risks and opportunities (Table 3). This assessment draws from the available literature and the available cross-cutting assessments (see, for example, (IPCC, 2022j, 2022e; Fuss et al., 2018), referenced throughout the chapter. This is structured around three overarching spheres of effects, based on a taxonomy defined by (Prütz et al., 2024) of the side effects of CO_2 removals:

1. **environmental and human health** – potential impacts relating to climate, air, water and soil quality, water resources and biodiversity;
2. **economic prosperity and well-being** – potential impacts on energy, food and land resources, as well as on markets and prices (e.g. costs, jobs, living conditions and welfare);
3. **implementation challenges** – including on MRV and effective policy.

Table 3 Opportunities, risks and implementation challenges associated with the scale up of removals

	Afforestation reforestation	Improved forest	Agroforestry	Soil carbon sequestration	Wetland and peatland	(Coastal) blue carbon	Biochar	Enhanced weathering	BECCS	DACCS	Ocean fertilisation	Ocean alkalinisation
Climate effects												
Risk of reversibility	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities
Performance risks	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Highly context dependent (some risks)	Generally significant opportunities	Highly context dependent (significant risks)	Generally significant risks	Uncertain or mixed impacts	Uncertain or mixed impacts
Net removal effect	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally some risks	Generally some risks	Highly context dependent (some risks)	Generally some risks	Highly context dependent (significant risks)	Generally some risks	Uncertain or mixed impacts	Uncertain or mixed impacts
Environmental effects												
Soil	Highly context dependent (significant opportunities)	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities			Generally some opportunities	Generally some opportunities	Highly context dependent (significant risks)			
Water	Highly context dependent (significant opportunities)	Generally significant opportunities	Generally significant opportunities	Highly context dependent (some opportunities)	Generally significant opportunities		Generally some opportunities	Generally some opportunities	Highly context dependent (significant risks)	Uncertain or mixed impacts	Uncertain or mixed impacts	Uncertain or mixed impacts
biodiversity	Highly context dependent (significant opportunities)	Generally significant opportunities	Generally significant opportunities	Highly context dependent (some opportunities)	Generally significant opportunities	Generally significant opportunities	Uncertain or mixed impacts	Generally some risks	Highly context dependent (significant risks)		Generally significant risks	Generally significant risks
Climate adaptation	Highly context dependent (significant opportunities)	Generally significant opportunities	Highly context dependent (significant opportunities)	Highly context dependent (significant opportunities)	Generally significant opportunities	Generally significant opportunities	Highly context dependent (some opportunities)	Generally some opportunities	Uncertain or mixed impacts			Generally some opportunities
Food, resource, and economic effects												
Land	Highly context dependent (significant risks)				Highly context dependent (significant risks)				Highly context dependent (significant risks)	Highly context dependent (some risks)		
Food	Highly context dependent (significant risks)				Highly context dependent (significant risks)		Highly context dependent (some opportunities)	Generally some opportunities	Highly context dependent (significant risks)		Uncertain or mixed impacts	Uncertain or mixed impacts
Energy resources	Generally significant opportunities	Generally some opportunities					Generally some risks	Generally some risks	Generally significant opportunities	Generally significant risks	Generally some risks	Generally some risks
Material resource	Generally significant opportunities	Generally some opportunities	Generally some opportunities		Generally some opportunities		Generally some risks		Generally significant risks	Generally some risks		
Income diversification	Generally significant opportunities	Generally some opportunities	Generally significant opportunities	Generally some opportunities	Generally some opportunities							
Implementation barriers												
MRV	Few barriers	Few barriers	Some barriers	Some barriers	Some barriers		Some barriers	Significant barriers	Some barriers	Few barriers	Significant barriers	Significant barriers
Technology readiness	**8-9**	**8-9**	**8-9**	**8-9**	**8-9**	**2-3**	**6-7**	**3-4**	**5-6**	**6**	**1-2**	**1-2**
Infrastructure	Few barriers	Few barriers	Few barriers	Few barriers	Few barriers		Generally some opportunities	Generally some opportunities	Significant barriers	Some barriers		
Acceptance and legal barriers	Some barriers	Few barriers	Some barriers	Few barriers	Some barriers	Few barriers	Some barriers	Some barriers	Significant barriers	Significant barriers	Significant barriers	Significant barriers

Effects

Generally significant opportunities	(dark blue)
Generally some opportunities	(light blue)
Uncertain or mixed impacts	(grey)
Generally some risks	(yellow)
Generally significant risks	(orange)

Not applicable or negligible	(blank)
Highly context dependent	(hatched)

Implementation barriers

Few barriers	(dark blue)
Some barriers	(yellow)
Significant barriers	(orange)

Source: Advisory Board from multiple sources, see methodology.

Notes: Assessments of the risks, opportunities and barriers facing the removal methods are intended as indicative assessments. These are based on the available evidence, as outlined in this chapter, although in many cases the potential impacts are complex and dependent on the numerous factors, making it difficult to generalise. The availability of evidence also differs between methods, with more evidence on established methods with a longer history (e.g. land sector removals) than more novel methods (e.g. the ocean-based methods). TRLs as assessed by the IPCC are also shown, with higher TRLs indicating technologies with higher technological and commercial maturity.

The side effects of removals are complex and dependent on multiple factors, which in many cases can be fully assessed only on a case-by-case basis. Effects can also depend heavily on the extent to and the approach with which removal methods are scaled; with considerable uncertainty on the effects of more novel methods (e.g. ocean-based methods), with limited field evidence available to assess effects at scale. Assessing effects in isolation can also lead to inaccuracies given the interlinked nature of different ecosystem services (e.g. water, soil, biodiversity) and associated potential benefits (e.g. farming, adaptation potential), the interactions of which are difficult to generalise. As a result, this chapter aims to signal the broad effects and implementation challenges that are prominent in the literature but does not seek to provide an exhaustive assessment.

3.2 Effects on the environment and human health

3.2.1 Climate

3.2.1.1 Removal performance and secondary emission effects

Removals in the land sector show significant potential but are primarily limited by lower storage duration and reversal. Overall performance may also be affected by non-CO_2 and biophysical effects.

As explained in Section 2.2.1, carbon stored in soils and biomass face a high risk of reversal, which can come from deliberate action and land use change decisions like deforestation or peatland drainage, or by changes to or cessation of management practices necessary to maintain carbon stocks (IPCC, 2023b). In addition to the stored CO_2 being released, reversals could also result in an increase in methane and nitrous oxide emissions, for instance resulting from land being converted for agricultural use or from wildfires (IPCC, 2022j). Closely linked to this is demand for biomass, regarding which various authors have highlighted the pressures from harvesting and bioenergy demand on carbon storage in the land sink, particularly in the short- to medium-term (EEA, 2023e; Jonsson et al., 2021).

The exact nature of CO_2 and non-CO_2 fluxes from wetland and peatland restoration can vary over time and across sites and climates, but in the short term, rewetting generally significantly reduces GHG emissions and the continued loss of stored carbon. Restored peatlands can initially emit more methane, which may result in a temporary net increase in GHG, though this is generally assumed to be a transient phenomenon that is quickly outweighed by greater emission reductions (Bacon et al., 2017). The time it takes for the net sink function to be fully re-established is uncertain, with some evidence suggesting a timescale of several decades (Bacon et al., 2017; Escobar et al., 2022; Humpenöder et al., 2020). While this means that rewetted organic soils generally remain net emitters of GHGs following rewetting in the mid-term (mostly due to increased methane emissions), overall GHG emissions are generally lower compared to their previous drained state, making wetland restoration an important mitigation strategy. Soil carbon sequestration may also trigger higher emissions of nitrous oxide from the soil, which could reduce the net GHG removal effect (Kelley et al., 2024).

Beyond the carbon effects, forests also play a role in local and global temperature regulation due to evapotranspiration, surface roughness, and albedo effects, meaning that large land use changes (e.g. from grassland to forests) can affect temperatures in uncertain and potentially even counterproductive ways (IPCC, 2021). Afforestation in the tropics provides a ‘win-win’ in terms of temperature by inducing both local and global cooling effects, while it can have a warming effect in boreal zones due to its influence on albedo (related to snow cover). There is significant uncertainty about the relative influence of these factors in temperate zones (Perugini et al., 2017; Pongratz et al., 2021). The effects of large-scale afforestation in the EU are therefore likely to be context dependent.

Removals using CCS technologies offer permanent storage if well-managed, though lifecycle emissions and their impact on net removals can be significant.

The lifecycle emissions of BECCS remain uncertain and, depending on how it is deployed may not lead to net-negative emissions, with the scale and source of biomass as well as efficiency of bioenergy conversion processes being a key consideration (Fajardy and Dowell 2017; Tanzer and Ramírez also 7.3). Lifecycle emission impacts from bioenergy are complex and context specific, depending on factors such as the source of biomass, conversion pathways, energy used for processing and transport of biomass, land use changes, the assumed analysis boundary and the time scale considered. Land cover change driven by the production of biomass for BECCS may cause albedo changes that impact the overall effectiveness of these mitigation strategies (Fuss et al., 2018; IPCC, 2022j).

As a result, lifecycle emissions from bioenergy production are uncertain and whether they can be considered carbon neutral is debated in the literature (IPCC, 2023d). BECCS also requires the transportation of captured CO_2 to a suitable storage site, with the potential for significant indirect emissions depending on the method of transportation (e.g. by boat or pipeline) and proximity to the storage site (Fajardy and Dowell, 2017). This uncertainty in life-cycle emissions of BECCS has led some to argue that the science does not support the conversion of existing large-scale forest biomass power stations to BECCS (EASAC, 2022a). Instead, deployment should initially focus on small-scale BECCS trials in which life-cycle emissions are minimised. The efficiency and environmental impacts of DACCS on the other hand, are heavily dependent on the carbon intensity of the electricity and heat energy input, along with other life-cycle assessment considerations (IPCC, 2022e). Both BECCS and DACCS require the storage of $CO_{2,}$ e.g. in geological reserves, where there is a risk of leakage of CO_2. Estimates of leakage risks suggest that realistically well-regulated storage is reliable and leakages are very unlikely (Alcalde et al., 2018; Daniels et al., 2023). However, studies caution that more direct experience is needed to derive reliable statistics on containment certainty over long periods of time, with limitations in the laboratory studies and simulations often used (Daniels et al., 2023; Gholami et al., 2021).

The mitigation and cost-effectiveness of removal methods using CCS technologies hinge on achieving an efficient carbon capture rate, which is subject to uncertainty. Small reductions in the carbon capture rate can have large impacts on the cost of removals, the amount of physical infrastructure required to deliver the same level of removals, and energy inputs needed (i.e. biomass for BECCS, heat and electricity for DACCS) (Broad et al., 2021). CCS demonstration plants typically assume a carbon capture rate of 90 percent, which is also often assumed for BECCS projects in IAMs (IEAGHG, 2019; Quiggin, 2021; Holz et al., 2021). However, reported capture rates have fallen short of the 90% capture rate (IEEFA, 2022; WRI, 2023). There is also a trade-off between carbon capture efficiency and the power produced by a BECCS-to-power facility, as the CCS equipment requires energy. Research and development trials at a UK facility indicate that this energy penalty, if not improved, would reduce the overall efficiency (i.e. the ratio of useful energy output to the energy input from the biomass fuel) of BECCS-to-power facilities to well below the efficiencies assumed within some IAMs (EASAC, 2022a). The literature on the carbon capture rate of DACCS is scarce, therefore it is not yet clear what role this uncertainty might play in DACCS performance.

Biochar offers promising long-term storage potential, but its performance is context specific and large-scale field studies of biochar addition to soils are needed to assess its potential.

The stability of biochar in the soil has been noted in the literature, which could offer the potential for long-term storage, but these effects can depend on the interactions of biochar types, soil types, environmental and management conditions (Fuss et al., 2018). Biochar can store carbon dioxide from decades to thousands of years, depending on feedstock, production conditions, and interaction with clay minerals and organic matter. In addition, the application of biomass to soil can in some cases lead to additional mitigation benefits by reducing the mineralisation of soil organic matter and newly added plant carbon (IPCC, 2022e). Studies have also shown that the application of biochar can reduce methane and nitrous oxide emissions, such as from soils (Joseph et al., 2021) and when applied to compost (Agyarko-Mintah et al., 2017; Wu et al., 2017). However, large-scale field studies of biochar addition to agricultural soils are still lacking, making its status as a permanent removal method more uncertain (Fuss et al., 2018). Further research is needed for biochar to demonstrate the ability to securely store CO_2 permanently without human intervention (Allen et al., 2024).

Land cover change driven by the production of feedstocks for biochar may cause albedo changes that impact the overall effectiveness of these mitigation strategies (Fuss et al., 2018; IPCC, 2022j). It has been suggested that biochar application can also darken soil, resulting in direct albedo changes, that could reduce biochar's overall mitigation potential; however, the extreme rates of application required make this an unlikely scenario. Potentially unfavourable albedo change can also be minimised by incorporating biochar into the soil (Fuss et al., 2018).

Enhanced weathering and ocean-based removal methods are not well understood in real-world conditions and require further research to assess their potential and risks.

As presented in Chapter 2, the literature has highlighted potentially large volumes of removals from methods like enhanced weathering and ocean alkalinity enhancement. However, to date enhanced weathering and ocean alkalinity enhancement have only been tested in small-scale field and lab studies (IPCC, 2022e). Key uncertainties about actual field weathering rates can make exact quantification challenging . The net effect of these removal methods can be called into question under some circumstances. In particular, the energy demand used to grind rocks to a suitable size, and to transport these to application sites may limit or even cancel out removals under certain conditions (Rigopoulos et al., 2018; Rinder and von Hagke, 2021; Meysman and Montserrat, 2017; Honegger et al., 2021b). For ocean alkalinisation, there are uncertainties in how the anthropogenic addition of alkalinity interacts with natural alkalinity, which may further reduce the net effect of these methods (Bach, 2024).

Ocean fertilisation appears technologically feasible, and the enhancement of photosynthesis and CO_2 uptake from surface waters is confirmed by several field experiments conducted in different areas of the ocean. Yet there is scientific uncertainty about the proportion of newly formed organic carbon that is transferred to the deep ocean, resulting in CO_2 storage, and about the longevity of storage (IPCC, 2022e). The efficiency of ocean fertilisation also depends on the region and experimental conditions, especially in relation to the availability of other nutrients, light and temperature. There is some evidence that ocean fertilisations can in fact increase methane and nitrous oxide emissions, during the subsurface decomposition of sinking particles, and lead to toxic algae blooms, driven by nutrient changes and deoxygenation with consequences for human health and livelihoods (IPCC, 2022e).

3.2.1.2 Climate impacts

The expected impacts of climate change could reduce the efficacy of some removal methods, particularly in the land sector, due to weaker sequestration or storage capacity, and higher risk of reversal events. However, there are also opportunities to help adapt to climate impacts through the implementation of some removal methods.

Europe's agriculture and forests face substantial climate risks in Europe as a whole and are at critical risk levels in southern Europe. Climate change can exacerbate periods of excessive heat and drought, wildfires, pests and diseases, and contribute to changing meteorological conditions (EEA, 2024a).This can affect the capacity of biomass and soils to absorb and store CO_2, and may indeed turn them into carbon sources (IPCC, 2022j). As Chapter 2 highlights, this also creates risks for the integrity of carbon pricing if removals do not reflect the costs associated with reversal (Edenhofer et al., 2024a).

The direct and indirect impacts of climate change could also constrain the availability of biomass for removals (which as explained in Chapter 2 will require significant land resources) and lead to land carbon losses (Table 4). While there are some agricultural opportunities derived from a changing climate this has generally led to losses in the European agriculture and forestry sectors. For example, severe and frequent droughts have negatively affected forest growth and stability. Such events have caused habitat loss, local species migration, the spread of invasive alien species and contributed to forest fires (EEA, 2023e).For people whose livelihoods rely on these sectors, income loss from reduced yields and increasing costs from climate hazards erodes their capacity to cope with further impacts in the future. To the extent that different removal methods compete for land with each other, there is a risk that changing land configurations expose sectors of the population to hazards they are less familiar with. Likewise, forest management practices that increase the capture and storage of CO_2, such as leaving deadwood on the forest floor, increase the chances of pest and disease outbreaks, and increase fuel load during wildfires.

There are also opportunities for removal methods in the LULUCF sector to provide adaptation benefits. Studies show that there are opportunities for synergies but outcomes depend on context, design and implementation, to minimise adverse effects (Kongsager, 2018; IPCC, 2022e). There are opportunities for climate-smart forestry approaches, which provide both mitigation and adaptation benefits (IPCC, 2022e). Adaptation opportunities are further elaborated in Section 3.2.3.

Table 4 Opportunities and risks relating to climate effects of the scale-up of removal methods

	Afforestation reforestation	Improved forest	Agroforestry	Soil carbon sequestration	Wetland and peatland	(Coastal) blue carbon	Biochar	Enhanced weathering	BECCS	DACCS	Ocean fertilisation	Ocean alkalinisation
Climate effects												
Risk of reversibility	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant risks	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities
Performance risks	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally some risks (highly context dependent)	Generally significant opportunities	Generally significant risks (highly context dependent)	Generally significant risks	Uncertain or mixed impacts	Uncertain or mixed impacts
Net removal effect	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities	Generally some risks	Generally some risks	Generally some risks (highly context dependent)	Generally some risks	Generally significant risks (highly context dependent)	Generally some risks	Uncertain or mixed impacts	Uncertain or mixed impacts

Effects

- *Generally significant opportunities*
- *Generally some opportunities*
- *Uncertain or mixed impacts*
- *Generally some risks*
- *Generally significant risks*
- *Not applicable or negligible*
- *Highly context dependent*

Source: Advisory Board from multiple sources, see methodology.

Notes: Assessments of the risks, opportunities and barriers facing the removal methods are intended as indicative assessments. These are based on the available evidence, outlined in this chapter, although in many cases the potential impacts are complex and dependent on the numerous factors, making it difficult to generalise. The availability of evidence also differs between methods, with more evidence on established methods with a longer history (e.g. land sector removals) than more novel methods (e.g. the ocean-based methods).

3.2.2 Environment

The deployment of some CO_2 removal methods at a large scale or in certain contexts can affect, directly and indirectly, ecosystems and the services that they provide.

Ecosystems like forests, wetlands, and agricultural lands provide a range of services and public and private goods, which can be both enhanced and harmed by the deployment of some CO_2 removal methods at a large scale or in certain contexts. This section gives an indication of the potential effects of scaling up CO_2 removal methods on water, soil and biodiversity, the most extensively studied environmental risks and opportunities. Adaptation, human health, and wellbeing are also considered as these are closely linked to environmental effects. The effects of large-scale land use change and of the deployment of removals are often context dependent, with mixed conclusions regarding the nature of the effect (Prütz et al., 2024).

3.2.2.1 Water and soil

There are opportunities and risks in terms of water and soil effects associated with most removal methods, with the effects often being context dependent.

Forests can reduce run-off into watercourses, reducing pollutants and providing flood regulation as a result of their own consumption, vegetative structure and effects on soil permeability. Consequently, afforestation and reforestation activities have the potential to improve water regulation and protect against soil erosion. Afforestation and reforestation can present both risks and opportunities, with evidence that well planned measures can address land degradation and desertification, while poorly planned ones can instead lead to localised trade-offs, such as, reduced water yield (IPCC, 2023b). The effects of vegetation on water infiltration though are conditioned by the species and the soil profile; rapid-growth tree species that can help accelerate the implementation of sinks for removal purposes may present trade-offs in water and soil regulation potential (Whitehead, 2011).

The effects of dedicated biomass production for BECCS and biochar would likely be similar with opportunities and risks depending on local factors such as the type of energy crop, management practice, and previous land use (IPCC, 2023b, 2022j). Dedicated biomass production can offer opportunities, but, as deployment scales up, the negative effects will eventually outweigh the positive ones though it is not possible to determine precisely at what scale (IPCC, 2023b). Restoring wetlands can improve water quality and availability (Nagelkerken et al., 2008).

The application of biochar and enhanced weathering have both been shown to have beneficial effects on soil and water. Both methods can improve water retention, nutrient availability and modify the soil pH resulting in improved soil health. In turn, this can provide protection from soil erosion and improve plant growth. The application of biochar has also been shown to reduce heavy metal pollution, a hazard to the environment and human health (Ibrahim et al., 2022). However, studies have also highlighted the environmental risks to soil and water, depending on the feedstock used to produce biochar. While some studies conclude that the risk of negative environmental impacts is relatively low, there are uncertainties on the environmental impacts associated with the wider application of biochar (Tisserant et al., 2023; Xiang et al., 2021). The application of enhanced weathering generally offers opportunities for soil and water health (e.g., counteracting soil acidification), although the risk of adverse water and soil effects have also been identified. The application of enhanced weathering to soils could cause release of heavy metals into groundwater, river water and coastal zone water, along with marine environments in the case of ocean alkalinity enhancement (Fuss et al., 2018). Mining activities for the materials in particular could adversely affect local water quality from heavy metal contamination.

Ocean alkalinity enhancement has similar risks and opportunities to enhanced weathering, with opportunities for water health (e.g. counteracting ocean acidification) along with risks (e.g. release of heavy metals affecting marine environments). The environmental risks from ocean fertilisation are complex, but accelerating the growth of phytoplankton could increase acidification (Cao and Caldeira, 2010) and patches of ocean oxygen depletion (Russell et al., 2012). Both methods require substantial materials, and mining activities are associated with adverse effects on water and soil (Younger et al., 2004; Honegger et al., 2021a).

The CCS-based removal methods risk increasing demand for water resources and reducing water availability. Large-scale deployment of BECCS risks significantly increase demand for water, for use in capturing carbon and storing it, and indirectly from the production of biomass, with water use varies by type of biomass (Smith, 2016; IPCC, 2022k; Wu and Zhai, 2021). DACCS systems also need substantial amounts of water and could reduce water availability (Fasihi et al., 2019), although the water use is substantially less than in BECCS systems (Smith et al., 2016a). Increased water use from DACCS could be offset with some DACCS designs that can potentially remove more water from the ambient air than needed for regeneration, delivering a surplus of water that could be beneficial in arid regions (Sandalow et al., 2018; Fasihi et al., 2019). The inadvertent release of CO_2 from geological storage could also affect groundwater chemistry and drinking water sourced from local groundwater wells (Honegger et al., 2021a; Wilkin and Digiulio, 2010).

3.2.2.2 Biodiversity

Removal methods in the LULUCF sector can have beneficial and adverse effects for biodiversity, with the effects depending on the context, although methods that enhance natural ecosystems generally offer positive opportunities if well managed.

Practices to increase carbon sequestration and storage in existing forests are generally associated with benefits for biodiversity, particularly through lengthened rotations, reduced disturbance and continuous cover management (Verkerk et al., 2022; Assmuth et al., 2024). The effects of afforestation are generally more context dependent: afforestation has been highlighted as an opportunity to improve biodiversity on degraded, abandoned or intensively-farmed agricultural land with low species richness, although specific risks have been identified in relation to species-rich grasslands and intact peatlands where afforestation could displace endemic species (Verkerk et al., 2022; Woziwoda and Kopeć, 2014). Tree composition is also significant; although historically preferred in Europe for fast-growing plantations, coniferous monoculture forests generally support lower levels of biodiversity and are less resilient to biological threats than mixed forests (Huuskonen et al., 2021). Agroforestry systems can increase biodiversity in agricultural ecosystems, although this depends on the diversity at the baseline and the choice of species in the system (Sollen-Norrlin et al., 2020; Torralba et al., 2016).

Healthy terrestrial and coastal wetlands are home to a variety of species, particularly flora, birdlife, amphibia, fish and insects, many of which are uniquely adapted to wetland habitats and are increasingly threatened due to habitat loss drainage and exploitation (Gopal, 2009). Peatland and wetland restoration would therefore provide important biodiversity benefits, particularly in locations where it is still possible to restore normal hydrological functions (Woziwoda and Kopeć, 2014).

The production of biomass, for biochar and BECCS, is associated with important risks to biodiversity, but these depend on the context and the scale of land use change. For instance, planting bioenergy crops on degraded land can increase biodiversity, while intensive agricultural practices to maximise the biomass yield may have significant negative ecosystem effects. It is unclear at what scale negative impacts outweigh the benefits with bioenergy for BECCS (IPCC, 2023b). The literature on the effects of DACCS on biodiversity tends to estimate fewer trade-offs than with BECCS. To the extent that these arise, they are linked to higher land demand if DACCS is coupled with renewable energy sources and power-to-X units than for natural sinks (Ekardt et al., 2023).

There is a high degree of uncertainty on the biodiversity effects of enhanced weathering, ocean alkalinity enhancement and ocean fertilisation, with opportunities and risks.

Significant questions remain regarding the potential impacts of ocean-based removals for marine biodiversity, with evidence of mixed effects. Ocean alkalinity enhancement has been highlighted as having a potential beneficial impact on biodiversity (e.g., for coral reefs or shellfisheries) by counteracting ocean acidification (Feng et al., 2016; Mongin et al., 2021; Meysman and Montserrat, 2017). However, it could also have adverse effects by creating perturbations in marine ecosystems (Bach et al., 2019) (Hartmann et al. 2013). There is also a high degree of uncertainty on the effects of the dissolution of the materials and the potential effect on local marine life (Bach et al., 2019; Meysman and Montserrat, 2017; Montserrat et al., 2017); few studies are available and mostly limited to single species (IPCC, 2022e). In addition, the mining of minerals used for this method (and for enhanced weathering), could also have large local impacts on ecosystems or species (IPCC, 2022j).

Ocean fertilisation aims to promote phytoplankton stocks by introducing nutrients to the subsurface, which could provide food larval or juvenile fish in subsurface waters. However, there is not enough evidence to assess this and the impact of ocean fertilisation is uncertain. The potential impacts of this method on food web structure are complex, with possible adverse effects leading to anoxia (i.e. oxygen depletion) in subsurface water and to an increase in potentially toxic species of diatoms (a type of phytoplankton) (IPCC, 2022e; GESMAP, 2019).

3.2.3 Adaptation, health and well-being

3.2.3.1 Climate adaptation

The externalities of some removal methods can support climate adaptation, increasing the resilience of people and ecosystems to climate hazards, such as droughts, floods and ocean acidification. Yet, the role of removals also presents trade-offs for adaptation.

We have already noted in this chapter that the various removal methods come with associated risks, including the creation of new hazards (e.g. algal blooms), the potential increase in magnitude of existing hazards (e.g. wildfires) and the fact that scaled-up deployment may shift the configuration of these hazards towards populations who may be less familiar with them and hence less adapted to them. Beyond these risks from specific methods, the large-scale introduction of removals may interact with adaptation goals in conflicting ways, as presented in Chapter 7 for the LULUCF sector (Table 5). However, many of the environmental effects mentioned above also have potential climate adaptation benefits. It is important to note that the balance of gains and losses for adaptation depends on the way the specific removal projects are designed and implemented, and for certain of the removal methods evidence on the consequences of implementation is still limited or hypothetical.

As noted in Section 3.2.2, on the ecological vulnerability side, afforestation, reforestation and agroforestry systems present opportunities to protect against soil erosion and land degradation and improve flood regulation. This can help areas exposed to climate pressures (e.g. drought, flooding) to become more resilient. For instance, studies show that agroforestry systems are generally more beneficial in regions subject to environmental pressures like poor soil health, drought or heat stress (especially in southern Europe) (Kay et al., 2019; Torralba et al., 2016). The biophysical effects of afforestation can also reduce the frequency of climate extremes, such as heat waves (IPCC, 2022j). Net biophysical effects on regional climate from afforestation are seasonal and can reduce the frequency of climate extremes, such as heat waves, improving adaptation to climate change and reducing the vulnerability of people and ecosystems. The impacts of climate extremes and heatwaves can be particularly severe in urban areas, although trees, urban forests and vegetation can counteract some of these local temperature (urban heat island) effects (IPCC, 2023f). The use of biochar can provide adaptation benefits by enhancing yields, although the effects are weaker in temperate zones, and it can counteract desertification and land degradation by improving soil water retention and nutrient use, and reduce heavy metal pollution (IPCC, 2022j).

On the social vulnerability side, in a review of adaptation practices, Reckien et al. (2023) found nature restoration and other ecosystem-based approaches to be among the measures with the highest adaptation potential, assessed in terms of the extent of people for whom exposure or vulnerability to climate hazards could be reduced (>5 billion worldwide) and with fewer trade-offs. New sources of income (e.g. fibre, biochar, market placement of regenerative agriculture), provision of goods and services (e.g. food, local/cheaper sources of energy), livelihood diversification within sector (e.g. agroforestry, recreation in forestry), increased local capacities (e.g. organising forest stewardship, access to extension networks, training in monitoring and new management practices) and increased buffers from hazards (e.g. alley cropping) can help enhance the resilience of people in these sectors to specific hazards (Buck et al., 2020). However, there may be winners and losers in shifting economies: as some livelihood opportunities arise, others may be adversely affected. For example, smallholder farmers may have fewer means to adopt agroforestry or other soil conservation practices than large farms, which can increase the difference in relative vulnerability between groups.

Healthy terrestrial peatlands and wetlands can also play an important role in reducing downstream flood risks (Maltby and Acreman, 2011), while restoration of coastal wetlands is especially important for providing protection from coastal erosion, rising sea levels and storm events (IPCC, 2022j). Ocean alkalinity enhancement could also counteract ocean acidification driven by climate change (Feng et al., 2016; Mongin et al., 2021; Meysman and Montserrat, 2017). Bulk materials from weathering and ocean alkalinity enhancement can also be used for coastal fortification as a way to attenuate coastal erosion (Buck et al., 2020), thus reducing people’s exposure.

Healthier ecosystems may increase agricultural yields, and greater access to nature could improve human health and well-being, but there are also risks from adverse effects on ecosystems, dust pollution and mining activities.

Beyond farmers and foresters who may benefit directly from more stable and potentially increased yields and reduced direct exposure to hazards, adaptation benefits of land removals are distributed to the wider population via ecosystem services (Quandt et al., 2023). Human health and well-being will be affected to varying degrees by the climate, environmental and adaptation effects covered in this section. Given the potential for both positive and negative effects, often highly dependent on context-specific factors, it is difficult to generalise the effect on human health and wellbeing. Human well-being will also be affected by the impact of removal methods on economic prosperity and food supply, which are elaborated in the next section.

Regarding other removal methods, air quality could be negatively affected by the spreading of rock dust from enhanced weathering (Edwards et al., 2017) although this can partly be ameliorated by water-spraying (Grundnig et al., 2006). While uncertain, both methods relying on CCS may be associated with air emissions and could increase noise pollution (EEA, 2011; Pett-Ridge et al., 2023).

Table 5 Opportunities and risks relating to environmental effects of the scale-up of removal methods

	Afforestation reforestation	Improved forest	Agroforestry	Soil carbon sequestration	Wetland and peatland	(Coastal) blue carbon	Biochar	Enhanced weathering	BECCS	DACCS	Ocean fertilisation	Ocean alkalinisation
Environmental effects												
Soil	Generally significant opportunities (highly context dependent)	Generally significant opportunities	Generally significant opportunities	Generally significant opportunities			Generally some opportunities	Generally some opportunities	Generally significant risks (highly context dependent)			
Water	Generally significant opportunities (highly context dependent)	Generally significant opportunities	Generally significant opportunities	Generally some opportunities (highly context dependent)	Generally significant opportunities		Generally some opportunities	Generally some opportunities	Generally significant risks (highly context dependent)	Uncertain or mixed impacts	Uncertain or mixed impacts	Uncertain or mixed impacts
Biodiversity	Generally significant opportunities (highly context dependent)	Generally significant opportunities	Generally significant opportunities	Generally some opportunities (highly context dependent)	Generally significant opportunities	Generally significant opportunities	Uncertain or mixed impacts	Generally some risks	Generally significant risks (highly context dependent)		Generally significant risks	Generally significant risks
Climate adaptation	Generally significant opportunities (highly context dependent)	Generally significant opportunities	Generally significant opportunities (highly context dependent)	Generally significant opportunities (highly context dependent)	Generally significant opportunities	Generally significant opportunities	Generally some opportunities (highly context dependent)	Generally some opportunities	Uncertain or mixed impacts			Generally some opportunities

Effects

Generally significant opportunities	dark blue
Generally some opportunities	light blue
Uncertain or mixed impacts	grey
Generally some risks	yellow
Generally significant risks	orange
Not applicable or negligible	blank
Highly context dependent	hatched

Source: Advisory Board from multiple sources, see methodology

Notes: Assessments of the risks, opportunities and barriers facing the removal methods are intended as indicative assessments. These are based on the available evidence, outlined in this chapter, although in many cases the potential impacts are complex and dependent on the numerous factors, making it difficult to generalise. The availability of evidence also differs between methods, with more evidence on established methods with a longer history (e.g. land sector removals) than more novel methods (e.g. the ocean-based methods)

3.3 Effects on economic prosperity and well-being

3.3.1 Land, food and resources

Large land use changes associated with afforestation and the production of biomass for BECCS and biochar may create risks for food production and security.

Climate change and food security are intrinsically interlinked; changes in temperatures and extreme weather events contribute to food insecurity at a the European and global levels (IPCC, 2023c). Although removals can therefore improve food security through their contribution to climate mitigation and managing temperature overshoot, large-scale deployment of certain removal methods can require large land use changes, with potential implications for food security and resource availability.

In particular, the potentially large land use changes associated with large-scale deployment of afforestation, BECCS and biochar could have negative impacts on food production and security without adequate measures to manage these risks (Doelman et al., 2020, 2019; Lee et al., 2019; IPCC, 2022k).

Although peatland restoration could have significant localised impacts in areas with larger shares of peatlands and organic soils under agriculture (Lloyd et al., 2023), the overall impact on EU-level food production is likely to be small, as organic soils only account for around 2% of the EU's agricultural area (ECA, 2021). Both risks and opportunities have been noted in relation to coastal wetlands preservation, including potential displacement of agriculture/aquaculture, but also greater protection of fishery stocks (IPCC, 2023b).

Compared with intensive agriculture, agroforestry will result in trade-offs in food production. In some cases, there is also evidence of productivity gains from agroforestry in European regions facing soil health and water availability challenges (Sollen-Norrlin et al., 2020; Kay et al., 2019; Torralba et al., 2016). Similarly, soil carbon sequestration does not usually displace existing agricultural production and can even have positive effects on yields (Fuss et al., 2018).

Several authors have highlighted the mitigating factor of dietary change in the availability of land for sequestration, with several scenarios showing that reduced livestock production and a greater shift to plant-based diets can free up land to enable greater deployment of removal methods like afforestation and BECCS (Doelman et al., 2020, 2019; Lee et al., 2019; Lehtilä et al., 2023). While these are changes that can be used to mitigate the land use pressure of removal methods, they would likely require enabling policies to materialise. Increasing crop yields and improved productivity also have the potential to free up land for carbon sequestration (Lee et al., 2019; Smith et al., 2016a).

Risks and opportunities for food production and yields have been highlighted for biochar and enhanced weathering on land. The effect of ocean-based removals on food supply are complex and subject to significant uncertainty and risks of adverse effects.

Biochar can have a wide range of positive and negative effects on crops yields depending on the soil, with a meta-analysis by Jeffery et al. (2011) finding a productivity increase of 10% on average. The application of biochar as a soil amendment can in some cases improve and stabilise soil carbon and rhizodeposits, increase the soil's water-holding capacity, increase the cycling of nutrients such as the fixation of nitrogen, and adsorb pollutants. The application of biochar could be particularly beneficial in sandy and acidic soils (IPCC, 2023b). Increasing crop yields can contribute to increasing the EU's food availability and security, reducing the impact of geopolitical interests on food prices. However, as noted, the benefits of biochar application are context dependent and on the feedstock used to produce biochar. If the feedstock is contaminated, so is the biochar. Hence, the quality of biochar is important, particularly if the technology is being scaled up. One study reports that the negative effects of biochar on soils from its current uses are relatively low (Tisserant and Cherubini, 2019).

Enhanced weathering can improve plant growth, although further research is required on the potential effects of the minerals in the field. Enhanced weathering can increase the pH, mineral supply, nutrient retention and availability, enhance soil carbon sequestration and protect against soil erosion. Increased yields can hence contribute to food security in the EU and reduce the pressure on land resources (IPCC, 2022e).

The effects of ocean fertilisation and ocean alkalinisation on food supply are highly uncertain and come with substantial risks. Ocean fertilisation could stimulate the fertilisation of phytoplankton, which could support larger organisms and contribute to increasing fish stocks. However, ocean fertilisation could alter local to regional food cycles in unpredictable ways, and comes with significant risks of perturbing food webs, causing deoxygenation and increasing the prevalence of toxic algae species with negative effects on human food supply (Fuss et al., 2018). Ocean alkalinisation can also have fertilising effects from the provision of minerals to biological systems, but similarly is subject to significant uncertainty and comes with risks of perturbation to the structure of marine ecosystems, and of releasing toxic trace metals from mined minerals (IPCC, 2022e). Further research is required to understand these potential impacts.

Removal methods in the LULUCF sector could create new opportunities for co-products, particularly for wood and bio-based resources.

Afforestation and reforestation can increase the availability of biomass for wood and other bio-based products. Wood products can both store carbon (potentially for longer storage durations when used in durable construction or other products), substitute for emission-intensive materials in manufacturing and construction, and contribute to the wider bioeconomy (Verkerk et al., 2020). Biomass converted to biochar has also been shown to have applications in products, for instance when added to concrete to lower the carbon footprint of concrete (Lin et al., 2023). However, the carbon sink in EU forests is under pressure from multiple factors, including wood demand. While there is ongoing debate on the role EU biomass policies have in driving the observed decline, increased harvesting for wood products could have trade-offs with other environmental dimensions (Advisory Board, 2024). In the longer-term, other authors have suggested that 'climate smart forestry' – an integrated planning approach to afforestation, sustainable and adaptive forest management and wood product substitution - could increase the size of the overall forest/harvested wood product sink, while also increasing the availability of wood products that could displace other emission-intensive products (Verkerk et al., 2020; Nabuurs et al., 2017).

Although wetland and peatland restoration is not compatible with conventional drainage-based agricultural practices, 'pluviculture' –the cultivation and harvesting of wetland crops like grasses or reeds – has been suggested as a way to create new income streams and preserve a 'productive' land use for rewetted peatlands (Tanneberger et al., 2021b). Other common co-products suggested in the literature include fibre, construction materials and bioenergy/biofuels. The potential for more novel products like insulation (which also provides carbon storage in products) (De Jong et al., 2021) or pharmaceutical components (Rowan et al., 2022) is the subject of research. However, exploiting these opportunities would require the development of viable business models, especially for more novel products and practices that currently lack mature markets and value chains. (Norris et al., 2021; Torralba et al., 2016; Lloyd et al., 2023). Agroforestry creates similar possibilities of supplying additional co-products such as fruit, nuts, timber and woodchips (Torralba et al., 2016; Kay et al., 2019).

With regard to EU energy resources, sustainably sourced BECCS could positively contribute to energy supply, while DACCS, enhanced weathering and ocean alkalinity enhancement could increase demand on the EU's limited energy resources.

Sustainably-sourced BECCS can present opportunities relating to the production of renewable energy, and hence contribute to the management of energy demand and supply in the EU. This applies to, for example, CCS combined with biomass-based district heating, or biomass-produced heat for industrial processes (e.g. cement kilns) (Pett-Ridge et al., 2023). Provided biomass is sustainably sourced and its use limited to activities with no or limited mitigation alternatives (see also Section 7.3), bioenergy production could contribute to reducing the use of and dependency on fossil fuel imports, with potential benefits in terms of reduced exposure to fossil fuel price fluctuations.

Current technologies for DACCS present a risk of competing for energy resources, as their process currently relies on a high level of energy consumption. One study estimated that capturing an amount equivalent to 5% of the EU's emissions in 1990, with a fully electric DACCS system, would require an additional 80–119 GW of onshore wind and 85–126 GW of PV (Lux et al., 2023). For comparison, in 2022 wind (onshore and offshore) and solar PV capacity for the EU-27 was 204 GW and 205 GW respectively (EC, 2025c). However, various direct air carbon capture technologies are still under development, and further technological developments might result in lower energy consumptions (Smith et al., 2024).

Enhanced weathering and ocean alkalinisation rely on the energy-intensive mining of mineral materials, and the energy demand is considered an important drawback of these methods (Rigopoulos et al., 2018; Rinder and von Hagke, 2021). Enhanced weathering can be achieved with silicate rocks such as basalt, but also with construction waste and waste materials from mining. The mining of minerals for enhanced weathering could significantly increase electricity use (IPCC, 2022e). The transport of minerals to deployment locations implies energy demand for transport, although for ocean alkalinisation this could be minimised by using existing marine activity (e.g. fishing). The production of biochar also implies some energy use for the heating process to produce it and for transport.

3.3.2 Costs and employment

Scaling up removals could create potential new opportunities for income diversification and economic development.

Income diversification opportunities have primarily been highlighted in the context of removals in LULUCF and on-farm removals, through incentive schemes and the sale of associated co-products. Income diversification is recognised as an important risk management strategy for farm households, as it reduces their exposure to variable market conditions and commodity price shocks (Table 6). Diversification strategies will also become relevant to future climate resilience, as climate change and extreme weather events increase the risk of crop losses and affect the availability and price of inputs (IPCC, 2022j).

In this context, removal methods in the LULUCF sector could provide economic opportunities to diversify incomes, both from direct payments and from supplementary co-products. However as described in Chapter 2, the opportunity cost in terms of land values and forgone agricultural productivity is one of the main drivers of financial viability, especially when it involves a large land use change, such as for afforestation (Grafton et al., 2021). In particular, loss of direct payments under the CAP – namely the exclusion of forestry and wetlands from the definition of an eligible agricultural area – and inconsistent rules regarding agroforestry have been highlighted as significant risks to farmers and as barriers to the deployment of these practices (Tanneberger et al., 2021b; ECA, 2021; Mosquera-Losada et al., 2018).

Beyond the potential for biomass production from afforestation and reforestation, there are economic opportunities from the increased manufacture and use of wood-based products. Forestry is an important sector in the European bioeconomy, supporting about 4.5 million jobs in primary production and downstream sectors like paper production and furniture manufacturing (EFI, 2021). Although there are economic opportunities from increased wood production and use, there are also trade-offs associated with rapid increases in biomass demand.

Increased demand for biomass production to support BECCS and biochar could contribute to new market opportunities, employment and economic diversification upstream (IPCC, 2022e). These new economic activities can require the development of supporting infrastructure, which could also benefit local communities near the operational sites (e.g. road, high-speed internet) (Pett-Ridge et al., 2023). Enhanced weathering could also provide employment opportunities for mining communities, though this will need to be carefully weighed against the potential for detrimental environmental impacts.

The realisation of these opportunities will depend on addressing both economic and social barriers to the adoption of removals.

Ensuring that removal practices in the LULUCF sector are financially attractive to farmers and landowners is a prerequisite for scaling up these methods. However, even when this is the case, other economic and social factors are likely to affect decision-making. Numerous studies from European countries have demonstrated that the combination of subsidies[8] and private forestry income can make afforestation a financially viable land use option, particularly when replacing low-productivity livestock farming systems. Yet afforestation rates in the EU have frequently underperformed targets even under profit-maximising conditions (Niskanen, 1999; Upton et al., 2013; Źróbek-Różańska et al., 2014; Hardaker, 2018; O'Neill et al., 2020). Reasons highlighted for this are the long-time lags (often decades) between forest establishment and harvest revenues (this can lead to cash-flow challenges, presented further in Chapter

[8] Although forestry is ineligible for direct payments under the CAP, Member States have put in place subsidy schemes - partly funded by the EU under the rural development pillar of the CAP - to encourage afforestation by farmers and landowners.

14); reluctance to commit to long-term land use change; and risk of future policy and funding changes (Źróbek-Różańska et al., 2014; Ryan et al., 2022). Farm size may also play a role; one study finds that smaller farms are less willing or able to commit the land required to achieve economies of scale (Duesberg et al., 2013).

Although many of these barriers and risks are likely to persist in the context of removals in the land sector, solutions to address these exist and are presented further in Chapters 4 and 13. While these may address financial viability barriers, uptake may also depend on wider economic and social considerations (Schirmer and Bull, 2014)). This is particularly true of methods that entail large-scale and permanent land use change, which represent a fundamental change in terms of lifestyle, heritage and personal identity (Howley et al., 2015).

The costs of permanent removal methods are currently estimated to be high, as explained in Chapter 2, and there is especially significant uncertainty about the current and future costs of technologies at a low level of technology readiness (Abegg et al., 2024). This uncertainty about the future costs and the lack of a business case providing a long-term outlook for investors is a barrier to deployment. The business case for removals might be hampered by a lack of policy incentives to enable the scale-up, as elaborated in Chapter 4. Where removals entail land use change, coordinated planning will be important to address trade-offs, which could act as a barrier, and to promote synergies, which could reduce costs and deliver positive environmental and adaptation externalities (IPCC, 2022e).

Table 6 Opportunities and risks relating to land, food, resources and income effects of the scale-up of removal methods

	Afforestation reforestation	Improved forest	Agroforestry	Soil carbon sequestration	Wetland and peatland	(Coastal) blue carbon	Biochar	Enhanced weathering	BECCS	DACCS	Ocean fertilisation	Ocean alkalinisation
Food, resource, and economic effects												
Land	Generally significant risks (highly context dependent)				Generally significant risks (highly context dependent)				Generally significant risks (highly context dependent)	Generally some risks (highly context dependent)		
Food	Generally significant risks (highly context dependent)				Generally significant risks (highly context dependent)		Generally significant opportunities (highly context dependent)	Generally some opportunities	Generally significant risks (highly context dependent)		Uncertain or mixed impacts	Uncertain or mixed impacts
Energy resources	Generally significant opportunities	Generally some opportunities					Generally some risks	Generally some risks	Generally significant opportunities	Generally significant risks	Generally some risks	Generally some risks
Material resource	Generally significant opportunities	Generally some opportunities	Generally some opportunities		Generally some opportunities		Generally some risks		Generally significant risks	Generally some risks		
Income diversification	Generally significant opportunities	Generally some opportunities	Generally significant opportunities	Generally some opportunities	Generally some opportunities							

Effects

Generally significant opportunities	dark blue
Generally some opportunities	light blue
Uncertain or mixed impacts	grey
Generally some risks	yellow
Generally significant risks	orange
Not applicable or negligible	blank
Highly context dependent	hatched

Source: Advisory Board from multiple sources, see methodology

Notes: Assessments of the risks, opportunities and barriers facing the removal methods are intended as indicative assessments. These are based on the available evidence, outlined in this chapter, although in many cases the potential impacts are complex and dependent on the numerous factors, making it difficult to generalise. The availability of evidence also differs between methods, with more evidence on established methods with a longer history (e.g. land sector removals) than more novel methods (e.g. the ocean-based methods)

3.4 Implementation challenges

3.4.1 Monitoring, reporting and verification

Monitoring, reporting and verification will be crucial to ensure the robustness of removals, but the methods to do this can be complex and are at different stages of development for different removal methods.

Transparent and robust MRV is crucial in order to scale up removal activities and ensure their contribution towards climate objectives. A lack of trust in MRV frameworks risks undermining confidence in removal methods, which could adversely affect investment, innovation and policy development (Mercer and Burke, 2023). In practice, robust MRV is complex with different methods needed at different stages of development and requiring different tools, instruments, and protocols, as seen in Table 7.

Table 7 Current state of key characteristics of monitoring, reporting and verification of removal methods

		Qualitative		Quantitative			
	Removal method	Ability to measure & quantify removals	Confidence in quantification	Share of academic literature	Protocol coverage	Protocol inter-connectedness	Regulatory oversight
Biological	Afforestation, reforestation, agroforestry, forest management	Dark blue	Blue	Dark blue	Dark blue	Blue	Blue
Biological	Bioenergy with carbon capture and storage	Dark blue	Dark blue	Light blue	Blue	Light blue	Dark blue
Biological	Biochar	Dark blue	Dark blue	Light blue	Light blue	Dark blue	Light blue
Biological	Peatland and coastal wetland restoration	Dark blue	Dark blue	Dark blue	Light blue	Light blue	Dark blue
Biological	Soil carbon sequestration in croplands and grasslands	Dark blue	Dark blue	Dark blue	Blue	Blue	Blue
Biological	Ocean fertilisation	Light blue	Light blue	Light blue			Light blue
Geochemical	Enhanced rock weathering	Light blue	Light blue	Light blue	Light blue	Blue	Blue
Geochemical	Direct air carbon capture and storage	Blue	Blue	Light blue	Light blue	Blue	Blue
Geochemical	Ocean alkalinity enhancement	Light blue	Light blue	Light blue	Light blue	Light blue	Light blue

Source: Reproduced from Smith et al. (2024), Table 10.4

Notes: Rating based on expert judgement and analysis by Smith et al. (2024). Dark blue, blue and light blue denote high, moderate and lower ratings

Processes for MRV of CO_2 captured are more developed for BECCS and DACCS than for other removal methods, as inputs are easily measurable and the foundational science is mature, having benefitted from advances in industrial CCS and CCU (Mercer and Burke, 2023). However, for BECCS, MRV processes also need to consider the biomass growth stage, which is more challenging with many different actors across more complex supply-chains. In the case of afforestation and reforestation, there are relatively well-established methods to measure removals based on changes in volume of tree bases or estimates based on context specific emission factors. Where removals are difficult to measure in isolation from natural processes, such as for the ocean-based methods, and where there is still uncertainty over the rate of CO_2 accumulation, as with enhanced weathering, ocean alkalinity enhancement and biochar, further research is needed (Mercer and Burke, 2023).

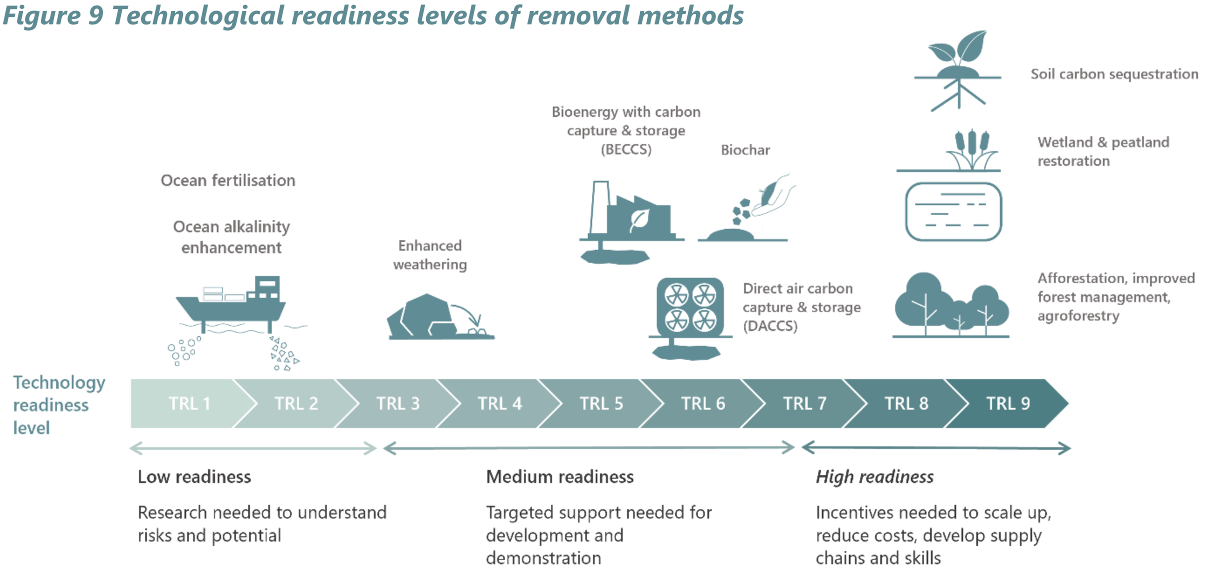
Soil carbon monitoring is complex and faces particular challenges, with different approaches having trade-offs between costs and confidence in accuracy (Carbonplan, 2021; UBA et al., 2021). In-field measurements provide the most accurate soil carbon measurements but can only be measured over the course of years, and are prohibitively expensive and administratively burdensome, making it difficult to monitor and report changes on a regular basis . On the other hand, modelling, action-based monitoring and large-scale remote sensing (e.g., using satellites) are more cost-effective options for large-scale MRV, although subject to significantly more uncertainty (Henry et al., 2022). Wetland and peatland restoration also poses similar challenges in terms of MRV, especially as net CO_2 fluxes, which depend on the balance between carbon sequestration and methane emissions, can be site-specific after rewetting (Bacon et al., 2017). Enhanced weathering on land relies on monitoring through expensive and time-consuming field sampling (Mercer and Burke, 2023; Runge-Metzger et al., 2022).

3.4.2 Knowledge and technological readiness

LULUCF removals are demonstrated methods that face fewer barriers to deployment at scale than other removal methods.

As noted in Chapter 2, and shown in Figure 9, most land sector removal methods are at TRL of 8 or 9. The IPCC described the land sector as the 'only one in which large-scale CO_2 removal may currently and at short term be possible', providing the potential for 'significant near-term mitigation potential at relatively low cost' (IPCC, 2022a, pp. 750-753). Removals from the land sector therefore face few technical or technological barriers to deployment at scale, in contrast to other emerging removal methods (IPCC, 2022k).

Figure 9 Technological readiness levels of removal methods



Source: Advisory Board, based on TRL assessments by IPCC (2022)

Notes: TRLs as assessed by the IPCC are shown here, with higher TRLs indicating technologies with higher technological and commercial maturity. As discussed below, TRL assessments may vary depending on the methodology and other factors

Biochar, BECCS and DACCS are at a moderate level of technology readiness, though the path to deployment at scale is subject to uncertainty with mostly demonstration projects to date.

Biochar has been deployed in several field-studies with promising results, but the lack of evidence from large-scale and long-duration projects creates uncertainty. There is strong evidence of sequestration for biochar, with the long-term persistence of biochar carbon in soils being widely studied (Lehmann et al., 2015; Woolf et al., 2021; Petersen et al., 2023; Sanei et al., 2024). However, biochar remains at an early stage of commercialisation with mitigation estimates based on pilot-scale facilities and significant uncertainty on whether there would be sufficient sustainably sourced biomass for biochar production (IPCC, 2022e).

Similarly, BECCS and DACCS have been assessed as at a moderate level of technology readiness and, to varying degrees, face uncertainties in terms of future costs, performance, and T&S infrastructure (IPCC, 2022e; Smith et al., 2024). The technology for carbon capture and storage has been developed since the 90s with support by the EU. While CCS deployment has been slow to date (Martin-Roberts et al., 2021), the capture and storage technology is now considered mature (Bukar and Asif, 2024). This has likely benefitted BECCS technologies, though because of the fundamental difference in the CO_2 concentration at the capture stage DACCS does not benefit directly (IPCC, 2022e). Small-scale DACCS demonstration projects exist and some integration with CO_2 transport and storage has taken place, though most early DACCS projects use the captured CO_2 rather than storing it. Without any large-scale plants, it is challenging to assess the future cost reduction opportunities and performance of DACCS, which is therefore uncertain (BEIS, 2021). The largest uncertainties requiring major assumptions are on capital costs, plant scaling factors, future cost reductions through learning, and solid adsorbent cost-performance dynamics.

With regards to BECCS, some technologies are more advanced, e.g., power BECCS, but technology readiness levels vary and critical technologies are still at the demonstration or pilot stage (IEA, 2023a; BEIS, 2021). While the IPCC assessed BECCS to be at a TRL of 5-6, it should be noted that TRL assessments differ and several other recent assessments have indicated that some forms of BECCS are at a higher level of TRL than DACCS (IEA, 2023a; BEIS, 2021; Shahbaz et al., 2024). The different applications of BECCS face different uncertainties, though generally the availability and price of sustainable feedstocks, along with the timing and access to transport and storage networks, are key uncertainties (BEIS, 2021). As mentioned in Section 3.3.1, the mitigation and cost-effectiveness of CCS technology removal methods hinges on achieving an efficient rate of carbon capture rate, which are subject to uncertainty with reported capture rates falling short of targeted rates (IEEFA, 2022; WRI, 2023). Larger-scale projects for are expected to become operational soon for both BECCS, such as the BECCS Stockholm in 2026 with an annual average of 0.7MtCO_2 of removals (EC, 2021a), and DACCs, such as a plant in the United States in 2025 with an expected capacity of 0.5MtCO_2 per year of removals (OnePointFive, 2025)

Enhanced weathering and the ocean-based methods are at a low level of technology readiness. Research gaps regarding feasibility, risks and benefits create uncertainty.

Enhanced weathering has been demonstrated in the laboratory and in small-scale field trials (TRLs 3–4) but has yet to be demonstrated at scale (IPCC, 2022e). Silicate mineral dissolution rates in soils, the fate of the released products, the extent of legacy reserves of mining by-products that might be exploited, location and availability of rock extraction sites, and the impact on ecosystems remain poorly quantified and require further research to better understand feasibility (IPCC, 2022e). Closely monitored, large-scale demonstration projects would allow these aspects to be studied (Smith et al., 2019; Beerling et al., 2020).

Surface level uptake of CO_2 from ocean fertilisation is confirmed by a number of field experiments, but there is scientific uncertainty about the extent of CO_2 stored in the deep ocean and the longevity of that storage (IPCC, 2022e). The efficiency of ocean fertilisation also depends on the region and experimental conditions, especially in relation to the availability of other nutrients, light and temperature (Aumont and Bopp, 2006). Ocean alkalinity enhancement has been demonstrated by a small number of laboratory experiments. Various methods for enhancing ocean alkalinity have been suggested, including the addition of silicate minerals such as olivine (Meysman and Montserrat, 2017; Montserrat et al., 2017), and maritime transport of calcium hydroxide (Caserini et al., 2022).

3.4.3 Infrastructure

The infrastructure needed for LULUCF removals is not substantial, although coordinated planning or deployment and distribution networks can be important. Scaling up BECCS and DACCS could require substantial infrastructure to ensure equitable access but is subject to risks and uncertainty.

Deploying new solutions at pace and scale can be dependent on the enabling infrastructure and supply-chains being in place. This is particularly relevant to CCS technologies, which require, in addition to the carbon capture infrastructure, an extensive network to distribute captured CO_2 from its sources to suitable storage sites (JRC, 2024b). Suitable storage sites are not evenly distributed across the EU and in some cases storage may not be feasible for other reasons, such as a lack of public acceptance. Transport infrastructure spanning several Member States and neighbouring countries will be needed to ensure equitable access. Given the complexity and cross-country nature of this infrastructure, there is a risk that diverging approaches, regulations and permitting processes becoming an obstacle to deployment at the pace and scale required (JRC, 2024b). This is compounded by uncertainty regarding future CO_2 volumes and complicated coordination across the value chains, which can also constitute significant barriers for investors dealing with high initial capital costs and long lead times (JRC, 2024b, 2022). Coordinated planning and international cooperation will be required to address these obstacles. This could also assess opportunities to optimise interactions with sectors where there are interdependencies, notably the electricity, gas and hydrogen sectors, and the potential to repurpose and re-use existing infrastructure for CO_2 streams.

The need for physical infrastructure is less important for other removal methods and is generally not viewed as a barrier. This allows for greater flexibility in where these methods are deployed, but supply-chain infrastructure can also act as a barrier. For instance, mineral resources needed for enhanced weathering are in abundant supply and can be deployed in a variety of settings (Tan et al., 2022). However, the set-up of the distribution networks, which will need to scale-up to support deployment, affects the magnitude of the net removal effect (as explained in Section 3.2.1). Similarly, scaling up biochar and BECCS may require scaling up of infrastructure for the distribution of biomass to carbon sink and capture sites, such as rail and shipping infrastructure, which particularly in the case of power BECCS can be significant (see Chapter 7).[9] With regards to the ocean-based methods, there may also be port and shipping infrastructure needs to enable ships to spread biomass or minerals in the ocean.

There may also be intangible infrastructure needs, which are more likely to be a barrier for land sector removal methods where the complexity and/or novelty of removals and the supporting schemes (e.g. administrative burden, familiarisation needs and challenges in managing reversal risks) (EC, 2020a) could act as a barrier. This also refers to the governance infrastructure needed to sustainably scale-up these methods, the environmental impacts of which are typically context specific and require effective and coordinated planning to minimise trade-offs and deliver multiple benefits.

3.4.4 Public acceptance and legal barriers

Understanding and engaging with public attitudes could play a crucial role in the development and deployment of removals.

Public attitudes could have a crucial influence on the speed and scale at which removal methods can be scaled up (Nemet et al., 2018a; Smith et al., 2024) (Table 8). For instance, public resistance to genetically modified crops, driven by a lack of trust in political and regulatory structures, preceded the EU

[9] As an example, the largest biomass power station in the United Kingdom is owned by Drax who hopes to retrofit the plant with CCS. It received an average of 17 trains every day transporting 30,000 tonnes of biomass, shipped from North America and Europe to ports in the United Kingdom (Drax, 2022).

moratorium on this technology Grove-White 1997). Research on public perceptions suggests a nuanced attitude towards removals, with public attitude influenced by perceptions of ‘naturalness’ and ecosystem impacts, along with underlying values and beliefs. In particular, better-known removal methods that are framed or popularly understood as ‘nature-based’ generally secure higher levels of public support, especially afforestation and reforestation, while ocean-based methods, geological storage and BECCS are viewed as riskier due to concerns about their reliability and environmental impacts (Smith et al., 2024). In contrast, a survey of experts found moderately strong levels of support for further research and the deployment of BECCS and DACCS (Kerner et al., 2023).

While the research highlights low awareness of removal methods, attention in the media and social media is growing and will likely continue to as removal methods begin to scale up. In the case of technologies where there is a risk or perception of negative impacts, such as mining for enhanced weathering, long-term proactive engagement and distributional fairness will be critical for acceptance . Involving diverse public actors offers an opportunity for mutual learning, recognising the enabling role the public plays in throughout the innovation process, and can improve the quality and legitimacy of decisions (Smith et al., 2024). Research also shows that with new technologies like CSS on which the public does not necessarily have a formed opinion, exposure to misinformation and conspiracy rhetoric has a strong influence on support (Bolsen et al., 2022).

In addition to wider public acceptance, social acceptance of landowners, farmers and local communities will influence the adoption and efficacy of removals. Land sector removal methods, that entail significant or permanent change, can represent a fundamental departure from the lifestyle, heritage and identity that are valued by agricultural communities (Howley et al., 2015). This can create resistance to change which can prevent uptake, as farmers and landowners based their decisions on their values and beliefs as well as the prevailing attitudes of others in their community (Schirmer and Bull, 2014). Similarly, communities can be reluctant to significant landscape-level changes, and afforestation (in particular) can become intertwined with issues of land ownership, rural decline and loss of agency (Fléchard et al., 2007; Collins and McFetridge, 2021). Resistance to change can also increase local community resistance to necessary infrastructure, which could constrain or slow the deployment of transport infrastructure for CCS. Beyond the question of whether it is adopted or not, social acceptance can even affect the efficacy of some removal methods: for example, successful peatland rewetting can require cooperation from all neighbouring landowners to remove all potential drainage sources (Tanneberger et al., 2021b).

The legal status of ocean-based removal activities faces long-standing uncertainty, which may act as a barrier to scaling up deployment.

The legal framework applicable to ocean-based removal methods will depend on where and how these activities are undertaken. While coastal countries generally have primary jurisdiction over areas within 200 nautical miles of their coastline, ocean waters beyond that fall under international law. For instance, the 1982 United Nations Convention on the Law of the Sea – the UNCLOS (UN, 1982) imposes a general obligation on countries to protect the marine environment and take all necessary measures to prevent, reduce and control pollution of the marine environment. Ocean-based removals as well as other offshore operations handling CO_2 may also be affected by the recently issued advisory opinion of the International Tribunal for the Law of the Sea, which concluded that anthropogenic GHG emissions meet the criteria to be considered pollution in the marine environment (ITLOS, 2024, see also Section 9.3.2). In addition, the London Convention and Protocol promote the effective control of all sources of marine pollution through the regulation of dumping waste materials into the sea.

At the time of adoption, the above-mentioned legal instruments were not intended to regulate ocean-based removal activities, but they have general provisions that could apply to these activities and restrict their deployment. For example, with regard to ocean alkalinity enhancement, under the London

Convention these activities could be permitted while under the more restrictive London Protocol these activities would likely be restricted (Webb et al., 2021). Similarly, ocean fertilisation would likely be restricted under the London Protocol as the materials discharged in ocean fertilization are not included in the list of materials that could be permitted (Webb, 2024). Upwelling and downwelling activities face similar legal uncertainty (Webb et al., 2021).

An amendment to the London protocol, adopted in 2013 (IMO, 2013) to regulate marine geoengineering activities lists activities that are banned from placing man-made structures into the sea. Ocean fertilisation is the only such activity listed so far, and may be conditionally permitted if it is part of legitimate scientific research (IMO, 2013). The amendment reflects the 2008 resolution of the Parties to the London Protocol and London Convention (LC-LP.1 2008). As of yet, the amendment has been accepted by six out of 53 parties to the London Protocol, which means it is not yet in force. When in force, the amendment is expected to create a binding regulatory and control mechanism for marine geoengineering (IMO, 2023). In 2023, the scientific groups which report to the London Protocol and London Convention Parties agreed that enhancing ocean alkalinity, macroalgae cultivation, as well as other biomass for sequestration including artificial upwelling 'have the potential to cause deleterious effects that are widespread, long-lasting or severe' (IMO, 2023).

Table 8 Implementation barriers to scaling removal methods

	Afforestation reforestation	Improved forest	Agroforestry	Soil carbon sequestration	Wetland and peatland	(Coastal) blue carbon	Biochar	Enhanced weathering	BECCS	DACCS	Ocean fertilisation	Ocean alkalinisation
Implementation barriers												
MRV	Few barriers	Few barriers	Some barriers	Some barriers	Some barriers	Not applicable or negligible	Some barriers	Significant barriers	Some barriers	Few barriers	Significant barriers	Significant barriers
Technology readiness	**8-9**	**8-9**	**8-9**	**8-9**	**8-9**	**2-3**	**6-7**	**3-4**	**5-6**	**6**	**1-2**	**1-2**
Infrastructure	Few barriers	Few barriers	Few barriers	Few barriers	Few barriers	Not applicable or negligible	(light blue)	(light blue)	Significant barriers	Some barriers	Not applicable or negligible	Not applicable or negligible
Acceptance and legal barriers	Some barriers	Few barriers	Some barriers	Few barriers	Some barriers	Few barriers	Some barriers	Some barriers	Significant barriers	Significant barriers	Significant barriers	Significant barriers

Implementation barriers

Few barriers	(dark blue)
Some barriers	(yellow)
Significant barriers	(orange)
Not applicable or negligible	(blank)

Source: Advisory Board from multiple sources, see methodology

Notes: Assessments of the barriers facing the removal methods are intended as indicative assessments signalling the extent barriers could constrain deployment at scale. These are based on the available evidence, outlined in this chapter, though in many cases these are complex and dependent on the numerous factors, making it difficult to generalise. The availability of evidence also differs across methods, with more evidence on established methods with a longer history (e.g., land sector removals) than more novel methods (e.g., the ocean-based methods). TRLs as assessed by the IPCC are also shown, with higher TRLs indicating technologies with higher technological and commercial maturity

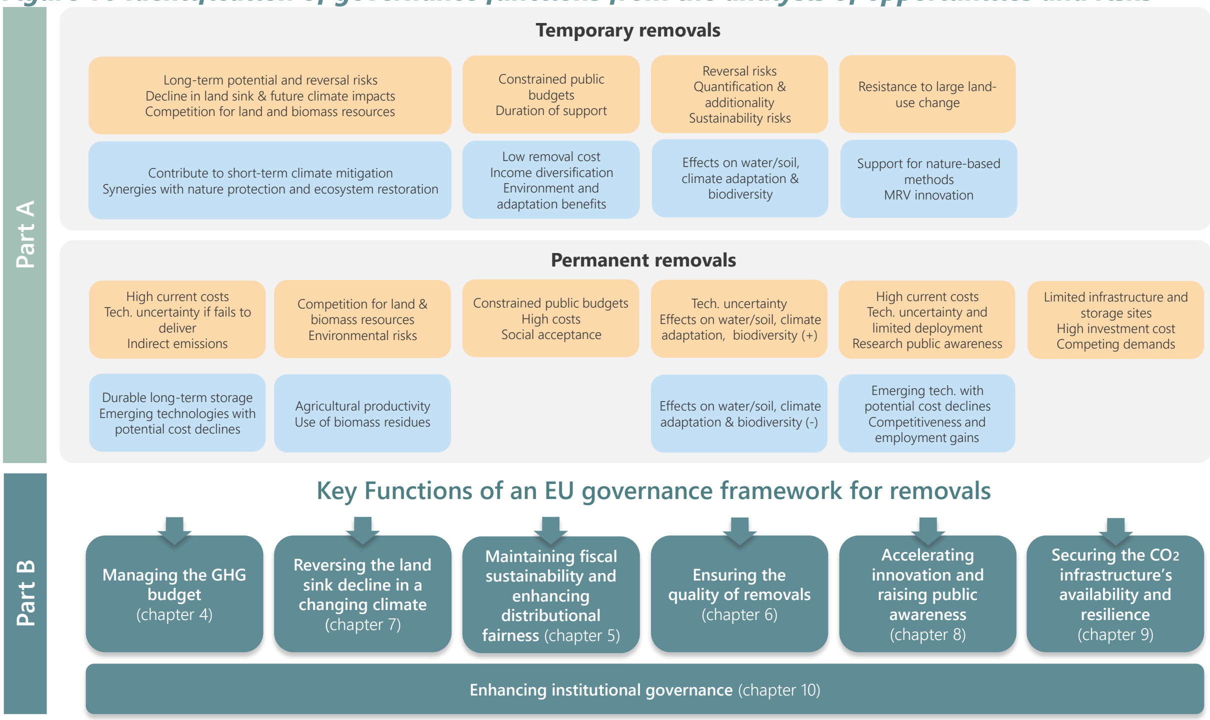
Under the Convention on Biodiversity, governments have been requested to ensure ocean fertilization activities do not take place until there is an adequate scientific basis on which to justify such activities, with the exception of small-scale scientific research studies within coastal waters. The joint group of experts on the scientific aspects of marine environmental protection reiterated that decisions taken in 2008 and 2010 under the convention may be seen as prohibitive to ocean fertilisation activities and other ocean-based removal methods 'in the absence of science-based, global, transparent and effective control and regulatory mechanisms for geoengineering' (GESMAP, 2019).

Part B – Key functions of an EU governance framework for removals

Based on opportunities and risks identified in Part A, the Advisory Board identifies seven functions for the EU governance framework to scale-up removals rapidly and sustainably, as shown in Figure 10:

- managing the GHG budget,
- ensuring the quality of removals,
- reversing the decline of the land sink in a changing climate,
- accelerating the innovation cycle and raising public awareness,
- securing the CO_2 infrastructure availability and resilience,
- maintaining fiscal sustainability and enhancing distributional fairness, and
- enhancing institutional governance.

Figure 10 Identification of governance functions from the analysis of opportunities and risks



For each of the functions, Part B of this report assesses the status of the existing EU policy framework and identifies policy gaps. The assessment of policy gaps is based on a similar framework as the one developed by the Advisory Board in its report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024), which distinguishes:

- **Policy gaps,** in case there are no EU policies in place which aim for the required outcome. This could refer to a lack of targets, or clear targets, but could also refer to the lack of a delivery mechanism to achieve those targets. It generally points at areas where the EU would need to develop new policies to achieve the required outcome.
- **Ambition gaps,** in case there are EU policies in place which target the required outcome, but their overall ambition level – either in terms of their objectives, or their delivery mechanisms – is considered inadequate to achieve the required outcome. It generally points at areas where the EU would need to adjust existing policies to achieve the required outcome.
- **Implementation gaps,** in case there are ambitious EU policies in place, but implementation at the EU, national or subnational level has been ineffective so far. It generally points at areas where achieving the required outcome does not per se require legislative changes at the EU level, but rather more effective implementation at the EU, national or subnational level.
- **Policy inconsistencies,** in cases where EU policies provide incentives that counteract the required outcome. Similarly to ambition gaps, this generally points at areas where existing policies would need to be adjusted.

4 Managing the greenhouse gas budget

- **Managing the GHG budget with removals requires fulfilling several roles.** To ensure that removals fulfil their role in managing the GHG budget over the near term (up to 2040), medium term (2040-2050) and long term (after 2050), the Advisory Board identified four needs as outlined below.

- **The deployment of removals needs to be cost-effective and balanced.** Removals need to contribute to climate neutrality in a cost-effective way, while factoring in externalities (including reversal) and preventing mitigation deterrence to ensure the EU achieves its climate objectives at the lowest societal cost. To this end:
  - early deployment of a portfolio of removal methods is needed to support their development and bring down long-term costs;
  - in cases where the risks of externalities (including reversals) are substantial and insufficiently captured in the price signal, additional safeguards or limitations are justified to prevent an increase in social costs;
  - the use of removals to counterbalance residual emissions needs to be limited to activities with currently no or limited mitigation alternatives that might otherwise face prohibitive costs to reach net zero, the exact level of composition of which is uncertain and dynamic (see Section 1.2).

  Combining separate targets for reductions and removals with price signals could provide a way forward to ensure a cost-effective approach while preventing mitigation deterrence. However, the EU's target structure has gaps.

- **The roles of permanent and temporary removals need to be clarified.** Differences in permanent and temporary removals' characteristics and equivalence need to be considered. Regardless of these differences, the declining trend in the LULUCF sink needs to be reversed urgently, as temporary removals are needed to contribute to short-term mitigation while the capacity of permanent removals is critical for the longer term.

- **Stronger incentives are needed to deploy removals.** Scaling up removals to the necessary levels will require substantial finance. That will not occur in the absence of strong incentives that are currently lacking. Policy options to address this are further explored in Chapters 11 to 14.

- **A framework is needed to deliver net negative**. After reaching climate neutrality, the policy framework should be focused on the aim of increasing ambition and reducing the EU's cumulative net GHG emissions over time. This could be considered both the responsibility of society as a whole and the responsibility of GHG emitters based on the concept of an extended emitter responsibility. The strategy for net-negative emissions needs to already be considered as soon as the next few years, as 2050 is only 25 years away and the potential impact of different options depend largely on the timing of their introduction.

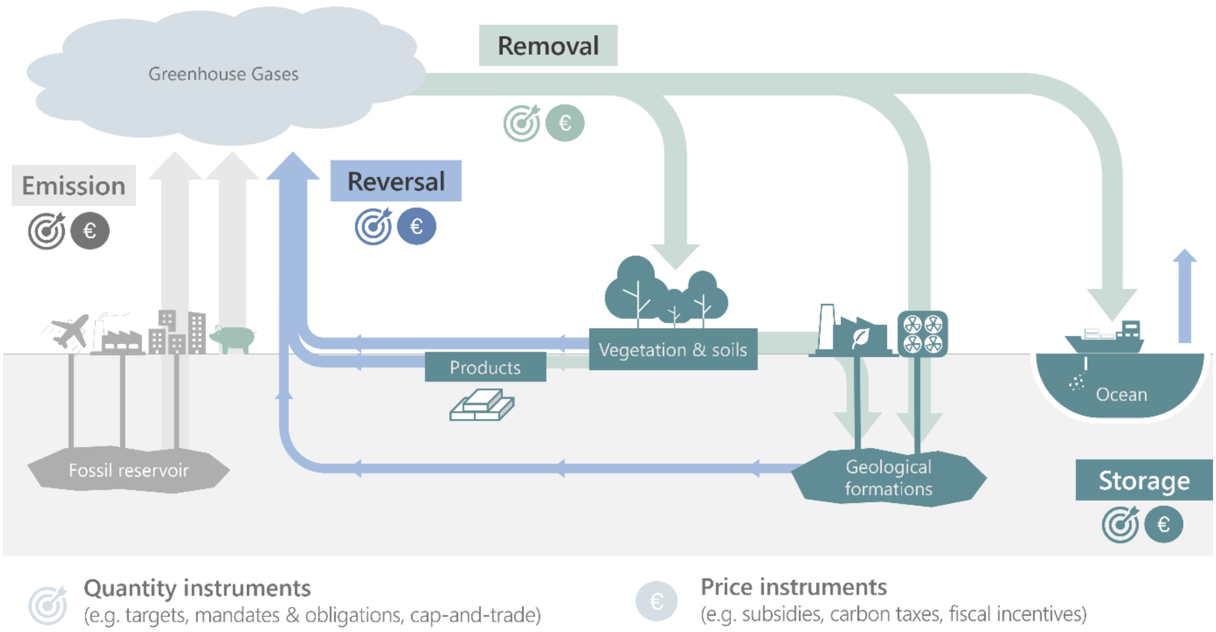
4.1 Introduction

As described in more detail in Chapter 1, removals serve distinct roles, complementary to those of deep emission reductions within the EU's GHG budget, both in the near, medium and long term. Managing the role and volumes of removals within the EU's GHG budget presents several challenges, and may require intervention at different points of the carbon cycle, as indicated by Figure 11 below. A policy framework for removals needs to be able to address four key governance needs:

1 The need to **manage the contribution of removals towards achieving and sustaining climate neutrality** in a cost-effective way, while preventing mitigation deterrence;
2 The need to **clarify the role of permanent versus temporary removals** in achieving the EU's climate objectives, considering their different characteristics in terms of quantifiability, additionality and storage duration;
3 The need to provide appropriate **incentives to deliver the required volume of removals** to accelerate net-reductions and achieve climate neutrality by 2050;
4 The need to provide **a clear framework for the delivery of net-negative emissions,** including who will be responsible for financing them.

This chapter provides an overview of the status of and potential gaps in the EU policy framework for each of these needs. The options to address the gaps identified in this chapter are assessed in Part C of the report.

Figure 11 Policy interventions to manage the greenhouse gas budget



Source: Advisory Board

Notes: Figure intended to be illustrative. Only anthropogenic activities and those directly related to removals are shown.

4.2 Managing the contribution of removals towards climate neutrality

4.2.1 Need

The level of residual emissions in 2050 and corresponding required volume of removals are uncertain. Nevertheless, there is a need to clarify how the respective contributions of reductions and removals towards climate neutrality will be managed, to provide long-term predictability for policymakers and economic actors.

As described in section 1.2, achieving EU climate neutrality by 2050 at the latest will require a rapid and substantial reduction in GHG emissions, complemented with a scale-up of removals to counterbalance residual emissions. Given their role in achieving climate neutrality, the required volume of removals by

2050 will thus ultimately depend on the future volumes of residual emissions remaining in the EU's economy by then. However, identifying these emissions is challenging due to uncertainty about future technological progress, activity levels and social change. Despite this uncertainty, the EU needs to provide clarity on how the respective contributions of reductions and removals towards a climate-neutral EU will be determined to enhance long-term predictability for policy makers and economic actors.

Removals need to contribute to EU climate neutrality in a dynamically cost-effective way while avoiding the risk of mitigation deterrence. To this end, there is a need to support the early deployment of a portfolio of removal options, to consider the wider social costs and benefits of reduction and removal methods, and to avoid overreliance on future removal methods with uncertain costs and potential.

Cost-effectiveness is important in climate policy design, increasing the feasibility of achieving ambitious climate objectives. Cost-effectiveness and economic efficiency[10] are identified in the European Climate Law (EU, 2021b) as key dimensions to consider when developing measures and targets to achieve climate neutrality, and they often guide the assessment of viable climate mitigation pathways (Advisory Board, 2023). From this perspective, it is important that reductions and removals contribute to EU climate neutrality in a cost-effective way; in economic terms, this generally occurs at the point where the marginal *social* cost of all mitigation options (reductions and removals) are equalised (Edenhofer et al., 2024a). Achieving this faces several challenges though, as further outlined below.

Firstly, evaluations of cost-effectiveness can be considered in either static or dynamic terms. Static efficiency focuses on the most efficient allocation of resources based on assumptions of current costs, technologies and market structures. In contrast, dynamic efficiency also considers how these are likely to evolve over time. When faced with emerging or uncertain technologies, it is necessary to consider both static and dynamic efficiency when evaluating climate policy instruments and pathways (Grubb et al., 2021; Gillingham and Stock, 2018). As many authors highlight in the energy transition literature, the cost trajectories of new technologies are not fixed, but typically decline dynamically due to experience-based learning effects and economies of scale, effects which depend on public and private support for innovation and early deployment (Anadón et al., 2022; Nemet et al., 2018b; Grubb et al., 2021). Incorporating dynamic efficiency means that the 'optimal' volume of removals and the appropriate incentive instruments can deviate from those indicated by static cost-effectiveness criteria alone. These depend on policy choices and strategies, and policy instruments must be adaptive to these needs over time (Edenhofer et al., 2024a; Dolphin et al., 2023). Therefore, from a dynamic cost-effectiveness perspective, it can be justified - and even necessary to support the early deployment of a broad range of removal options that may still be costly now, in order to support their development, reduce their costs and increase their scalability in the future (see also Chapters 2, 3, 8 and 11).

Furthermore, it is important to note that both reductions and removal options have direct financial costs, but also costs and benefits that may not be directly reflected in their price, referred to as 'externalities'. As further described in Chapter 3, despite potential for some positive externalities, the large-scale deployment of some removal options in climate pathways may create significant negative externalities, such as e.g. higher energy, mineral, land or biomass use (Fuss et al., 2018; Prütz et al., 2024). For both reduction and removal options, accounting for externalities in evaluations or instruments based on marginal costs is necessary to ensure that this results in a cost-effective balance of reductions and removals from the perspective of society (Merfort et al., 2024; Sultani et al., 2024). However, in practice, the financial costs of removals - such as many of the estimates shown in Chapter 2 – often do not capture all negative externalities and sustainability limits. This can lead to a greater deployment of certain removal methods than what might be considered cost-effective or efficient from society's perspective, which is particularly the case in cost-optimising IAMs for technologies that require significant land or biomass resources (Merfort et al., 2024). Furthermore, there are often temporal externalities (in particular for the land sector), where the long-term costs and risks of reversal are underestimated or not adequately captured. This can create misplaced perceptions of land sector removals as a seemingly cheap long-term removal method, which can contribute to mitigation deterrence (see Box 2 below) and impose significant costs on future generations from reversals (Prado and Mac Dowell, 2023; Franks et al., 2022). Therefore, where the risk of negative externalities (including the risk of reversals) is substantial, additional safeguards or limitations are justified to prevent an increase in societal costs.

As already described in Chapter 1, there is considerable uncertainty about the future level of residual emissions, as well as the future costs, scalability and reliability of removals. Pursuing a seemingly cost-effective contribution of removals towards climate neutrality based on overly optimistic assumptions about future removal costs and potentials risks leading to mitigation deterrence, which can jeopardise the achievement of the EU climate objectives if the expected volume of removals does not materialise (see Box 2). To avoid this risk – and in line with the precautionary principle – the use of removals to counterbalance residual emissions needs to be restricted to activities with no or limited mitigation alternatives (see also Chapter 1), which might otherwise face prohibitive costs to reach net zero.

Box 2 Definition and different forms of mitigation deterrence, and related risks

What is mitigation deterrence?

Mitigation deterrence is defined by (Markusson et al., 2018). as 'the prospect of reduced or delayed mitigation resulting from the introduction or consideration of another climate intervention'. In the context of removals, it could be further refined as the prospect of reduced or delayed emission reductions from the introduction or consideration of CO_2 removals. Such refinement, would make the term 'mitigation deterrence' somewhat misleading (Carton et al., 2023), as both emission reductions and removals are included under the broader term of mitigation as defined by the IPCC (2022b).

How can mitigation deterrence occur?

Based on scientific literature (Markusson et al., 2018; McLaren, 2020; Carton et al., 2023), mitigation deterrence generally occurs in two ways:

- delay to or deterrence of reductions in the near term, in anticipation of removals becoming available at scale and affordable costs in the future;
- the offsetting of emissions with seemingly low-cost removals within a given time period.

Mitigation deterrence can occur at different levels and be driven by different actors. Overall, Carton et al. (Carton et al., 2023) identified three different ways that mitigation deterrence might manifest through different actors, as outlined below.

Mitigation deterrence can be an attribute of **IAMs**, which inherently substitute reductions with removals in pursuit of cost-effective pathways to a given net reduction or temperature target. The magnitude of this substitution effect depends on several factors such as assumptions about future cost developments and discount rates. There is a broad acknowledgement within the scientific literature that mitigation deterrence within modelled scenarios IAMs can then trickle down to real-world decisions (see below).

Mitigation deterrence can happen at the level of **individual decision-makers**, for instance individual companies that postpone or cancel investments in abatement, and instead rely on removals to meet their mandatory or voluntary climate commitments now or in the future.

Finally, mitigation deterrence can happen at a more **structural level within political, economic or social processes**. Policymakers may put in place less ambitious near-term reduction targets and related policies, in anticipation of future removals and/or while allowing current removals to account towards net reduction objectives. Removals may also enable carbon-intensive industries to legitimise their fossil-based business models and avoid stranded assets. Finally, societal support for ambitious reductions, including through structural changes, can be eroded if the general public believes that the future, large-scale deployment of removals can avert the most harmful impacts of climate change.

Mitigation deterrence can thus be the result of intentional decisions, but can also be the unintentional consequence of a system's collective behaviour resulting from the interactions of its individual components (referred to as an 'emergent effect') (Carton et al., 2023; Markusson et al., 2018). For example, policy makers may set near-term climate targets in good faith but base their decisions on IAMs that are overly optimistic about the future scalability and affordability of removals. Subsequently, individual companies risk making undesirable investment decisions based on flawed policy signals. This means that even when actors did not have had an active intention to substitute reductions with removals, mitigation deterrence occurs nonetheless.

Why is mitigation deterrence a reason for concern?

Mitigation deterrence is not inherently a problem (Markusson et al., 2018), as long as removals can deliver similar outcomes for the climate and other societal objectives to reductions. The substitution of reductions with removals could even be desirable to some extent, for example, if these reductions would lead to prohibitive abatement costs or substantial negative welfare impacts.

However, it is not guaranteed and, in some cases, it is even unlikely that removals will deliver climate and other societal outcomes similar or better than those of emission reductions, for several reasons:

- The future large-scale deployment of removals relies on many new technologies that have not yet been proven at scale. If they fail to materialise as expected, it will be impossible to retroactively reduce emissions, and atmospheric GHG concentrations and corresponding climate risks will increase. This 'substitution and failure' risk is highlighted as one of the main risks of mitigation deterrence (Carton et al., 2023; McLaren, 2020; Markusson et al., 2018).
- Even if future removals deliver as anticipated, delaying near-term reductions would still temporarily increase atmospheric GHG concentrations, which risks triggering climate tipping points and irreversible damages (Schleussner et al., 2024).
- Removals could also lead to less-than-anticipated climate benefits due to rebound effects, e.g. increased emissions throughout the removal value chain, spill-over effects (e.g. indirect land use change), and the lock-in of fossil fuel infrastructure (McLaren, 2020).
- Future reversal from temporary removals would undermine the climate benefit of removals, unless these are compensated by a new removal. The latter might not be feasible or undermine intergenerational fairness (Markusson et al., 2018). The risk of mitigation deterrence is particularly high if the costs for continuous monitoring and compensating potential reversals are insufficiently reflected in the price of removals, making them seem less costly than they actually are (Prado and Mac Dowell, 2023).
- Using removals to substitute reductions from activities that have mitigation alternatives risks to leave insufficient removal potential to meet the required scale of net-negative emissions, as also presented in Section 1.3 (Schleussner et al., 2024).
- Removals are likely to deliver fewer positive externalities and have a higher risk of negative externalities and spillover effects outside the EU than emission reductions (Carton et al., 2023; Markusson et al., 2018; McLaren, 2020)

How serious are the risks of mitigation deterrence?

Based on a systematic literature review, Carton et al. (Carton et al., 2023) summarises the considerable disagreement and viewpoints within the scientific community on how serious the risks of mitigation deterrence are. Some argue that removals are already distracting from reductions or seriously risk doing so in the future. Others have pointed out that the empirical evidence on the occurrence of mitigation deterrence is inconclusive, and consider that its risks in the real world are overstated. Finally, some have argued that the debate is counterproductive and unduly selective, as future emission reduction technologies might also fail to materialise, and that an exclusive focus on emission reductions could similarly deter the development of removal pathways that might ultimately be needed to reach climate neutrality (Carton et al., 2023).

Source: Advisory Board

The contribution of removals towards climate neutrality can be shaped by policymakers through both target-led and price-led approaches.

Broadly speaking, there are two main approaches that policymakers can use to shape the eventual balance between emission reductions and removals for reaching climate neutrality. Under the first approach, policymakers decide the balance directly, with separate targets for removals and gross emission reductions (hereafter referred to as a 'target-led approach'). Under the second approach, the policymakers put in place policies to create a price signal for emission reductions and removals, based on which the market determines the balance between removals and reductions such that marginal costs are the same. Depending on this overall approach, different instruments can then be applied to create private incentives for deploying removals, as described in more detail in Section 11.1.

A target-led approach can be more effective at reducing the risk of mitigation deterrence and negative environmental externalities, whereas a price-led approach could help identify activities with currently no or limited mitigation alternatives and increase cost-effectiveness in the context of uncertain future reduction and removal costs.

Climate targets are the foundation of climate policy frameworks, embedding a clear direction and long-term commitment for policymakers, providing strong signals for markets and industry to encourage and coordinate investments, and creating a means for civil society to measure and monitor progress (Dolphin et al., 2023; Pahle et al., 2018). While the EU and most countries have set *net* emission reduction targets (i.e. including both reductions and removals within the same target), proposals to set separate targets for emission reductions and removals have been increasingly highlighted in the literature and public debates. Several authors have argued for separate targets for reductions and removals to manage expectations regarding their respective contributions to EU climate goals, and to reduce the risks of mitigation deterrence (Koponen et al., 2024; McLaren et al., 2019). Many of these authors have similarly argued for a further separation in targets between permanent and temporary removals (see Section 4.3). Others have also argued that from a dynamic efficiency perspective, targets can provide crucial early-stage market signals for investment in and deployment of removal methods (Edenhofer et al., 2024a).

Depending on the weight given to these objectives, policymakers can design targets in different ways, with different implications for mitigation deterrence and cost-effectiveness. To avoid an overreliance on removals to achieve climate objectives and reduce mitigation deterrence risks, they could define the *maximum* contribution of removals to a net reduction target (*de facto* setting a minimum target on gross reductions). On the other hand, to increase ambition and encourage early deployment, targets could also set the *minimum* level of removals to be achieved. Both approaches could also be combined, as currently done under the EU 2030 climate framework: the LULUCF regulation (EU, 2018b) sets a minimum target of 310 $MtCO_2$ net removals in the LULUCF sector, whereas the European Climate Law (EU, 2021b) limits the potential contribution of net removals to the 2030 objective to 225 $MtCO_2$. Furthermore, targets could be defined either as point year targets or as cumulative net GHG emissions that allow for greater intertemporal flexibility.

While targets signal commitment, the main challenge with these approaches is that this requires policymakers to set the future balance between emission reductions and removals directly, based on long-term assumptions regarding the evolution of residual emissions and the future costs of reduction and removal options. As described in Section 1.2, these future trends can be uncertain for both removal and reduction options, and in this context of imperfect information, setting separate and static targets can result in economic inefficiencies emerging over time. If the evolution of costs and technologies begins to deviate significantly from these assumptions, a lack of flexibility to adjust the balance between removals and reductions can create additional economic costs to meeting climate neutrality targets. The ultimate impact on cost-effectiveness would depend on the extent to which this targeted balance deviates from the balance implied by cost-effectiveness criteria, as well as the presence of externalities (Edenhofer et al., 2024b; Merfort et al., 2024; Paul et al., 2023a). Similarly, if this results in insufficient investment in removals or other mitigation technologies, it could result in overall net-zero and net-negative objectives being missed entirely. Furthermore, while setting separate targets can be seen to limit mitigation deterrence, they are also not fully immune to these risks: as noted previously, policymakers may (intentionally or unintentionally) set higher removal or lower reduction targets that reduces pressure on activities to reduce emissions (Brad and Schneider, 2023; Merfort et al., 2024; Edenhofer et al., 2024a). Some of these risks and challenging in target-setting could be mitigated by allowing targets to be dynamic in some form; for example, by embedding key milestones or mechanisms where this balance can be adapted to reflect technological development or new information over time (Dolphin et al., 2023).

Under a price-led approach, covering both reductions and removals with a common price signal under an overall climate neutrality target would create financial incentives for firms and consumers to find the least expensive balance of reductions and removals to achieve an overall net-reduction target (Paul et al., 2023a). Given the challenges in projecting residual emissions by 2050 (see Section 1.2), a well-functioning price signal can help to both determine and reveal the activities that truly have few alternatives to decarbonise, helping to limit residual emissions and ultimately the volumes of removals necessary to reach net zero (Edelenbosch et al., 2024). However, relying solely on a price signal to determine the balance between removals and reductions towards climate neutrality also has its shortcomings, as it is understood from the economics literature that that approach provides what is called a 'first-best solution' only under fully optimal conditions. Firstly, market actors may be short-sighted or face other non-market barriers, meaning that a short-term price signal alone may not be sufficient to incentivise the early deployment of emerging and high-cost removal methods, which is necessary from a long-term dynamic efficiency perspective (Anadón et al., 2022; Nemet et al., 2018b; Grubb, 2022). Secondly, relying solely on a common price signal could also risk mitigation deterrence in several ways, particularly as if it fails to (fully) capture the cost of reversals, or the price signal is shaped by overly optimistic market expectations on costs or potentials of removals (see Box 2 above). Finally, as previously described, many removals are associated with externalities, which, when not internalised in market prices, may cause unwanted environmental or social effects. To address this, a price-led approach could be combined with qualitative supply-side limits to restrict the use of those removals that carry a high risk of negative externalities (see also Chapter 7 in Section 11.1).

A combined approach using both targets and price signals provides a way forward to pursue a cost-effective contribution of removals towards climate neutrality while preventing mitigation deterrence and reducing negative externalities.

Under perfect market conditions – namely with perfect and symmetric information, no uncertainties and a price that can capture all social costs and benefits – a target-led or price-led approach would lead to what economic literature refers to as a *first-best* solution or a socially optimal outcome. However, in the absence of these ideal conditions, achieving a first-best setting becomes unattainable, and the use of multiple policy instruments may be justified as optimal within a *second-best* framework. Targets and price signals can play complementary roles in this policy framework, identifying residual emissions and determining the required volume of removals towards climate neutrality, with potential trade-offs between the shortcomings of second-best cost-effectiveness approaches in capturing all costs or externalities and the avoidance of mitigation deterrence.

Several studies have suggested a combined approach of targets and price-signals as a way forward to pursue a cost-effective outcome while reducing the risk of mitigation deterrence and of negative externalities (Paul et al., 2023a; Edenhofer et al., 2024a).

- A minimum target for required removals can incentivise early deployment, thereby supporting technological development and dynamic efficiency.
- A maximum limit on the possible contribution of removals towards a net reduction target, which *de facto* sets a minimum target for gross emission reductions. This reduces the risk of mitigation deterrence and provides an incentive to continuously reduce residual emissions.
- A price signal could then allow the market to determine a cost-effective balance between this minimum target and maximum limit, and to identify activities that have no or limited mitigation alternatives. Where possible, such a price signal would ideally need to account for potential externalities of reductions and removals, although where this is not possible, additional restrictions or limits can be justified to address specific risks.

Furthermore, policy mixes and sequencing approaches (see also Section 14.3) would allow for adjustments to these approaches as market conditions improve towards a 'first-best' setting.

4.2.2 Status and policy gaps

The EU currently has neither targets nor price signals in place that could determine the contribution of removals to its 2040 and 2050 climate objectives.

The European Climate Law (EU, 2021b) is the cornerstone of the EU's climate policy framework, setting objectives for the EU to reduce net GHG emissions by at least 55% by 2030 (compared with 1990 levels), to achieve net-zero emissions by 2050 and to aim for negative emissions thereafter (Table 9 and Figure 12). However, these targets correspond to *net* emission reductions (i.e. emissions after the deduction of removals). While the law sets out the extent to which net-removals can contribute to the EU's overall 2030 climate target, limited to 225 $MtCO_2e$, it does not specify the expected scale of emission reductions and removals or the balance between them in achieving the EU's climate neutrality objective by 2050 **(policy gap)**. Furthermore, the European Climate Law does not yet include any targets for 2040 but requires the European Commission to submit a legal proposal to this end. The European Commission is expected to propose a 90% net reduction target for 2040 (compared with 1990 (EC, 2024i), although this is not yet a legislative proposal. While the communication and accompanying impact assessment provides estimates of the level of residual emissions and removals from the Commission's scenarios[11], it is not yet clear whether this proposal for 2040 will specify separate targets for removals and for reductions.

[11] Residual emissions of less than 850 $MtCO_2$ and removals up to 400 $MtCO_2$.

The LULUCF regulation is currently the only piece of EU legislation with a binding target for removals, aiming for an EU-wide net removal target of 310 $MtCO_2$ from the LULUCF sector by 2030[12]. This EU-wide target is then translated into binding national targets for individual Member States. However, it does not currently provide targets for after 2030 **(policy gap)**. Outside of the LULUCF sector, the Net-Zero Industry Act sets a target to achieve at least 50 Mt of CO_2 injection capacity in geological storage per year by 2030, including an individual obligation for fossil fuel producers to contribute to achieving this capacity target, but does not distinguish between removals and fossil-CCS. Furthermore, this target does not currently extend beyond 2030, although a review of the Net-Zero Industry Act in 2028 will examine the need to extend this target beyond 2030 **(policy gap)** (EU, 2024e).

Finally, the EU has not yet put in place any price signal that could determine the contribution of removals towards climate neutrality by means of a price-led approach. As explained in more detail in Section 4.4.2, the EU emission trading system (EU ETS) – which is the EU's main GHG pricing instrument – does not (yet) cover removals, so it does not enable the market to find a cost-effective balance between reductions and removals in meeting a net reduction cap. However, the EU ETS directive does require the European Commission to assess by 2026 how removals could be covered by emission trading, and to submit a legal proposal to this end where appropriate.

Table 9 Relevant targets and price signals related to removals in EU climate legislation

	2030	2040	2050	Beyond 2050
European Climate Law	Net emission reduction Target of -55% from 1990 levels, with maximum contribution of 225 $MtCO_2$ removals.	No formal proposal yet, but communication from the European Commission indicates net emission reduction target of -90%.	Net Zero GHG emissions by 2050. No formal proposal yet on 2030-2050 GHG budget	Aim to achieve net negative GHG emissions thereafter
LULUCF Regulation	Net LULUCF sink of 310 $MtCO_2$.			
Net Zero Industry Act	50 $MtCO_2$ injection capacity with individual obligations fossil fuel producers. No distinction between removals and fossil CCS.			
EU ETS Directive	Emissions cap to decrease by -62% from 2005, with removals excluded. Integration of removals to be examined in 2026 review.	Cap to reach zero by 2039 (2045 for aviation).		

Source: Advisory Board

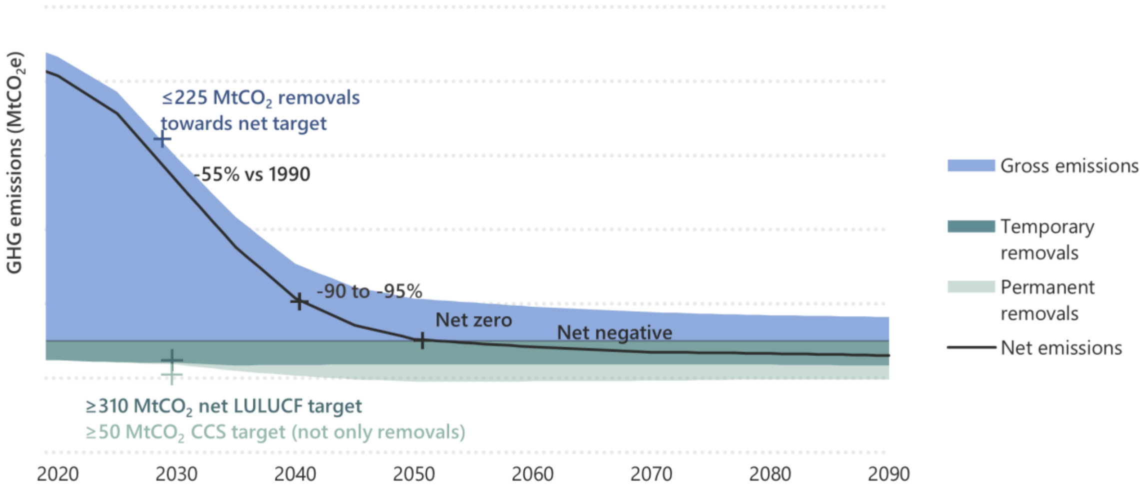
The upcoming revision of the European Climate Law and subsequent discussions on the post-2030 climate policy framework need to provide more clarity on the respective contributions of removals and reductions towards the EU climate objectives.

As described in Chapter 1, removals need to be scaled up rapidly for the EU to keep within reach a 90-95% reduction by 2040 and climate neutrality by 2050 at the latest, while managing the risks associated

[12] It should be noted that while the LULUCF regulation sets a target of 310 MtCO2e by 2030, other pieces of legislation put more stringent limits on the extent to which net removals from the sectors can contribute to other 2030 targets. Under the European Climate Law, removals can contribute a *maximum* of 225 $MtCO_2$ to achieving the EU-wide target of a 55% reduction in *net* emissions by 2030. The Effort Sharing Regulation (ESR), which sets binding annual emission reduction targets for Member States in sectors not covered by the EU ETS or LULUCF regulation, also includes limited flexibility to use removals generated by the LULUCF sector to compensate for underachievement in the ESR sectors, up to a maximum of 262 $MtCO_2$ over 2021-2030 (Fridahl et al., 2023).

with removals. Achieving such a rapid—while sustainable—scale-up requires clarity and direction for policymakers and economic actors on the expected contribution of removals towards the 2040 and 2050 targets, and how this contribution will ultimately be determined. Setting targets for both minimum levels of removals and maximum contributions from removals towards net emission reduction goals can provide the flexibility needed to pursue cost-effective solutions, while safeguarding against market failures and mitigation deterrence. This clarity can be provided through near-, medium- and long-term targets as part of the upcoming revision of the European Climate Law or in developing the post-2030 climate framework (e.g. LULUCF regulation, EU ETS directive, Net-Zero Industry Act).

Figure 12 Status of EU climate targets and the need to define the contribution of removals towards net targets



Source: Advisory Board

Notes: EU legal climate targets shown in this figure correspond to commitments in the European Climate Law, LULUCF Regulation and Net-Zero Industry Act.

4.3 Clarifying the roles of permanent and temporary removals

4.3.1 Need

To assess environmental integrity and pursue the highest possible ambition in climate action, it is essential to consider the quantifiability, additionality, duration and substitutability of residual emissions and the removals that are used to counterbalance them.

When removals are used to counterbalance residual emissions within a GHG budget or within carbon markets, equivalence between the removal and the emitting activity must be considered. This means that the volume of CO_2 captured by the removal activity must be quantifiable and additional, and the timeframe over which the storage is maintained should be considered. These characteristics change depending on the source of the emission or removal. In particular, fossil CO_2 emissions represent a near-permanent increase in atmospheric carbon stocks, transferring carbon from otherwise permanent geological sinks to the atmosphere, where it remains for centuries to millennia (Carton et al., 2021). Some removal methods, particularly where carbon is stored in biomass or terrestrial sinks, store CO_2 for a potentially much shorter time.

Temporary removals present greater challenges to ensuring environmental integrity than permanent removals due to lower typical storage durations, higher reversal risks and unclear

additionality. It is therefore important to clarify the different roles of temporary and permanent removals in counterbalancing near-permanent fossil CO_2 or other emissions.

For temporary removal methods, particularly those in the land sector, a lower typical storage duration and a higher risk of reversal means that carbon captured and stored will generally return to the atmosphere in a shorter timeframe (e.g., within decades to centuries) compared to permanent removal methods (see Chapters 2 and 3). Furthermore, when temporary removals are provided by the land or ocean sinks, it is important to distinguish 'passive' (i.e. natural CO_2 uptake that would have occurred without human intervention) from 'active' or 'anthropogenic' effects, as only removals that occur in addition to these passive sinks contribute to halting global warming (Allen et al., 2024). Establishing this type of additionality can be challenging for many temporary removal methods, and instances of incorrect or questionable additionality have been frequently highlighted in the literature, such as due to inadequately-set baselines, or broader challenges for robust monitoring, reporting and verification over a diverse range of projects and actors (Probst et al., 2024; Badgley et al., 2022b; Nolan et al., 2024). All these challenges mean that temporary removals, permanent removals and emission reductions are not fully equivalent, and that the temporary removal of 1 tCO_2 will – over the long term – generally have a lower mitigating impact compared to a permanent removal or the reduction of one tonne of CO_2 (Carton et al., 2021; Brander et al., 2021).

Within shorter timeframes defined by concrete policy objectives, temporary removals could be partially equivalent to permanent removals, meaning that within this timeframe (e.g. from several decades to a century), the temporary removal of more than 1 tCO_2 could have a comparable mitigating impact as the permanent reduction or removal of 1 tCO_2 (Groom and Venmans, 2024). The quantity of CO_2 temporarily removed required to have a comparable mitigating impact to that of 1 tCO_2 of permanent reductions or removals has been referred to as the equivalence ratio, which represents the degree of equivalence within a certain time horizon (Burke and Schenuit, 2023). Over longer timeframes, maintaining equivalence would require reversals to be continually compensated for by further removals, presenting additional challenges in terms of financing, enforcement and governance (Franks et al., 2023).

Overall, the literature has identified two broad approaches to managing the different degrees of equivalence between temporary removals on one hand, and permanent removals and emission reductions on the other hand. Firstly, some authors have argued that since temporary removals cannot reliably be considered equivalent to long-lived GHG emissions over the long term, they should therefore not be used to counterbalance fossil CO_2 emissions when assessing compliance with climate targets or within a market setting. Instead, they argue that only permanent removal methods with reliable long-term storage duration should be used in this role to ensure environmental integrity and maintain climate ambition (Allen et al., 2024; WKR, 2024; McLaren et al., 2019; Carton et al., 2021). Allen et al. (2024) describe this as geological net-zero, meaning that one tonne of CO_2 is permanently[13] restored to the solid Earth for every tonne still generated from fossil sources. Others have argued that reversal risks and other equivalence issues largely reflect governance and commitment challenges (i.e. ensuring reliable certification, MRV, management of reversal risks and liabilities etc.). Provided that robust instruments and institutions are put in place to manage these risks, they see a possibility of establishing equivalence between temporary removals and long-lived GHG emissions within certain timeframes (Edenhofer et al., 2024a; Sultani et al., 2024). The different options for approaches and instrument to address these options and challenges for temporary removals are described in more detail in Section 13.3.

[13] They further elaborate that 'geological-timescale storage' requires secure storage over multi-century to millennial timescales without ongoing human intervention. They further highlight that current evidence suggests that geological sequestration can meet this standard, while further evidence is required for other methods (like biochar) to demonstrate a similar level of security and durability.

Despite limited equivalence to other mitigation options, the EU still needs to maintain and increase the volume of temporary removals, as they can contribute to climate mitigation in the near term, thereby limiting the EU's peak warming contribution. This requires policies to incentivise temporary removals, to maintain existing sinks and to restore natural ecosystems.

As described in Section 1.3, near-term mitigation action through accelerated reductions, combined with a rapid and sustainable scale-up of removals, remains the most effective strategy to reduce climate risks and damages. It is therefore crucial to both accelerate the pace of reductions and to increase removals in the near term. Given the relative immaturity of permanent removal methods, the LULUCF sector is the only one that currently provides negative emissions in the EU at scale; the 'only one in which large-scale CO_2 removal may currently and at short term be possible' (IPCC, 2021). Even when temporary removals cannot guarantee the same long-term storage as permanent removals, several authors demonstrate the importance of temporary removals to climate mitigation, helping to reduce risks and climate damages until more permanent removal options become available at scale, thereby reducing costs to society in the transition towards climate neutrality (Franks et al., 2023; Balmford et al., 2023; Groom and Venmans, 2024). With recent literature suggesting a growing likelihood of 1.5°C of global warming being exceeded (Bertram et al., 2024), and with this bringing greater risks of triggering irreversible climate tipping points (Ripple et al., 2024), urgently incentivising temporary removals is a necessary climate mitigation strategy.

This also entails stronger efforts to protect existing land sinks (Allen et al., 2024), which as described in more detail in Chapter 7, have declined in the EU and are increasingly threatened by current and projected climate change impacts. However, as outlined further in Chapters 2 and 6, there may also be practices in the LULUCF sector that are necessary to preserve and enhance existing sinks, but may still not meet the strict additionality or quantifiability criteria that are needed to establish a reliable equivalence with permanent removals or emission reductions (Nolan et al., 2021). Furthermore, as outlined in Chapter 3, some practices that do provide temporary removals can still have negative impacts on other environmental or social dimensions, such as the displacement of species-rich habitats from monoculture forestry plantations. At the same time, it is well recognised that delivering temporary removals and protecting existing sinks through well-managed and appropriate ecosystem restoration efforts can have multiple benefits: supporting climate mitigation goals, while also helping to address the global biodiversity crisis, improving climate resilience and delivering other environmental or wellbeing benefits (IPCC, 2021).

While at a minimum, policy incentives aimed incentivising the provision of new permanent or temporary removals need to be applied in a way that does not harm other environmental dimensions, there is also a need to also consider the role of policy mixes and other instruments, including those aimed at maintaining existing sinks, and those with a primary focus on nature, ecosystem restoration and other environmental outcomes. Chapter 7 elaborates on synergies and conflicts with the EU's biodiversity, agrifood, and bioenergy policies; and how these could be leveraged for better alignment with the EU's climate and removal objectives.

4.3.2 Status and policy gaps

The current EU policy framework does not explicitly address the differences between emission reductions, permanent removals and temporary removals, and does not yet have a comprehensive approach to addressing the issues of equivalence and reversibility.

The European Climate Law requires the EU to achieve climate neutrality by balancing GHG emissions with removals but does not directly address the different characteristics of temporary and permanent removals **(policy gap)**. The EU ETS directive is clearer on this point: the above-mentioned requirement for the European Commission to explore the integration of removals into emission trading refers explicitly to removals that are stored safely and permanently, while the CCS directive already provides mechanisms to manage reversal risks from geological storage sites (in the context of fossil-CCS), by requiring the surrender of emission allowances for any leakage or reversal events (Rickels et al., 2023). This suggests that any future extension of the EU ETS to cover removals may be limited to permanent removals.

The Effort Sharing Regulation currently allows Member States to counterbalance emissions (including long-lived emissions) in the non-ETS sectors with temporary removals in the LULUCF sector, even if only up to a certain extent (262 $MtCO_2e$ in total for 2021-2030) and only to the extent that the Member State has overachieved its national objective under the LULUCF regulation. If temporary removals are reversed at a later stage, the same Member State will ultimately be responsible for that reversal in the form of binding national targets for the LULUCF sector. However, there is currently no clarity that national targets for the LULUCF sector will continue after 2030. As a result, the current flexibility between the LULUCF sector and Effort Sharing Regulation targets includes a risk that long-lived GHG emissions under the regulation are counterbalanced by temporary removals, without clarity on who will be liable if those temporary removals are reversed after 2030 **(policy gap)**.

If the EU continues to allow the use of temporary removals to counterbalance long-lived GHG emissions, it will (at a minimum) need to put in place a clear approach to addressing and managing equivalence challenges. As described in more detail in Chapter 6, the CRCF regulation (EU, 2024g) does acknowledge the need to address these challenges and puts forward some principles and high-level rules for certification, which need to be further elaborated in delegated acts. Specific options to address and manage these different issues are described in more detail in Section 13.3.

Finally, as described in more detail in Section 4.4.2, current incentives to maintain and increase temporary removals in the LULUCF sector are not delivering at the required level of ambition, and stronger incentives are needed. In previous reports, the Advisory Board has recommended addressing this gap by extending GHG pricing to the LULUCF sector, in a way that would also reward. Policy options to achieve this are described in more detail in Section 13.2 and assessed in Section 14.2.

4.4 Providing incentives for removals towards climate neutrality

4.4.1 Need

Scaling up removals requires mobilising substantial financial resources, with current estimates ranging from EUR 30 billion to over EUR 80 billion per year by 2050.

While a cost-effective balance between reductions and removals would reduce the overall costs of achieving the EU climate objectives, even this requires mobilizing financial resources for scaling up removals. The total financing need for removals in the EU under climate-neutral scenarios is uncertain but could be substantial, with estimates based on the volumes and costs contained in Chapters 1 and 2 ranging from approximately EUR 30 billion to EUR 80 billion per year by 2050, approximately 0.1-0.3% of EU GDP (see Box 3 for more details). Reflecting the uncertainty in costs and potentials, other estimates from the literature indicate the potential for an even wider range, with total removal costs of up 0.2-0.8% of EU GDP by 2050 (Edenhofer and Leisinger, 2024). By comparison, achieving the EU's broader climate objectives for the energy and transport sectors requires an average investment of EUR 1.24 trillion over 2021-2030[14] (ECB, 2024; Advisory Board, 2024). These estimates may not fully

[14] Quantifying investment needs involves significant uncertainty; therefore, a broad range of input resources were considered, including the European Commission's impact assessments, and information from Bloomberg New

account for the costs of investment in infrastructure, innovation etc.; or the needs for net negative after 2050.

Box 3 Illustrating the scale of the financial challenge

As outlined in Chapter 2, the potential and costs of different removal methods are wide-ranging, particularly for novel removal methods whose feasibility and future technological progress are highly uncertain. Given this, estimates of the future costs of removals are approximate, and generally based on relatively straightforward assumptions regarding total volumes and future cost ranges. For example, Edenhofer et al. (2024a) suggested that global removal costs could reach USD 0.5 trillion to USD 4.5 trillion per year by the mid-century, assuming average volumes of 5–15 $GtCO_2e$ and removal costs of USD 100–300 per tCO_2e - or approximately 0.3 – 3% of global GDP. McKinsey (2023) estimated global *cumulative* investments of USD 6 trillion to USD 16 trillion by 2050 in order to reach net-zero emissions, or an average of USD 275 billion to USD 700 billion per year between 2030 and 2050. For the EU, Edenhofer and Leisinger (2024) have estimated expenditures on removals to reach 0.2–0.8% of EU GDP in 2050, following the EU Commissions assumption of 450 $MtCO_2e$ removals by mid-century and assuming removal costs of EUR 100–500 per tCO_2. The cost of net negative and managing temperature overshoots is potentially even more significant: with a temperature rise of 0.1℃ associated with approximately 220 $GtCO_2e$ of global removals on average, at similar cost ranges, each 0.1℃ of temperature overshoot could require trillions of dollars globally to reverse through net-negative emissions (WKR, 2024).

As a similar example to illustrate the scale of future removal costs, permanent and temporary removal volumes from the Advisory Board's scenario database in Chapter 1 were compared with cost ranges described in Chapter 2. An 'average cost' scenario, as well as low and high ranges, were developed based on the costs and potentials described in Chapter 2, assuming:

- Average LULUCF removal costs of EUR 50 per tCO_2, with low and high costs of EUR 30 per tCO_2 and EUR 100 per tCO_2 respectively.
- Average 'best estimate' costs for BECCS and DACCS found in Abegg et al. (2024), along with average minimum and maximum values (see Figure 8). These cost estimates were derived from an expert elicitation study, and provided for 2030, 2040 and 2050.

Figure 13 below illustrates the total costs implied by these assumptions, based on the volumes of removals contained in the Advisory Board's target advice range. Based on these average cost scenarios, this EU could entail annual costs of EUR 20 to 22 billion by 2030, EUR 43 to 50 billion by 2040, and EUR 51 to 57 billion by 2050 to deliver the levels of removals envisaged in the scenarios. Given the inherent uncertainty in future removal costs, taking the wider ranges implied by the low and high cost estimates above, this could range between EUR 12 to 24 billion by 2030, EUR 29 to 66 billion by 2040, and EUR 33 to 82 billion by 2050.

At these ranges, the cost of removals could reach 0.1-0.3% of the EU's GDP by 2050 (assuming that real GDP grows by an average of 2% per annum). While these figures are approximate, based on the removal portfolios in the Advisory Board's scenario database, and do not take into account any

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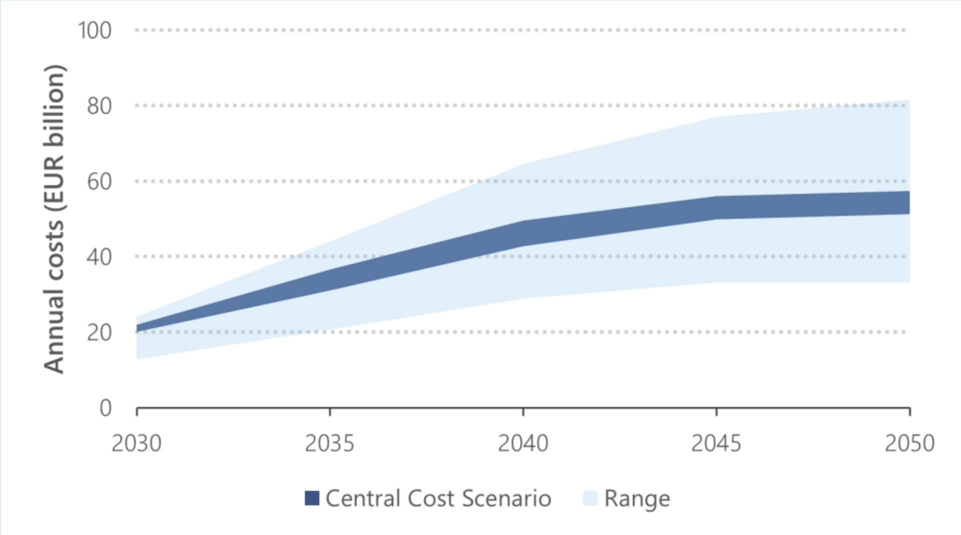
Energy Finance and the European Investment Bank. However, differences in the definition of categories and the calculation of investment needs across scenarios prevent a precise attribution of removal costs to those investment needs.

dynamic responses between removal volumes and prices, they highlight the scale of the finance that may need to be mobilised and sustained to reach EU removal objectives.

Figure 13 Annual cost scenarios for removals



Source: Advisory Board scenario database and cost estimates from Chapter 2

As removals have relatively high costs and generate little to no financial value on their own, mobilising the necessary financial resources requires strong policy incentives.

As described in more detail in Chapter 2, current and future removal costs can vary strongly between removal methods, with estimates reaching up to several hundreds of euro per tCO_2 removed for some permanent removal methods. However, for most removals – and in particular for permanent removals – the primary value (i.e. reduced climate impacts) is not reflected in the price, making it challenging to generate revenue and develop a viable business case to support investment. Therefore, policy instruments are required to create sufficient incentives for private actors to deliver the volume of removals needed.

4.4.2 Status and policy gaps

The current EU policy framework provides only limited incentives to deploy removals, which are insufficient to deliver removals at the required scale towards climate neutrality.

The EU ETS is the EU's main emissions pricing instrument to deliver the climate targets, and its importance will grow over the coming years as its scope will be expanded to new sectors. While the EU ETS provides financial incentives for installations to reduce emissions – including through fossil-CCS, and some instances of CCU when captured CO_2 is chemically bound in durable construction products (EC, 2024f) - it currently does not include mechanisms to incentivise removals[15] (Rickels et al., 2021) **(policy**

[15] Under the ETS directive, installations are required to surrender an ETS allowance for each fossil CO_2 emission to the atmosphere. However, it is not necessary to surrender emission allowances for any emissions that are captured and permanently stored geologically or in certain construction products that bind CO_2 chemically and permanently. Depending on the cost of CCS and the prevailing emission allowance price, this creates a financial incentive for firms to capture and store *positive* emissions. However, this mechanism does not provide any recognition of *net-negative* emissions, as it does not allow for the generation of additional allowances or credits by providing a removal. Similarly, the zero-rating of biomass emissions means that there is no additional incentive to apply CCS processes to bioenergy (Rickels et al., 2021).

gap). However, the latest EU ETS directive does require the European Commission to report by 31 July 2026 on how removals could be reported and accounted for under the EU ETS, and make a legislative proposal to this end if appropriate (EU, 2023b).

Sectors that are not covered by the EU ETS are covered by the effort sharing regulation and per tCO_2 removed the LULUCF regulation. Both regulations set nationally binding targets to reduce emissions (under the effort sharing regulation) and increase net removals (under the LULUCF regulation). As described in Section 4.3.2, Member States that overachieve their LULUCF target can, to a limited extent, use that overachievement towards their reduction target under the effort sharing regulation. Whereas these regulations do not provide a direct incentive for market players to achieve removals, the underlying logic is that they would encourage Member States to provide such incentives at the national level (Delbeke and Vis, 2021). However, in practice this approach has so far been ineffective at increasing removals in the LULUCF sector **(implementation gap)**. Assessments by the Advisory Board (Advisory Board, 2024, 2023a) and others (Korosuo et al., 2023) have warned that the LULUCF sector is off track and even heading in the wrong direction compared with its 2030 net-removal target. Furthermore, the European Commission has assessed that, in aggregate, the measures included in the draft updated national energy and climate plans (NECPs) would not be enough to reverse the trend, and would decrease the overall net-sink by a third by 2030 (compared with 2005) and even turn it into a net emission source after 2030 (EC, 2023d). Both the historical trend and these projections suggest that the effort sharing regulation and LULUCF regulation have not so far resulted in strong policy incentives for removals at the national level.

The Advisory Board has previously also highlighted that the absence of strong, direct price signals for individual land managers that prices emissions and reward removals is a significant gap in EU climate policies (Advisory Board, 2024) **(policy gap)**. At the same time, subsidies and misplaced incentives from EU bioenergy and agri-food policies have further skewed financial incentives away from providing removals, and have instead incentivised practices that drive land emissions rather than removals (e.g. peatland drainage) or make less efficient use of land and biomass resources (e.g. livestock production, less efficient bioenergy uses), and discouraged their use to provide greater carbon sequestration and storage **(policy inconsistency)**.

Finally, as described in more detail in Chapter 5, there are a range of EU funding mechanisms that could potentially contribute towards incentivising removals, such as the common agricultural policy, and nature and biodiversity funding. However, their actual effectiveness in driving such removals is unclear (and in some cases even doubtful) due to low levels of funding, implementation challenges, and other purposes competing for the same funds.

Voluntary markets currently only play a limited role in driving removals, and their environmental credibility has been contested. Despite recent EU initiatives to improve credibility, voluntary markets on their own are unlikely to achieve removals at the required scale.

Voluntary carbon markets are platforms where individuals and companies can finance projects that aim to reduce emissions or remove greenhouse gases. Driven by environmental values or corporate marketing goals, buyers purchase credits directly from projects or through intermediaries with certification systems. However, voluntary markets make up only 2% of the total carbon trade, a far smaller amount than compliance markets (Smith et al., 2024).

In the absence of stronger policies from governments, voluntary carbon markets have so far been the main source of finance for the nascent removals sector. Nevertheless, removals currently account for less than 10% of all credits in voluntary carbon markets and come mainly from temporary removal projects in the land sector. Credits from ‘novel’ permanent removal options like BECCS, DACCS and biochar have been smaller, even if they grew rapidly to 4.6 $MtCO_2$ in 2023. This growth was largely driven by a few high-profile deals with major corporate buyers, and most recent data show a decline in the numbers of both buyers and deals (Smith et al., 2024).

While voluntary carbon markets can be an important source for climate finance, their environmental integrity has often been undermined by governance and oversight issues. Literature and media reports have highlighted that often credits fail to deliver the claimed climate benefits due to inadequate accounting, low MRV standards or poor risk management (Smith et al., 2024; SBTi, 2024). One study found that only 16% of credits in voluntary markets achieved their stated benefits, with some practices, like improved forest management, offering no real impact (Probst et al., 2024). These issues may enable greenwashing, allowing companies to justify emissions without meaningful counterbalancing emissions, while also deterring buyers who seek high-quality removals (Smith et al., 2024). To address these concerns, the CRCF regulation (described in more detail in Chapter 6) aims to enhance the credibility of and demand for high-quality removals in voluntary markets. The European Commission expects this to attract additional private funding for removals through voluntary carbon markets, particularly from buyers who value these quality attributes. Other recent initiatives, such as the EU taxonomy regulation, the green claims directive, the directive on corporate sustainability due diligence and the regulation on environmental, social and governance ratings, also aim to improve the transparency and validity of environmental claims made by firms, including those relating to removals (EC, 2023j) which may similarly boost demand for high-quality removals through voluntary carbon markets.

Despite recent growth and new legislation, voluntary markets alone are highly unlikely to fund removals at the scale needed for the EU's climate goals. Private willingness to pay in these markets remains low with estimates ranging between EUR 0 and EUR 20 per tCO_2e (Berger et al., 2022; Rodemeier, 2022; Hickey et al., 2023), and recent growth has relied heavily on a few large deals. While the recent policy initiatives described above may boost demand and willingness to pay, they are highly unlikely to mobilise at any meaningful scale the required finance for high-cost permanent removals like BECCS and DACCS, whose costs exceed EUR 100 per tCO_2e. Given the physical and financial challenges in scaling up removals to a level needed to meet EU climate objectives, voluntary markets are more likely to complement an integrated public policy response than to provide a substitute for it.

The EU needs to put in place stronger policy incentives to scale up removals, to keep its climate objectives after 2030 within reach.

Given the need to substantially scale up investments in removal options, the limited incentives in the current policy framework and the limited contribution that can be expected from voluntary carbon markets, the EU needs to put in place new and strengthened policy incentives to achieve the deployment of removal options at the required scale. Several options exist, with each their respective strengths and potential shortcomings. These are described and assessed in Part C of this report.

4.5 Establishing a framework for net-negative emissions after 2050

4.5.1 Need

To achieve net-negative emissions after 2050, the EU needs to provide clarity on the role and required volume of net-negative emissions, who will be responsible for delivering these net-negative emissions and how this will be incentivised.

As described in Chapter 1, the European Climate Law requires the EU to aim to achieve net-negative emissions after 2050, which could increase the fairness of the EU's contribution to global climate action;

help to avoid, limit and reverse a global temperature increase beyond the 1.5°C limit; and allow for intertemporal flexibility to reduce the cost of meeting climate objectives over time.

To achieve net-negative emissions after 2050, the EU needs to clarify how it will determine the required volume of net-negative emissions, who will be responsible for delivering them, and what type of instruments will be put in place to incentivise or fund them. These elements are much less straightforward for net-negative emissions than for the role of removals in achieving climate neutrality, where the need and incentives to deliver removals are inherently linked to residual emissions.

Since 2050 is only 25 years away, the EU needs to consider these aspects in the next few years, as they can have implications for the near term. This is because the required volume of removals to achieve net negative after 2050 inherently affects the volume of removals available to achieve net zero, and thus the required gross emission reductions. Moreover, as further described in Section 12.2, the capacity of possible instruments to generate net-negative emissions is often determined by the timing of their introduction: the later these instruments are introduced, the smaller volumes of net-negative emissions they could generate. This provides an additional argument for the EU to consider approaches for after 2050 already in the near term.

Delivering and financing removals towards net negative can be considered both a public responsibility and the responsibility of emitters.

One approach to assigning responsibility for net-negative emissions is to consider it a public responsibility that therefore needs to be primarily financed through public funding. For example, Sultani et al. (2024) argue that, for the most part, the need for large-scale removals after 2050 stems from societies' historic failure to mitigate climate change with appropriate and timely abatement measures, and therefore it will fall mainly to governments and society at large to drive demand for removals and to take (financial) responsibility for overshoot management (in other words, to finance net-negative emissions through public funds).

Another approach would be to apply a concept that has been explored in recent scientific literature, commonly referred to as 'carbon debt' (Bednar et al., 2021; Lessmann et al., 2024) or a 'CO_2 emitters liability' (Lyngfelt et al., 2024). Drawing on similar principles for waste management, such concepts – which are referred to in this report by the term of an 'extended emitter responsibility'[16] - would assign an explicit responsibility to emitters to eventually clean up the waste they have deposited into the atmosphere, by requiring existing emitters to contribute (in some form) to providing a future removal. This concept aims to reduce potential fiscal burdens for future generations, for whom the costs of net-negative emissions could otherwise be substantial. Enforcing such a responsibility over time can be challenging, and several recent proposals to operationalise this concept have emerged in the literature. These range from proposals to create national investment funds for future removals, financed by saving levies or taxes from current emitters (WKR, 2024), to more complex financial instruments that could be integrated as extensions to existing emission pricing systems (Bednar et al., 2021; Lessmann et al., 2024; Lyngfelt et al., 2024). Specific proposals are described in more detail in Section 12.2.

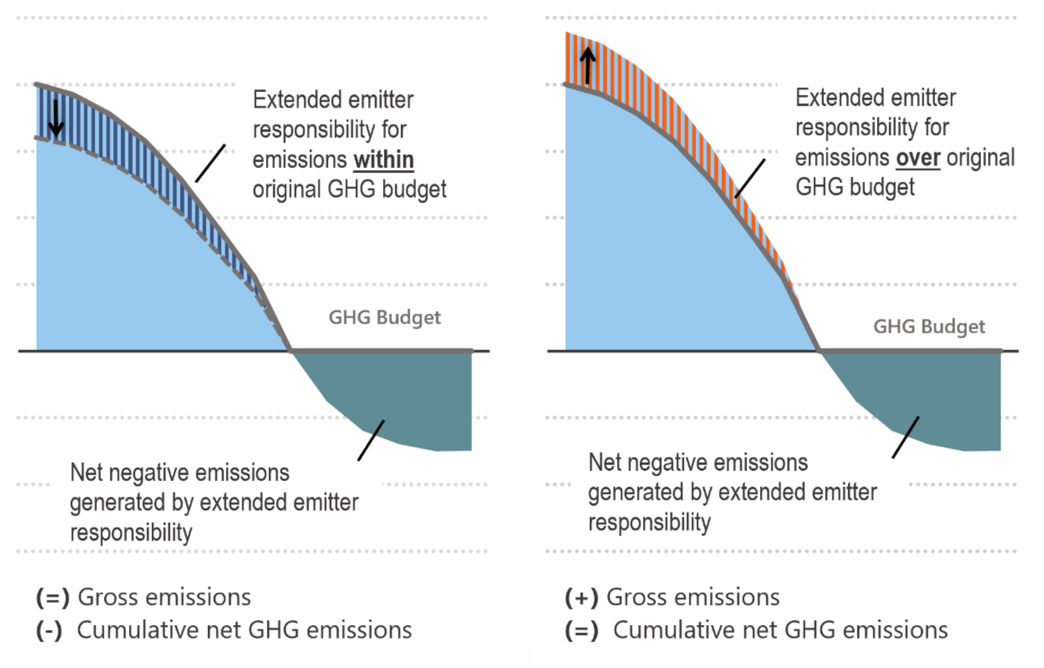
Extended emitter responsibility, and the intertemporal flexibility it provides, could be used to either increase ambition over time or lower costs over time.

In line with the overall intertemporal flexibility provided by net-negative emissions (see Section 1.3), the concept of *extended emitter responsibility* have been discussed as serving two potential purposes in relation to a given GHG budget (Lessmann et al., 2024), as illustrated in Figure 14.

[16] As an overarching term, the Advisory Board calls several related concepts from the literature the 'extended emitter responsibility'. This also aims to distinguish this concept from the 'carbon debt' concept, which is sometimes used to describes the initial GHG emission from biomass harvesting and combustion (Mitchell et al., 2012).

- The left panel illustrates how an extended emitter responsibility could be used to reduce cumulative net GHG emissions, often described as a way to increase ambition over time. It implies that, for a certain share of emissions that occur *within* a GHG budget in the first period, the extended emitter responsibility is attached. For these emitters, this creates an explicit responsibility for these emissions in the first period to be counterbalanced by net-negative emissions in the second period. As described in more detail in Section 12.2, the literature that assessed this approach generally assumes that the emitter would pay for the future removal, but not for the original emission. Governments (or in the case of an ETS, the market regulator) would reduce the emission budget available to the economy in the first period accordingly to prevent a temporary increase gross emissions and ensure that cumulative net greenhouse gas emissions are lower over time. It could also be considered to require emitters to pay both for their emissions in the near term (as a price to temporarily stock their GHGs in the atmosphere) and for removing those emissions at a later stage, but to the knowledge of the Advisory Board the potential distributional impacts and potential welfare impacts of such an approach have not yet been assessed.
- The right panel illustrates how an extended emitter responsibility could make it possible to reduce the overall cost of achieving a set GHG budget over time. In the first period, the extended emitter responsibility is attached to emissions over the original GHG budget, which are then required to be counterbalanced by net-negative emissions at a later stage. Under this approach, cumulative net GHG emissions remain constant over the long term, but are shifted over time (with a net increase in the GHG budget in the first period, and a net decrease in the second). This approach is generally described as an option that could improve cost-effectiveness, assuming that the marginal reduction and removal costs in the first period are higher than the marginal cost of net-negative emissions in the second period as removal costs decrease over time (Lessmann et al., 2024). It has also been described in the event of a global depletion of the global GHG budget, in which case, all emissions would require to be counterbalanced with future net-negative emissions in order to ensure that net cumulative GHG emissions remain constant (Bednar et al., 2023a; Lyngfelt et al., 2024).

Figure 14 Illustrative roles of net-negative emissions with an extended emitter responsibility



Source: Advisory Board, based on concepts and descriptions in (Bednar et al., 2021; Lessmann et al., 2024; Lyngfelt et al., 2024)

Given uncertainty about future removal costs, risks of climate tipping points and irreversible damages from climate change impacts, the challenge of enforcing liabilities and considerations of intergenerational fairness, net-negative emissions should be primarily used to increase the ambition of the EU's GHG budget over time.

Under ideal conditions, using intertemporal flexibility as implied by the second approach could achieve the same climate outcome at lower social costs. This would require two main conditions: that decision-makers have perfect information about current and future reduction and removal costs, including climate sensitivity and future climate impacts; and that future compliance with intertemporal removal commitments is a certainty (Edenhofer et al., 2024b). However, in practice these conditions are not fulfilled. As described in Section 4.2.1 (and in particular in Box 2), postponing reductions in anticipation of (uncertain) future removal capacities increases the risk of exceeding the GHG budget if these removal capacities don't materialise, as well as triggering climate tipping points and irreversible damage caused by climate impacts if the GHG budget is 'frontloaded' to the first period. Furthermore, uncertainty about future climate sensitivity and potential tipping points make it impossible to accurately determine the required amount of future net-negative emissions to counterbalance the climate risks of delayed mitigation action today. Ensuring future compliance with such intertemporal removal commitments is challenging, as entities carrying an extended emitter responsibility could default on their commitment (e.g. due to limited firm liabilities or bankruptcies). Finally, whereas such an approach could be made compatible with the climate objectives under the European Climate Law – provided that the point year targets for 2030, 2040 (forthcoming) and 2050 are met – it is more challenging to reconcile with the Advisory Board's previous recommendations for a 2030-2050 GHG budget (Advisory Board, 2023).

Therefore, options to implement an extended emitter responsibility and achieve net-negative emissions in the EU should be primarily considered with the aim of increasing ambition and reducing the EU's cumulative GHG budget over time. This approach can be considered and applied in different contexts and instruments in the EU, but would support global efforts to avoid and limit a temperature overshoot, while increasing the fairness of the EU's contribution to global climate action (Advisory Board, 2023).

4.5.2 Status and policy gaps

The current EU climate framework insufficiently addresses the need for net-negative emissions after 2050. Addressing this represents a paradigm shift for EU climate policy.

Whereas the European Climate Law requires the EU to aim to achieve net-negative emissions after 2050, this objective and the instruments to achieve it have to date received little or no further consideration in the EU climate policy framework, as further elaborated in Chapter 10. For the above-mentioned reasons, the EU needs to start clarifying its approach to this in the coming years, which will represent a paradigm shift for EU policies. Possible approaches to incentivise net-negative emissions are described in Chapter 12 and assessed in Section 14.1.

4.6 Summary of EU policy gap assessment

Table 10 summarises the policy assessment carried out in this chapter, by providing an overview of the current status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024).

Table 10 Summary of the EU policy assessment of Chapter 4

Policy	Status	Gaps and inconsistencies
European Climate Law	Sets binding targets for net emission reductions in 2030 and 2050, including maximum contribution of net removals in 2030 of 225 $MtCO_2$. Ambition to achieve net-negative emissions after 2050.	Lack of clear targets and clarity on role of emission reductions and removals beyond 2030. → **policy gap** Unclear distinction regarding roles of permanent and temporary removals. → **policy gap**
EU Emissions Trading System	EU ETS provides financial incentives to apply fossil-CCS on point source installations, but no incentives for removals. European Commission to report on possibility of integrating removals by 2026.	No mechanisms or incentives for removals within current market structure, for instance for BECCS or DACCS. → **policy gap**
Effort Sharing Regulation	Allows a limited use of LULUCF credits to counterbalance emissions under the Effort Sharing Regulation.	Risk or consequences of reversals of temporary removals not explicitly addressed. This will be an issue if the LULUCF sector is no longer subject to national, binding targets in the future. → **policy gap**
LULUCF regulation	Sets binding EU-wide and national targets for net removals from the LULUCF sector for 2030.	LULUCF net sink currently going in the wrong direction from its 2030 target. → **implementation gap** Exclusion of LULUCF sector from emissions pricing, providing few financial incentives for land managers to reduce emissions and increase removals. → **policy gap** Signals and pressures from other policies (e.g. energy, agri-food) undermine incentives to increase the LULUCF sink. → **policy inconsistencies** Lack of clarity on long-term targets for the LULUCF sector post-2030. → **policy gap**
Net-Zero Industry Act	Sets an EU-wide target to achieve at least 50 $MtCO_2$ injection capacity in geological storage per year by 2030, including an individual obligation for fossil fuel producers to contribute to achieving this capacity target.	Does not distinguish between removals and fossil-CCS. → **policy gap**

Policy	Status	Gaps and inconsistencies
	Does not currently contain an EU-wide target for after 2030, but requires Commission to assess and (if necessary) make a proposal by 2028.	Lack of clarity on long-term targets for after 2030, with assessment by European Commission required by 2028. → **policy gap**

5 Maintaining fiscal sustainability and enhancing distributional fairness

- **Substantial investments are needed.** Achieving net-zero and net-negative emissions will require substantial, long-term investments in removals. In the meantime, fiscal sustainability needs to be maintained, with increasingly constrained public budgets. The EU should combine public funds with leveraging private capital through innovative financing mechanisms and applying the polluter pays principle to ensure sustainable funding pathways for removals.

- **Current EU funding is inadequate.** The EU's funding instruments under the multiannual financial framework are not fully aligned with strategic climate priorities. Furthermore, inadequate tracking of spendings on climate action hinders transparency. The EU should enhance the alignment of funding mechanisms with climate objectives and improve resource-tracking methodologies.

- **Distributional fairness should be a priority.** The deployment and funding of removals risks exacerbating socio-economic disparities if cost-effectiveness is prioritised without addressing fairness. Policies should include compensatory measures, such as subsidies and rebates to mitigate regressive impacts on vulnerable households and regions.

- **Equitable investments can build on EU principles.** Core EU principles and values, including polluter pays and solidarity, provide a strong foundation for equitable removal investment strategies. Policymakers should use them to balance the benefits and trade-offs of removals while striving for intergenerational equity within a just and inclusive transition.

5.1 Introduction

Scaling up removals to address escalating climate risks and prevent catastrophic impacts on human health and Europe's economy will require substantial investments, but this poses fiscal sustainability challenges.

Climate risks in Europe are already significant and projected to rise. By the end of the century, they could result in hundreds of thousands of deaths from heatwaves and annual economic losses exceeding EUR 1 trillion from coastal flooding alone (EEA, 2024b). Even with additional mitigation efforts, Europe is likely to see per capita income losses of approximately 11% (median) by the mid-century in comparison to a baseline without climate change (Kotz et al., 2024). Without rapid GHG emission reductions and preparations for limiting temperature overshoot, fiscal pressures on Member State budgets are likely to grow.

Removals can help mitigate the rising costs of climate impacts, but scaling them up will require substantial investments, with estimates from the literature and scenarios suggesting that annual costs could range from 0.1-0.8% of EU GDP by 2050 (see Section 4.5.1). The scale of the investment needed, at a time where public budgets are increasingly constrained, highlights the importance of identifying stable funding sources and ensuring fiscal sustainability.

Fiscal sustainability refers to the ability of a public body to sustain its current spending, tax and other-related policies in the long run without threatening its solvency or defaulting on some of its liabilities or promised expenditures. This is also important from an intergenerational fairness perspective as an unsustainable fiscal position will burden future generations and constrain the ability of Governments to issue new debt to ensure the smooth functioning of the economy and respond to unforeseen circumstances. The scale up removals will require significant levels of investment, necessary to address global warming and mitigate the worst climate impacts, but this will need to be done while ensuring fiscal sustainability and ensure intergenerational fairness.

Achieving and sustaining net-zero and net-negative emissions will require long-term financial commitments, combining private sector contributions, government support and upfront investments to address cost uncertainties and ensure fiscal sustainability.

Reaching and sustaining net-zero and net-negative emissions require a long-term political commitment and a stable financial foundation. While private sector contributions are essential, government support will remain critical to lower the risk for private investors in emerging technologies and attract private funding, particularly for less mature technologies. GHG pricing instruments could play a key role by enabling emitters to contribute to the financing of removals (see Section 14.2).

In addition to operational costs, scaling up removals will require substantial upfront investments in innovation (Chapter 8), CO_2 infrastructure (Chapter 9), ecosystem restoration and land sink preservation (Chapter 7) and MRV systems (Chapter 6). The scale of funding needed for development and up-scaling removals is affected by the uncertainties around financial returns for certain technologies due to their low TRLs (Chapter 8). Long-term financing frameworks should address these technological risks through sufficient funding, while ensuring the removal volumes needed to sustain net-zero and net-negative emissions.

Addressing the distributional impacts of financing removals is critical to the just transition, as decisions on financing options for removals affect fairness, resource allocation, and public acceptability across society and between EU countries.

Ensuring a just transition requires careful consideration of how the costs, benefits, and impacts of removals are distributed across society. Financing options for removals raise critical economic, political, and ethical questions about who bears the costs and how these are shared. Additionally, the opportunities and risks associated with removals, such as resource availability e.g., energy, food, water, land and environmental externalities, such as seismic risks, pollution and ecosystem disruptions, also have significant distributional implications both within society and across EU countries (Chapter 3). Implementation challenges — such as administrative burden, skills gaps, or the geographical distribution of CO_2 infrastructure — add further complexity to achieving fairness. The Advisory Board has consistently emphasised the need to systematically address distributional impacts of climate policies and measures, as doing so improves policy effectiveness (Advisory Board, 2024, 2023b).

5.2 Maintaining fiscal sustainability

5.2.1 Need

The EU's limited fiscal capacity, exacerbated by recent crises and long-term challenges, underlines the need for innovative financing solutions to meet climate objectives and address strained public budgets.

The EU and its Member States face growing fiscal pressures due to recent crises, including the COVID-19 pandemic, the Russian invasion of Ukraine, and the energy crisis. These events have led to higher deficits and debt levels across the EU, which are further strained by long-term challenges such as an ageing population and the escalating impacts of climate change (Advisory Board, 2023). Despite these pressures, significant additional investments are needed to meet EU climate objectives, including decarbonising energy and transport systems, fostering innovation, and supporting vulnerable households during the transition (Advisory Board, 2024).

While the EU's long-term budget is expected to contribute to these investments, the budget's size – approximately 1% of EU GDP per annum – limits its capacity to address all future spending needs (Eurostat 2024). The EU's long-term budget relies mainly on contributions from Member States, which account for over 70% of its revenues, and its own resources that are currently limited, despite the European Commission's proposal to expand them (EU, 2024c). Securing new financial resources at EU level faces significant hurdles, including unanimity requirements for taxation measures and strained fiscal space in many Member States (Cornillie et al., 2024; Efstathiou and Wolff, 2023). The Recovery and Resilience Facility provided an instrument to raise finance at the EU level, providing some fiscal space for investment in climate mitigation and adaptation, but this is set to expire at the end of 2026.

A coordinated EU approach leveraging private investment and applying the polluter pays principle offers a sustainable pathway to fund removals.

The EU has a limited fiscal capacity as compared to its Member States: the combined national budgets of the 27 Member States amount to nearly 50% of the EU's GDP, outweighing the EU's long-term budget (Eurostat, 2024a). However, national public investment also faces affordability challenges, administrative constraints and the risk of fragmenting the single market (WKR, 2024; Honegger et al., 2021b). Most funding for climate mitigation – including for removals – need eventually to come from private sources, which can be mobilised through an EU-coordinated, long-term approach to both public and private investments (ECB, 2024).

A key guiding principle to fund removals could be the polluter pays principle, foundational in EU law (Article 192 of the Treaty on the Functioning of the European Union), and echoed, among others, in the European Climate Law (EU, 2021b), the industrial emissions directive (EU, 2010), the waste framework directive (EC, 2008) and the environmental liability directive. In a general context, applying the polluter pays principle means that polluters bear the costs of their pollution including the cost of measures taken to prevent, control and remedy pollution and the costs it imposes on society (ECA, 2021). Within the context of the different incentive instruments for removals explored in Part C of this report, applying the polluter pays principle implies that the instrument requires GHG emitters to pay for their emissions (to compensate for the costs these emissions impose on society), or to deploy or finance the deployment of removals to counterbalance their residual emissions. It can be operationalised through tools like carbon taxes or cap-and-trade schemes, such as the EU ETS. Such an approach would allow removals to be rewarded directly or indirectly while reducing the burden on public finances: if GHG emitters pay for their emissions, the revenues of these payments can be used to reward removals through subsidies and public procurement. If GHG emitters counterbalance their emissions with removals, the reward is provided directly in the form of either avoided costs (if the emitter deploys removals itself) or financial payments (if the emitter remunerates a provider of removals).

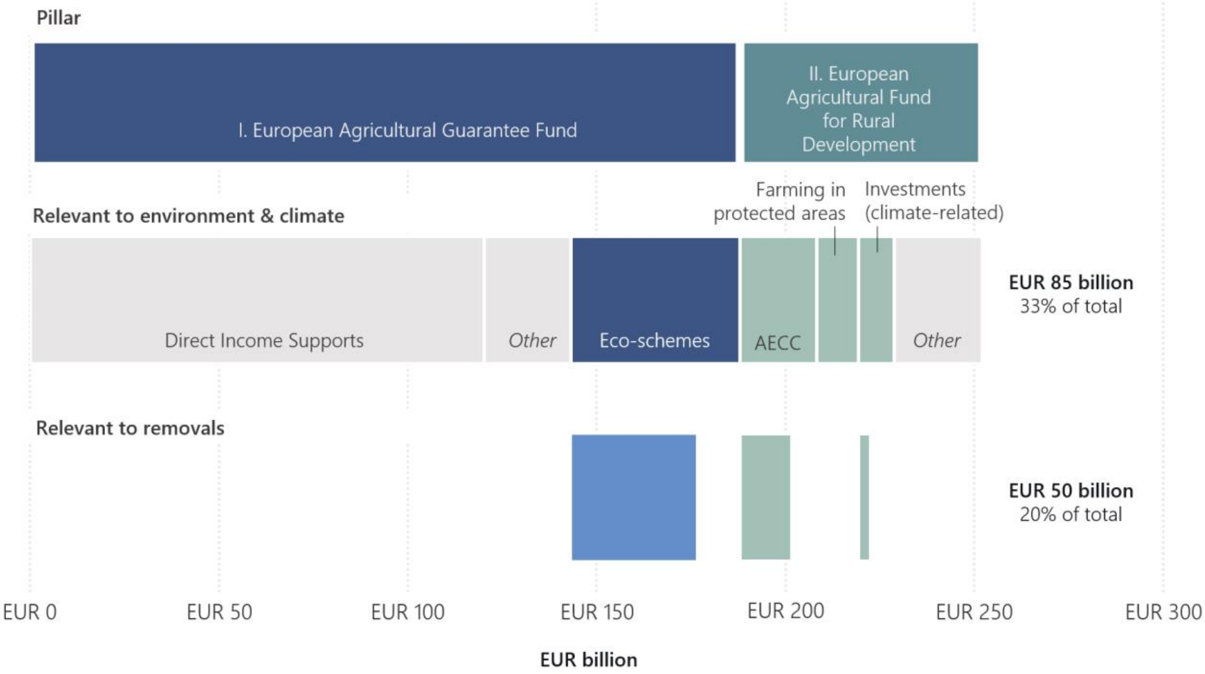
5.2.2 Status and policy gaps

Direct EU funding for removals has been minimal so far. Insufficient alignment of the EU's long-term budget with climate priorities and inadequate tracking methodologies hinder transparency and effectiveness.

Direct public funding for removals from the EU budget remains minimal. While some programmes under the 2021-2027 multiannual financial framework, the EU's current long-term budget, indicate eligible funding for temporary and permanent removals (shown in Table 11), these resources are often disbursed across multiple policy goals, with limited data on the specific amounts allocated to removals. Current potential funding sources can be categorised into three main groups:

- **CAP**. As shown in Figure 15 below, Approximately EUR 85 billion over 2023-2029 supports interventions related environment and climate, including eco-schemes, agri-environment climate commitments (AECCs), farming in protected areas, and or other climate-relevant investments. Within these categories, up to EUR 50 billion over 2023-2029 supports interventions that are relevant to removals, including interventions targeting carbon storage in soils and biomass, and support for forestry or sustainable forest management. It should be noted that many of these interventions support multiple policy objectives, meaning that in many cases, removals may only be a secondary or indirect objective. Furthermore, several assessments warn that the impact of climate and environment-related funding under the CAP could be limited, due to its focus on agricultural productivity and due to insufficient incentives for large-scale carbon sequestration (ECA 2020; ECA, 2024; 2021; Pe'er et al. 2020). This issue is explored further in Chapter 7.
- **Nature and biodiversity funding**. Programmes such as EU LIFE and regional development policies contribute to ecosystem restoration projects (e.g. forests, wetlands), which can provide temporary removals. However, implementation challenges and insufficient funding have limited their effectiveness (Hermoso et al., 2022; ECA, 2013), as presented in Chapter 7.
- **Funding for permanent removals and carbon management technologies**. Subsidies for permanent removals are primarily available through the EU Innovation Fund, supported by EU ETS revenues, with additional contributions from the Recovery and Resilience Facility. These funding streams are further explored in Chapter 8.

Figure 15 Disaggregation of cumulative funding in the EU's common agricultural policy by funding stream, 2023-2029



Source: Advisory Board analysis, based on data from DG AGRI (2024)

Note: Removal-relevant interventions identified by relevant 'result indicators', as indicated in data submitted by member states under their national strategic plans. Relevant indicators for removals included R.14 (carbon storage in soils and biomass), R.17 (afforested Land), R.18 (investment support to the forestry sector), R.19 (improving and protecting soils), and R.30 (supporting sustainable forest management). Climate-relevant investments identified by those under specific objective 4 (climate mitigation). As CAP interventions are often mapped under multiple result indicators, removals may only be one of many objectives targeted by a particular intervention.

Despite these efforts, the allocation of resources under the current multiannual financial framework does not fully align with the EU's strategic climate priorities. A significant portion of the 2021-2027 framework is allocated to cohesion and CAP policies, leaving critical areas like innovation and climate underfunded (Draghi, 2024; Advisory Board, 2024) **(ambition gap)**. Furthermore, flaws in the methodology for tracking climate-related spending hinder transparency and the effective monitoring of investment in removals (Advisory Board, 2024) **(ambition gap)**.

Table 11 Existing EU funding instruments available to potentially support temporary and permanent removals, excluding the common agricultural policy

Programme	Period	Type of removals	Stream	Funding (EUR, million)
European Regional Development Fund	2021-2027	Temporary	*RSO2.7 Nature protection and biodiversity*	5,800
Cohesion Fund	2021-2027	Temporary	*RSO2.7 Nature protection and biodiversity*	1,600
European Maritime Fisheries and Aquaculture Fund	2021-2027	Temporary	*MSO1.6 Protection and restoration of biodiversity*	370
EU LIFE Programme	2010-2020	Temporary	*Funding for various projects involving forests, wetlands, agroecosystems etc.*	1,414
	2020-2020	Permanent	*Funding for carbon capture and storage*	15
Innovation Fund	2021-2024	Permanent	*Funding awarded to CCS and carbon management projects up to 2024*	3,291
Recovery and Resilience Facility	2021-2026	Permanent	*Funding allocated for CCS and carbon management measures*	4,845
	2021-2026	Temporary	*Funding allocated for various ecosystem and biodiversity measures*	2,920
Connecting Europe Facility	2021-2023	Permanent	*Funding awarded for carbon capture and storage infrastructure*	572
Horizon Europe	2021-2024	Temporary	*Horizon Europe mission 'a soil deal for Europe'*	423
	2021-2024	Permanent	*Horizon Europe Cluster 5 on climate, energy and mobility*	1,040
Temporary				**13,187**
Permanent				**9,763**

Source: Advisory Board

Note: Funding amounts presented here are indicative, based on a high-level assessment of instrument budgets and project portfolios. Figures reflect the total funding made available for programmes or themes that could potentially support removals. While some of this funding may directly or indirectly benefit removals, it is likely that removals only accounted for a small share of the funding. Where possible specific funding calls that are relevant for removals have been identified but in some cases broader categories have been used, where only a subset of the funding volumes are relevant for removals.

The EU lacks long-term regulatory clarity, targeted funding mechanisms, and streamlined administrative processes to support large-scale removals.

Whereas the EU climate policy framework sets out the broad direction of the transition towards climate neutrality, key gaps in the framework undermine long-term regulatory visibility and certainty needed to support investments in climate mitigation measures. These include lack of clarity on how the EU ETS will be managed when its emission cap approaches zero (Advisory Board,) ,on the respective contributions of reductions and removals towards the 2040 and 2050 targets (see Section 4.3), on the different roles of temporary and permanent removals (see Section 4.4), and on the framework to manage net-negative emissions after 2050 (see Section 4.5).

Furthermore, there is a lack of sufficiently strong incentive schemes (see Section 4.5) or dedicated funding instruments to stimulate financially viable removal projects. Existing EU instruments, such as Horizon Europe and the Innovation Fund, provide some support but are insufficient in scale and often focus broadly on decarbonisation, leaving removal methods underfunded (Chapter 8). Technologies like DACCS and biochar remain in early development stages, posing high risks for private investors seeking medium-term returns. Targeted policy mixes are needed to address these challenges, including funding mechanisms for early-stage development and risk reduction strategies (Chapters 5 and 8). Moreover, fostering public-private partnerships could leverage both expertise and capital to scale infrastructure (Advisory Board, 2024; Dolphin et al., 2023).

Administrative barriers may hinder investment. Complex permitting processes and cumbersome access to EU-level funding discourage investors and may limit the participation of small organisations and start-ups in climate technologies (Draghi, 2024). Navigating extensive documentation, meeting stringent eligibility criteria, and engaging with multiple regulatory bodies at the national and EU level often delay projects or even become prohibitive altogether. As a result, the EU lags behind other jurisdictions like the United States and China in advancing commercial-scale CO_2 removal initiatives (Smith et al., 2024). Simplifying permitting processes, reducing administrative burdens and improving access to EU-level funding are critical to accelerating progress and attracting private investment in removals.

The Recovery and Resilience Facility expanded EU investment capacity but is set to expire in 2026. The common debt approach and new own resources can help sustain public investment and manage upcoming debt repayments.

The EUR 648 billion (in 2022 prices) Recovery and Resilience Facility, established in response to the COVID-19 pandemic, significantly expanded the EU's ability to invest directly in climate and other policy objectives (EC, 2023b). Prior to its entry into force, the European Commission lacked the ability to raise finance outside the regular budgetary framework. However, the Recovery and Resilience Facility is set to expire at the end of 2026, with no current plans for an extension.

The Advisory Board has recommended that the EU consider extending the common debt approach to enhance investor certainty and boost public investment in climate action (Advisory Board, 2024). A similar recommendation was made by Mario Draghi in his report on the future of European competitiveness (Draghi, 2024). Additionally, the repayment of NextGenerationEU bonds, which funded the Recovery and Resilience Facility, begins in 2028. Without a decision on new own resources to finance these repayments, the EU budget could face significant strain (Draghi, 2024). At present, there are no plans for extending this instrument or securing alternative mechanisms to sustain public investment **(policy gap).**

The inconsistent application of the polluter pays principle highlights the need for targeted policy adjustments to unlock funding for removals while balancing distributional fairness and public acceptability.

Whereas the extension of the EU ETS to buildings and road transport expands the application of the polluter pays principle to a majority of EU GHG emissions, the EU's GHG-pricing regime still has some gaps as the agricultural and LULUCF sectors are currently not yet included in any EU-wide GHG-pricing system (Advisory Board, 2024). Furthermore, the European Court of Auditors has highlighted the inconsistent implementation of the polluter pays principle in broader environmental policy areas, including air, water, soil and waste (ECA, 2021). Further extending the scope of the EU GHG-pricing regime would raise additional revenues to fund climate objectives including removals. Further strengthening the enforcement of the polluter pays principle in other environmental areas could also increase public revenues overall, which might also be used to fund social policy interventions that are affected by EU's climate policy measures.

As explained in more detail in Part C of this report, proposals for GHG emitters to contribute to funding removals through carbon taxes or targeted levies are gaining traction in the scientific literature (WKR, 2024; Lyngfelt et al., 2024). Different ways of leveraging EU ETS revenues have been considered to scale up removals (Rickels et al., 2023). Similarly, discussions on and proposals for introducing GHG pricing instruments for the EU's agri-food sector have also highlighted the possibility of directing revenues towards subsidising temporary, land sector removals (Trinomics 2023; Danish Climate Council 2024).

The use of EU ETS revenues faces competing priorities. Most of the EU ETS auctioning revenues flow back to Member States, who are required to allocate it to climate mitigation and adaptation measures. The EU ETS directive allows Member States to use the revenues to fund both temporary and permanent removals. However, reporting on how these revenues are invested in practice has been considered inadequate, and not all revenue is directed towards climate action as intended (Ecologic, 2022a). A share of EU ETS revenues flow to the Innovation Fund and the Modernisation Fund, which also focus on energy and industrial decarbonisation (EEA and ACER, 2023).

5.3 Enhancing distributional fairness

5.3.1 Need

There is a need to recognise the potential positive distributional impacts from scaling up CO_2 removal methods.

Distributional fairness and fiscal sustainability are interlinked, as equitable policies require a stable financial foundation to ensure consistent support for vulnerable groups. There is a policy need to mainstream the role of removals as an instrument that can address distributional fairness. If removal methods either contribute to lowering carbon prices or facilitate the attainment of ambitious climate objectives, they can produce a positive distributive impact on vulnerable households, as both high carbon prices and severe climate impacts are typically regressive in nature (IPCC 2023b,Honegger et al. 2021, Bardazzi and Pazienza 2024).

Potential distributional challenges need to be acknowledged, as some permanent removal methods risk concentrating benefits among the wealthy, while temporary removals present governance and sustainability challenges.

Some permanent removal methods, such as BECCS and DACCS, will most likely tend to concentrate control and benefits among large operators or well-capitalised entities due to the high upfront costs and technical expertise requirements (Brack and King 2021; Lyngfelt et al. 2024). This concentration risks exacerbating inequalities, as wealthier Member States or established companies are better positioned to capitalise on innovations and patents related to these technologies. Furthermore, local communities hosting such facilities may see limited benefits, as the technologies often lack ancillary social or environmental advantages and may bear the local externalities that often comes with such facilities. BECCS plants, for instance, require substantial biomass inputs, which can create trade-offs, such as competition for land or water resources, disproportionately affecting local populations (Fuss et al., 2018) (see Chapter 3).

In contrast, temporary removals, such as reforestation or carbon farming, as well as some permanent removals, such as biochar, are often viewed as more accessible and scalable across diverse regions, but with their own distributional challenges. Reforestation can provide broader benefits, including biodiversity conservation, ecosystem services, recreative value, and support for local livelihoods (see Chapter 3), but the distribution of such benefits is conditioned on local property rights. Carbon farming offers potential economic opportunities for rural areas by diversifying incomes and creating new business avenues to farmers. However, land governance for LULUCF removals can lead to conflicts, marginalising rural communities that depend on these ecosystems. Moreover, while temporary removals may be cost-effective in the near term, they require long-term commitments for monitoring and management.

Considering distributional fairness in policies that support removals is needed to prevent exacerbating inequalities, maintain social cohesion and support the EU's climate objectives.

There is a need to address consider distributional fairness, as scaling up removals can disproportionally affect certain social groups and regions (IPCC, 2022k). These include vulnerable households (e.g. if removals are incentivised through carbon pricing, the impacts of which are discussed in Box 4) and regions dependent on industries with limited mitigation alternatives. Without ensuring distributional fairness – the equitable sharing of costs and benefits across society – these policies risk exacerbating existing inequalities or creating new ones.

The choice of instruments to manage, incentivise and fund removals can have uncertain distributional impacts, particularly on households. Research on the specific distributional effects of removal incentives is currently limited. One study from the UK (Owen et al., 2022a), focusing on incentive mechanisms for BECCS and DACCS, suggests that the distributional impacts these instruments can mirror the underlying tax or financing structure. Their modelling results suggest that funding removals through carbon pricing or targeted emitter obligations could have regressive effects if costs are passed on to households, with lower-income households disproportionately affected through spending on essentials like energy and food. Conversely, they suggest that funding removals through general taxation has the potential to be more progressive, assuming that the underlying tax structure is also progressive, although some pass through of costs may be desirable to ensure polluters pay a more equitable share (Owen et al., 2022a; Andreoni et al., 2024). highlight the risk that policies to incentivise removals could lead to large windfall profits for private companies, which could exacerbate economic inequalities if technology value chains predominantly benefit richer countries. On the other hand, removals may also contribute to mitigating adverse distributional impacts of carbon pricing in future, particularly if used to counterbalance residual emissions from activities for no or limited mitigation alternatives, and those who face prohibitively high marginal abatement costs to fully reduce emissions (Edenhofer et al., 2024b; Sultani et al., 2024).

These findings highlight the complexity of balancing equity with incentives for emission reductions, and the design of removal incentives and redistributive measures will also need to consider public perceptions, which can act as an obstacle even when policies are progressive, to ensure public acceptance (Douenne and Fabre, 2022; Carattini et al., 2019).

To mitigate these risks, policymakers should proactively identify and address the regressive economic and social impacts of CO_2 removal policies. Targeted measures to support vulnerable groups and regions, which take into account of public perception, are essential to fostering social cohesion and ensuring the success of the EU's climate transition.

Box 4 Addressing distributional impacts in carbon pricing

Carbon pricing can disproportionately affect lower-income households, making measures like rebates and targeted subsidies essential for ensuring a fair and equitable transition to a low-carbon economy.

Carbon pricing, while consistent with the polluter pays principle, can have regressive impacts, disproportionately affecting lower-income households, depending on the country context (e.g. Feindt et al., 2021). This occurs because carbon pricing mechanisms increase the cost of energy and goods, which comprise a larger share of expenses for poorer households. Although wealthier households typically generate more emissions due to higher consumption, lower-income families spend a greater proportion of their income on carbon-intensive essentials like heating and transportation (Gough, 2011). For example, rising fuel or electricity prices from carbon taxes can strain household budgets, especially as these families have limited means to invest in energy-efficient technologies or adopt cleaner alternatives.

Mitigating these regressive effects is critical to ensure a fair transition to a low-carbon economy. Measures such as (targeted) income support, rebates, targeted subsidies, or social welfare adjustments can help alleviate the burden on vulnerable households, making carbon pricing more equitable and socially just (Owen et al., 2022b).

Source: Advisory Board

EU values and principles, such as solidarity and polluter pays, provide a foundation for removal strategies, guiding policymakers in balancing trade-offs between cost-effectiveness and social fairness through evidence-based and transparent approaches.

The EU's foundational principles values, embedded in EU treaties and laws (Advisory Board, 2023) provide a strong framework for addressing distributional fairness. These include the precautionary principle, the polluter pays principle, the 'do no harm' principle of the European Green Deal and the 'energy efficiency first' principle of the Energy Union. In addition, the principles of proportionality, subsidiarity and better lawmaking, along with the EU's fundamental principle of solidarity, emphasise the fair sharing of both benefits and burdens (Treaty on the Functioning of the European Union, Article 2; Eurofound 2021). These values offer a foundation for developing future policy frameworks for removals.

These principles have already informed the Advisory Board's recommendations for the EU's 2040 climate target and can guide the design of removal strategies to align with social, environmental and economic objectives. However, developing a policy framework for scaling up removals entails making value-based decisions that can reveal tensions, such as balancing cost-effectiveness with social equity (IPCC, 2022e). Addressing these trade-offs requires scientific, evidence-based policy making and transparent communication to build public trust and ensure fairness (EU, 2008a; Advisory Board, 2023).

Removals policies may need to address intergenerational, societal and geographical equity, balancing responsibilities, mitigating regional disparities and ensuring fair access to resources and infrastructure.

Addressing potential regional disparities in removal policies requires considering multiple dimensions of equity and fairness.

- **Intergenerational equity** is critical, as today's emissions increase the burdens of future removals and climate change impacts on future generations (Davies, 2020), including making adaptation more expensive and difficult. This principle can incentivise stronger and fairer climate action, help weigh trade-offs and enhance public participation. An equitable approach also balances responsibility for past emissions, guided by the polluter pays principle, with the 'ability to pay' approach, which assumes that wealthier Member States with higher GDPs per capita are better positioned to finance the deployment of removals (Brad and Schneider, 2023; Kwasiborska et al., 2023; Koponen et al., 2024)
- **Societal distributional impacts** vary between removal methods, reflecting differences in how benefits and burdens are shared (Minx et al., 2018). For instance, large-scale removals like BECCS could reduce land availability for food production, potentially increasing food prices. As food expenses constitutes a larger proportion of the consumption costs of low-income households, increases in food prices can disproportionately affect these households and may also lead to reduced food security (see Chapter 3).
- **Geographic disparities** could also emerge in terms of access to removal methods, challenges in implementing them, and the risks and opportunities. For example, Member States far from offshore geological storage hubs face challenges in accessing transport and storage infrastructure (see Chapter 9). High energy and water demands of some removal methods may disproportionately strain regions already experiencing resource scarcity (Jaiswal et al., 2024). There may also be disparities in terms of how climate impacts affect Member States, which could reverse removals.

Addressing these dimensions of equity requires carefully designed policies that balance responsibilities, mitigate impacts on vulnerable communities and ensure fair access to resources and infrastructure.

5.3.2 Status and policy gaps

The lack of systematic measurement of distributional impacts and insufficient public involvement in EU climate policies undermines societal buy-in, highlighting the need for greater transparency and meaningful engagement to ensure policy legitimacy and effectiveness.

The European better regulation toolbox (EC, 2023d) provides policymakers with guidance on best practices for conducting impact assessments, including evaluating the socioeconomic and distributional effects of proposed policies on removals. It requires that new regulations undergo thorough impact assessments to analyse potential disproportionate effects on vulnerable populations, regional disparities, and income inequality (EC 2021a). The Toolbox serves as a critical resource to ensure these impacts are systematically evaluated and addressed, promoting equity in the transition to a low-carbon economy.

Despite the better regulation toolbox providing guidance on assessing distributional and wider socioeconomic impacts, EU climate policies often lack systematic measurement of these effects (Advisory Board, 2024) **(implementation gap)**. Evidence from recent studies highlights this gap, showing inconsistent evaluation of the societal impacts of EU climate measures. This oversight can undermine the successful adoption and implementation of policies, as insufficient societal buy-in reduces perceived legitimacy (Advisory Board, 2024). There are also risks that are very localised and context-dependent (see Chapter 3), which might not be covered in common data collection indicators and thus go unaddressed.

Public participation in climate policy planning, such as the development of NECPs, has also been insufficient in many Member States, as further explained in Section 10.2. Limited opportunities for consultation hinder citizens' ability to understand and influence the implications of climate actions. Transparent dialogue and meaningful public engagement are crucial but remains underutilised, particularly in the context of early-stage removals options. Engagement through deliberation, inclusion, and reflectiveness is essential to assess the feasibility and effectiveness of diverse mitigation strategies (Kotz et al. 2024).

Addressing these gaps in measurement and public involvement is critical for fostering trust, ensuring policy legitimacy, and enhancing the effectiveness of EU climate policies.

Compensatory measures, like the EU's Social Climate Fund, are crucial to mitigating the regressive impacts of carbon pricing, fostering public support and ensuring a socially equitable transition.

To mitigate the regressive impacts of carbon pricing, compensatory measures can support low-income households and ensure a fair transition. For instance, targeted subsidies for energy-efficient appliances, home insulation, and public transport can further reduce energy consumption for lower-income households, helping them adapt to price changes and benefit from long-term savings. A common approach is to use revenue from carbon taxes or ETS to provide direct transfers to vulnerable groups. The Social Climate Fund addresses these regressive impacts by using revenues from the expanded EU ETS, which includes emissions from road transport and buildings. The fund strengthens governance by requiring Member States to prepare social climate plans, detailing planned measures and investments to alleviate energy poverty. These plans complement the NECPs, which also cover energy poverty (Stojilovska et al., 2022). However, reliance on EU revenues alone may result in insufficient funding, underscoring the need for additional financial contributions (Advisory Board, 2024); see Section 5.2).

The Just Transition Fund provides support, targeted to regions that are the most-carbon intensive or with the most people working in fossil fuels, to help alleviate the socio-economic impact of the transition. The fund is intended to support the economic diversification and reconversion of regions most affected by the transition. This type of support could provide the dual benefit of helping to scale-up removals while also addressing socio-economic impacts of the climate transition. One notable example of Just Transition Fund investments is in peatland rewetting in Ireland (Farrell et al. 2024), which helps create sustainable jobs in environmental conservation and landscape management, benefiting communities historically dependent on peat extraction.

The instruments were not intended to address the potential distributional impacts of scaling up removals. Therefore, there is a lack of compensatory measures to mitigate potentially regressive impacts of policies to scale-up removals **(policy gap)**.

5.4 Summary of EU policy gap assessment

Table 12 below summarises the policy assessment carried out in this chapter, by providing an overview of the current status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024).

Table 12 Summary of the EU policy assessment of Chapter 5

Policy	Status	Gaps and inconsistencies
Recovery and resilience facility	The facility significantly expanded EU investment capacity for climate and policy objectives as part of post pandemic recovery efforts.	Facility ends after 2026, there are currently no plans for extending this instrument or securing alternative mechanisms to sustain public investment thereafter. → **policy gap**
Multiannual financial framework	The framework allocates funding for various EU priorities, including climate objectives.	Insufficient targeting of resources for removals and flaws in tracking methodologies hinder transparency and effectiveness. → **ambition gap**
Other		Lack of systematic measurement of distributional impacts and insufficient public involvement in EU climate policies undermines societal buy-in. → **implementation gap** Lack of future compensatory measures to mitigate the potentially regressive impacts of policies to scale-up removals. → **policy gap**

6 Ensuring the quality of removals

- **The EU's certification regulation (CRCF) aims to close policy gaps**. The LULUCF regulation supports inventory-level accounting of removals but lacks the granularity to quantify specific removal activities. The upcoming certification methodologies are expected to fill this gap and underpin the integration of removals within the EU's corporate compliance schemes and carbon markets.

- **Determining the additional GHG effect is key**. Determining the net carbon benefit of a certified removal activity requires distinguishing its impact on all GHG compared to a baseline. Net benefit is a mark of additionality that helps with effective funding allocation. The EU should ensure robust additionality tests through the certification methodologies. This calls for timely updates to the baselines, and adequate monitoring length and verification frequency, which may be challenging for temporary removals.

- **The storage duration should be reflected.** Certification of removals should reflect storage duration and reversal risks. The CRCF regulation differentiates between permanent and temporary removals but conflates emission reduction and removals under the 'carbon farming' definition, obscuring temporary removals' role in the EU's climate mitigation efforts.

- **The CRCF methodologies should include measurable sustainability indicators.** Certified removal activities need to advance broader sustainability goals, but the CRCF regulation includes undefined and mostly optional sustainability safeguards. The CRCF methodologies should include measurable sustainability indicators that encourage community benefits, as well as require and document safeguards to uphold the 'do no significant harm' principle, including binding climate adaptation benefits.

- **Reliable data and methods are a necessity.** Monitoring, reporting and verification systems must provide transparent and reliable data, science-led methodologies, and credible verification. To overcome current challenges with the collection and use of land monitoring data, the EU should deploy advanced remote sensing and digital tools and adopt an ambitious Forest Monitoring and Law and Soil Monitoring and Resilience Law. It should ensure regular updates of the certification methodologies, establish independent market oversight and safeguard the integrity of removals certification.

- **Certification and national inventories can complement each other.** CRCF regulation and national GHG inventories operate on separate MRV paths and have different purposes. Insufficiently transparent and harmonised accounting and reporting of removals in public and private commitments risks lowering climate policy ambition. The EU should address complementarity between activity-level and inventory-level GHG data to boost both the accuracy of GHG inventories and the clarity of removals' role in national obligations and climate pledges, including the EU's nationally determined contribution.

- **Net zero is required domestically.** Any upcoming revision of the CRCF regulation should not jeopardise the EU's commitment to achieve net zero through balancing of its domestic emissions and removals, or the Paris Agreement ambition for Article 6 to uphold the overall mitigation of global emissions.

6.1 Introduction

The quality of removals is assessed through the essential steps of MRV. By enabling data transparency, risk management, and accountability, MRV ensures effective mitigation and builds trust in EU climate policies.

As explained in Chapter 4, removal methods need to meet strict standards in terms of quantifiability, additionality, and storage duration in order to contribute effectively to climate goals, particularly in any context that aims to establish equivalence between removals and emissions (e.g., balancing emissions within a GHG budget, trading within carbon markets) (Oldfield et al., 2022). Given the risks and opportunities described in Chapter 3, removals need to meet strict standards in terms of sustainability and environmental integrity, and ensure that they do not create or contribute to risks that might cause harm to ecosystems or communities. The difficulty to assess and compare the quality of removal claims from a diverse range of methods, locations and actors creates a risk that incentives go towards activities that cannot be relied upon as effective mitigation actions (EC, 2022d; Mercer et al., 2024).

Certification refers broadly to the systems or processes that establish the veracity and quality of an environmental claim and, in this context, can be used to establish whether a removal practice meets these key quality standards i.e. if the removals are quantifiable, verifiable, additional, and sustainable (Smith et al., 2024). The quality of removal activities is assessed through three equally important steps: measuring, reporting and verifying (MRV). Establishing robust certification and MRV systems is a foundational measure in EU's efforts to scale-up removals and will be key to building carbon market trust and getting a social license encouraging further efforts (Smith et al., 2024, Mercer and Burke, 2023). Certification and MRV systems also form the basis of any instruments that aim to incentivise removals, as further elaborated in Part C. Monitoring, reporting, and verification are essential to (i) closing information gaps and asymmetries between public and private sectors, (ii) managing the risks and opportunities of removals (see Chapter 3), and to (iii) informing policies with evidence from projects. Monitoring, reporting, and verification underpins GHG emission accounting for several purposes (IPCC, 2005), most commonly: national-level GHG inventories, project-level certification, and company-level performance assessment. The three steps of the MRV can be generally described as follows.

- **Monitoring** is about periodically collecting data and information that quantify impacts of the removal activity, in terms of emissions and removals, future reversals, and often other sustainability dimensions.
- **Reporting** means compiling these data and information in a standardized manner and making it available to the target users.
- **Verification** consists of independent checking of the reported data and information to assess whether they reflect reality.

Monitoring, reporting, and verification have been mainstreamed in climate policy thanks to the Paris Agreement putting it at the heart of the NDC governance (Singh et al., 2016). Ensuring the robustness of MRV of removals is therefore key not only to the success of EU's climate policy efforts, but also to climate change mitigation at a global level. A list of EU policies requiring MRV of GHG emissions and removals is presented in Table 13 below.

Table 13 Selected EU policies requiring MRV of GHG emissions and removals*

Climate policy area	Law	Purpose
Governance	European Climate Law	National GHG inventories/target achievement
	Governance regulation	
Land	LULUCF regulation	
Agriculture	Effort Sharing Regulation	
Industry, energy, buildings, transport	EU ETS directive	Activity-level obligations **accounting of GHG emissions, removals not yet covered*
	CCS directive	
Energy	REDII/III	
Transport	Fuel Quality Directive	
Industry	F-gases Regulation	
Corporate sustainability	Green Claims Directive *not yet adopted*	Company-level performance assessment
	Corporate Sustainability Due Diligence Directive	
	Sustainable Finance Taxonomy Regulation	
All	CRCF regulation	Activity-level certification

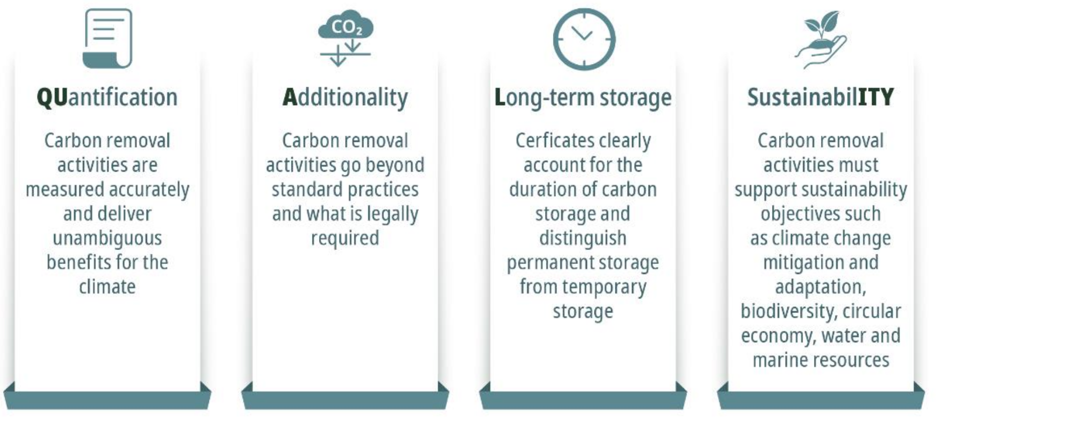
Source: Advisory Board

Beyond the LULUCF regulation (EU, 2018b) and the CRCF regulation (EU, 2024g) presented below, the EU ETS directive and its associated implementing regulations – the monitoring and reporting regulation (EC, 2018) and the accreditation and verification regulation (EC, 2018) – set out protocols for measuring and reporting project on-site emissions, including their reduction through CCS. The EU ETS compliance cycle is complemented by the CCS directive (EU, 2009b) with its MRV methodologies for carbon capture and storage activities. The CCS directive provides a framework for the selection and operation of geological storage sites and for the identification and measurement of leaks or reversals associated with the transport and storage of CO_2 (see also Chapter 9). The RED II/III and the Innovation Fund's GHG emissions calculation methodology (EC, 2024q) also include principles and rules for quantifying and assessing removals (EC, 2023p). In addition, the ongoing legislative developments aiming to establish the Forest Monitoring Law (EC, 2023l) and the Soil Monitoring Law (EC, 2023i) are important building blocks for the quantification of removals (see Section 7.5).

The EU's MRV framework for removals under the CRCF regulation is designed to ensure that removal activities meet quality criteria related to quantification, additionality, storage duration, and sustainability. The interlinkages between the CRCF rules and other EU laws should allow for dynamic information loops between the policies and foster their integration.

The EU develops MRV of removal activities under the CRCF regulation. While the CRCF framework initially applies to voluntary initiatives, it is increasingly relied on in EU binding rules e.g. under the proposed Green Claims Directive (EC, 2023e, see also Table 13 above). To be eligible for certification, a removal activity is required to fulfil four quality criteria linked to: quantification, additionality and baselines, long-term storage and sustainability (see Figure 16 below).

Figure 16 QU.A.L.ITY criteria of the EU's carbon removals and carbon farming certification framework



Source: European Commission, 2023

The QU.A.L.ITY criteria are designed to build on existing EU legislation: the CCS Directive, the LULUCF Regulation, the Taxonomy Regulation, the Renewable Energy Directive, and the Common Agricultural Policy. They are also designed to support the corporate sustainability accounting, incentives for nature-based solutions to achieve the restoration targets under the Nature Restoration Law, and the LULUCF sector's removal data for the national GHG inventories. The interlinkages between the CRCF and other EU laws necessitate a system perspective in developing MRV protocols for removals and dynamic information loops ensuring that detailed criteria for removals' quality assessment are in line with the latest technological progress and complement other EU policies. From a global system perspective quality of removals depends on the complementarity between MRV of removal activity under the CRCF regulation and MRV of other GHG emission reporting and accounting schemes. EU policy needs to avoid decreasing climate ambition by inadequately double-counting of removals (e.g. certifying a single removal under two programmes, using a removal credit as an offset twice, claiming of a removal by two entities without appropriate nesting) (Smith et al.,2024).

This chapter focuses on the following aspects of the emerging removals quality assessment framework at the EU level, which are identified as key to ensuring removals' economic, environmental, and social integrity:

- **quantification** of removals,
- ensuring removals **additionality**,
- reflecting **storage duration**,
- safeguarding wider **sustainability**,
- enhancing **data and processes** and
- addressing the **complementarity** of activity-level MRV and national GHG accounting.

6.2 Quantifying removals

6.2.1 Need

A key task in assessing the quality of a removal is quantifying its net GHG impact so it can be determined if emissions from the activity are lower than the amount of GHG removed. Harmonised, method-specific MRV methodologies are essential for the quantification's accuracy and consistency, and for trust in the integrity of the market.

A central task in assessing the quality of removal activity is quantifying the net GHG removal benefit. To achieve a net benefit, the amount of GHG being emitted as a result of a removal activity must be less than the amount extracted from the atmosphere (Terlouw et al., 2021). The MRV methodologies for quantifying net removal benefit need to ensure the highest feasible measurement accuracy and be tailored to each removal method, reflecting their respective system boundary emissions and temporal characteristics (Liu et al., 2015). Harmonised rules for quantifying removals are essential to ensuring consistency of the measurement so that activities can be compared and credited in a fair manner and their impacts meaningfully aggregated. Fragmentation of accounting rules undermines trust in the integrity of carbon markets (Ahonen et al., 2022).

6.2.2 Status and policy gaps

The LULUCF regulation sets Member State commitments for removals in the land sector and MRV rules on how to reflect such removals in national GHG inventories. It lacks the granularity and scope needed to quantify practices like biochar application or BECCS.

Until recently, there was no robust, harmonised quantification methodology for removals within the EU. To date, reporting and accounting of removals was mainly done under the LULUCF regulation, which sets Member States' commitments for the LULUCF sector with a view to achieving the EU's 2030 climate target and the objectives of the Paris Agreement. The regulation does not provide a sufficient basis for quantifying removals: its scope is limited to removals in the LULUCF sector and its accounting rules have not been granular enough to capture practices like biochar application or BECCS (see Box 5). The LULUCF regulation binds the Member States and applies attributional accounting in line with the UNFCCC guidelines for national inventories, which, as outlined in Chapter 2, differ from the definition of removals adopted by the IPCC, with a defined inventory boundary (Brander, 2022) and a lack of distinction between human and natural drivers of emissions and removals on managed land, such as in gross-net accounting as further explained in Section 6.3.

Box 5 Quantifying biomass combustion emissions and BECCS removals in IPCC reporting

The reporting of anthropogenic GHG emissions and removals is mandatory for all parties to the UNFCCC. Under the UNFCCC, it assumed that the combustion of biomass fuels results in zero net CO_2 emissions if the biomass fuels are produced sustainably. In this case, the CO_2 released by combustion is balanced by CO_2 taken up during photosynthesis. In GHG inventories, CO_2 emissions from biomass combustion are, therefore, not reported under energy supply; in other words, they are not incorporated into the total emissions for the energy sector (zero-rating). CCS applied to biomass combustion is therefore reported as negative CO_2 emissions in the energy sector (IPCC, 2006).

The IPCC reporting guidelines require that CO_2 emissions from the combustion of biomass for energy be disclosed for reference purposes, and only the methane and nitrous oxide emissions are reported in the total emissions of the energy sector. It is expected that any unsustainable production of biomass becomes evident in the calculation of CO_2 emissions and removals in the LULUCF sector reporting of carbon stock changes. This expectation has been challenged however, due to reporting asymmetry between Annex I and non-Annex I parties to the UNFCCC (IEA, 2011). In addition, all parties share challenges with accurate and timely monitoring of LULUCF carbon fluxes, which due to capacity issues are more pervasive in non-Annex I parties which, for example, may struggle to collect and monitor forest data accurately, making it hard to track emissions and removals effectively (OECD, 2024).

Source: Advisory Board

The CRCF regulation introduces a methodology for quantifying net removal benefits at the removal activity level, requiring conservative reporting of associated GHG emissions, and transparency to ensure traceability and prevent double counting.

The CRCF framework is a promising step to fill the abovementioned policy gap by providing a harmonised quantification methodology at the activity level and for the different methods of removals.

The CRCF regulation (recital 7 of the preamble (EU, 2024g) signals a two-step approach to quantifying removals which will be further elaborated in the methodologies through the delegated acts. The regulation considers a removal activity to have a positive climate impact only when it delivers a net removal benefit. The two-step calculation of the net removal benefit consists of:

- step 1: quantify the amount of additional removal that an activity has generated in comparison to a baseline, and
- step 2: subtract any associated GHG emissions occurring during the lifecycle of the activity and related to the implementation of the activity.

The baselines used in the quantification of removals (see Section 6.3) are applied to determine if the achieved removals come on top of a prior or counterfactual carbon stock.

> *'The baselines shall be highly representative of the standard performance of comparable practices and processes in similar social, economic, environmental, technological and regulatory circumstances and take into account the geographical context including local pedo-climatic and regulatory conditions' (*Article 4(8) of the CRCR Regulation).

The CRCF regulation requires the emissions to be reported and accounted in a conservative manner reflecting uncertainties. This is to "limit the risk of overestimating the quantity of CO_2 removed from the atmosphere or of underestimating the quantity of direct and indirect GHG emissions generated by an activity" (recital 10 and Article 4). By promoting a consequential accounting approach to determining the net removal benefit (i.e., by considering both direct and indirect emissions from the removal activity), the CRCF framework helps to avoid unintended side effects of the removals. In addition, the conservative accounting required by the regulation reflects the challenge of accurate quantification of removals (Grassi et al., 2008), due to lack of data (e.g. limited sample sizes), systematic errors resulting from failure to capture all relevant processes involved, and uncertainty about future developments and management decisions.

The information related to the certification process will be published in the newly created EU registry. The aim of the registry is to enable the tracing of the quantity of certified units and avoid double-counting (Article 12). The registry is a welcome measure as it can support data sharing for cross-comparison, as further indicated in Section 6.6.

The development of the CRCF methodologies faces challenges in balancing administrative feasibility of verification audits, life-cycle emission accounting, the availability of robust data and alignment with complementary EU laws such the EU ETS directive, the CCS directive and REDII/III.

It remains to be determined if the method-specific quantification methodologies under the CRCF regulation provide a robust enough basis for net carbon benefit quantification, and how it will deal with the potential reversals (see also Section 6.4). The CRCF regulation hints at the need to balance the robustness of MRV in this respect with administrative feasibility and minimisation of compliance costs. Nevertheless, scientific contributions suggest that to be robust, the CRCF methodologies should:

- Set out clear MRV rules for each removal method within predefined system boundaries, that is, at least scope 1, 2, and 3 emissions including which indirect emissions to quantify and how and what monitoring methodology to use. Quantification of removals should properly account for increases in emissions in the wider economy due to the removal activity, for instance activity shifting, market leakage or ecological leakage. Baselines should be based on verifiable and transparent assumptions (Brander et al., 2021).

- Robustly apply the conservativeness principle in calculating net removal benefit, as required in the CRCF regulation (Article 4) and report on uncertainty analysis in order to attenuate the integrity risks stemming from uncertainties in consequential accounting (Bamber et al., 2020).
- Require a sufficiently long monitoring period and sufficiently frequent verification audits before and after the activity is launched. There is a need for checks to ensure that the removal activity actually delivers what was planned over time. This may prove particularly challenging in the LULUCF sector due to ownership and management complexity and the land sinks' susceptibility to exogenous factors such as weather. For instance, in the case of afforestation, it is not sufficient to verify the activity's GHG impacts only in the first year following its start and then certify all expected removals based on the extrapolated result. Temporal disturbances of forests can greatly influence the life-cycle emission results and could determine whether the activity delivers net removal benefit (JRC, 2021b; Terlouw et al., 2021).
- Provide information about the timing of when activities deliver negative emissions. This matters because, among other things, GHG removals are not equivalent to GHG mitigations in the present (Carton et al., 2021). Reliance on future removals risks overshooting the Paris Agreement targets and increasing the burden of climate impacts on future generations. It is also important to understand the GHG fluxes for biomass based methods over time (Stuart-Smith et al., 2023).

6.3 Ensuring removals additionality

6.3.1 Need

Determining the net carbon benefit of a removal activity requires distinguishing its effects from the baseline. This distinction is critical for accurate emission accounting, effective funding allocation, and maintaining public trust in carbon markets.

To determine the net carbon benefit of the certified removal activity, GHG measurement needs to distinguish between the baseline, including the background land sinks, and the GHG effects of a removal activity (Allen et al., 2024; Nolan et al., 2024). It is in essence the concept of additionality, which often involves a baseline or a counterfactual as a means to determine the net benefit based on what would have occurred in the absence of the activity. Ensuring additionality matters not only for emission accounting (i.e. carbon additionality) but also for effective allocation of funding (i.e. financial additionality), and the wider public perception of removals (Nolan et al., 2024; Salzman and Weisbach, 2024). Non-additional crediting is among the most significant quality challenges for removals in voluntary carbon markets to date (Haya et al., 2023).

6.3.2 Status and policy gaps

6.3.2.1 Additionality in the framework

The CRCF regulation's additionality criterion requires removal activities to exceed statutory requirements for operators, and to depend on certification for financial viability. For GHG effects, it relies on baselines subject to periodic review to align with evolving scientific and regulatory contexts.

Additionality is one of the CRCF quality criteria, although specific additionality tests will only be set out in the certification methodologies which at the time of writing still need to be further elaborated in delegated acts to the CRCF regulation **(policy gap)**. Their definition will be key to ensuring the additionality of removals. For the additionality criterion set out in Article 5 of the CRCF regulation to be met, the removal activity operators are required to demonstrate that (a) the activity goes beyond EU and national statutory requirements (i.e., binding obligations at the level of an individual operator) and (b) the incentive effect of the certification is needed for the activity to become financially viable (Article 5). The CRCF regulation therefore requires the standardised baselines to go beyond 'the common practice', and to this end embeds a regular review process of the baselines, which should happen at least every five years and reflect the latest regulatory context and scientific evidence while encouraging increased ambition over time. Where it is not possible to set a standardised baseline, the CRCF framework allows for an activity-specific baseline based on the operator's individual performance.

The extent to which baselines in CRCF methodologies mitigate risks of over-crediting and systematic biases is yet to be determined. They risk overlooking uncertainties and economic, technological or policy changes.

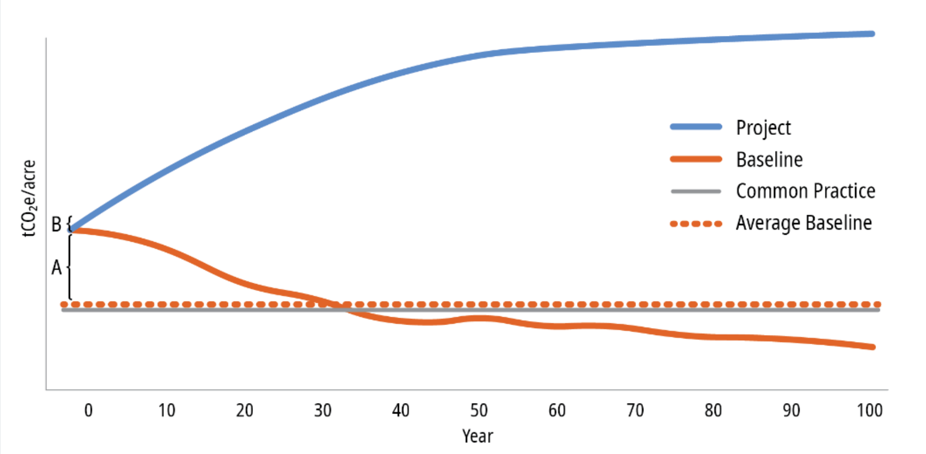
It is important that the applicable baselines mitigate the risk of exaggerated activity-level benefit (Badgley et al., 2022b; Haya et al., 2023). Standardised baselines come with some inherent risks, such as unclear assumptions or methodological inconsistencies detected in the assessment of the forest reference levels set by the Member States under the LULUCF regulation (JRC, 2021a). The standardised baseline may create a systematic selection bias allowing operators whose true baseline exceeds the standardised baseline to be certified, even though these activities would, in principle, be non-additional (Probst et al., 2024). This is also echoed by Paul et al. (2023) in the context of carbon farming measures, suggesting that claims of additionality often assume that farmers' management decisions are driven exclusively by short-term economic factors, which is found to not be the case for credited removals in agricultural soils (Barbato and Strong, 2023). These claims typically use the current situation as the counterfactual scenario, neglecting potential future changes in markets, technology and policy.

Activity-specific baselines risk being based on scenarios at the lowest permissible levels, leading to over-crediting and non-additional offsets that exaggerate the actual carbon benefits. An example of a pitfall in MRV rules for establishing an activity-specific baseline is presented in Box 6.

Box 6 Example of a pitfall in MRV rules for establishing baseline

A study of the forest offsets programme operated by the California Air Resources Board – the largest compliance market active today – find that the approach in which project baselines were set has resulted in systematic over-crediting amounting to 30 $MtCO_2e$ (Badgley et al., 2022b). The programme awarded the bulk of its offset credits to projects based on a comparison between the projects' initially measured carbon stocks and the 100-year average of aboveground carbon in its baseline scenario (Figure 17). Common practice constrained the minimum carbon in that baseline scenario and was computed separately (Badgley et al., 2022a). Two key flaws have been highlighted with regard to this approach. Firstly, several project developers chose baseline scenarios at the lowest possible level allowed by the programme rules, and selected project locations where the carbon stock naturally outperforms the regional averages (Badgley et al., 2022a). Secondly, forest projects were mostly credited upfront (i.e. in the initial 1-year reporting period against the 100-year-average baseline), which usually represents a sharp, unlikely drop from initial carbon stocks (Haya et al., 2023).

Figure 17 A sample of improved forest management project and baseline scenario based on a project in Oregon, United States under the California Air Resources Board's forest offset protocol



Source: (Haya et al., 2023)

Note: 'A' represents the credits generated in the 1st year of the project from the difference in actual onsite carbon stocks compared to the 100-year-average baseline. 'B' represents the credits generated in years 2-5 of the project from forest growth

Baseline setting should reflect evolving market, technology and policy conditions, with regular reviews to address risks of underestimating counterfactual carbon stocks, and inconsistencies in regulatory and incentive frameworks.

The additionality test under the CRCF regulation requires a dynamic approach to baseline setting reflective of market, technology and policy changes. This applies not only to the update of the standardised baseline, but also to the additionality test looking at existing statutory requirements and the incentive effect under the CRCF regulation. For DACCS and BECCS, the absence of EU rules or national rules mandating such activities, coupled with them currently not being widespread, makes the risk of non-additionality low (Ecologic, 2023). In both cases, concerns have been raised that the standardised baselines in the CRCF framework may fail to fully reflect the different regulatory requirements and available incentive schemes, such as those under the CAP (EC, 2023o; Ecologic and Oeko-Institut, 2023b). This risk may be reflected in the regular baseline review to be initiated by the European Commission *at least* every five years and more frequently if needed (Article 4). The approach of dynamic baselines, in which changing conditions are integrated into the baselines, could help ensure that the counterfactual carbon stock is not underestimated (Haya et al., 2023).

While maintaining strict additionality criteria is key to avoiding over-crediting and establishing equivalence in contexts where removals are used to directly counterbalance emissions, there may be trade-offs with some practices to protect and enhance the LULUCF sink.

For some removal methods in the LULUCF sector, it may be difficult to demonstrate additionality and to distinguish the effects of human intervention from natural processes, especially for interventions that enhance or conserve existing sinks, or those that are a side-effect of nature conservation efforts. For example, Nolan et al. (2024) highlight challenges in establishing appropriate baselines for interventions aimed at conserving intact forests, where applying standard baseline methodologies may overlook the necessity of interventions aimed at maintaining and protecting these sinks. Similar challenges and questions have been highlighted in the context of the CRCF framework; for example for peatlands, where challenges in identifying appropriate baselines and uncertainties in how legal, financial and common practice tests will be designed and applied, have led to uncertainties as to which habitats or projects will be eligible for certification (e.g. see questions in EC 2024o).

Nolan et al. (2024) sum up one of the core dilemmas of balancing robust additionality requirements with wider policy objectives for the land sink: "baselines that lead to over-crediting threaten the credibility of nature-based carbon credits, whereas baselines that result in under-crediting threaten the financial viability of [these] projects". Despite the intention that the CRCF regulation would contribute to wider EU LULUCF and biodiversity objectives (EU, 2024g), this raises the possibility that it may yet fail to recognise practices aimed at maintaining existing sinks, requiring other ways to recognise and – by extension – incentivise practices that may not meet these definitions of additionality. Wider nature and land use policies are presented further in Chapter 7.

6.3.2.2 Additionality in GHG inventories

National GHG inventories follow IPCC guidelines, which already reflect removals on managed land and are gradually extending to capture all removal methods. With the inventories reflecting all removals, including certified ones, the two MRV systems (i.e. activity- and inventory-level MRV) can complement each other.

The concept of additionality is not reflected in the accounting of removals for national GHG inventories (Nolan et al., 2024). The reporting and accounting rules set out under the governance regulation and the LULUCF regulation follow the IPCC guidelines, which require that, in the LULUCF sector, emissions and removals that occur on managed land are accounted for. Managed land covers 97% of the EU's land area (EEA, 2024d), allowing Member States to account for nearly all removals and sink enhancement in the land sector (Smith et al., 2023). Until 2025, the LULUCF regulation requires Member States to account for GHG emissions and removals through different methods depending on the land type.

- In managed forest land, accounting is done against the **forest reference level** to separate direct human-induced effects (e.g. caused by management changes), from natural and indirect human-induced effects in the forest (e.g. due to the age structure of forests). The forest reference level is the counterfactual value of emissions and removals that would occur in managed forest land in the future based on the continuation of sustainable forest management practices as documented from 2000 to 2009 and assuming a constant ratio of raw material and energy use. Annex IV of the LULUCF regulation defines criteria for the establishment of such forest reference levels and their estimation for each Member State.
- In managed cropland, grassland and wetlands, **net-net accounting** applies. It consists of a comparison between average annual net emissions and removals in the compliance period with the reference value (i.e. historic net emissions and removals).
- In afforested and deforested land, accounting follows the **gross-net** method. It considers all emissions and removals that occur during the accounting period, which could be compared to a baseline set at zero (EEA, 2024d).

According to the European Environment Agency (2024):

> *Accounting against a reference level means that in the category managed forest land – which makes up most of the LULUCF removals in the EU – the generation of accountable removals is much more limited than under a net-net or even a gross-net approach.*

The use of different accounting approaches under the LULUCF regulation was criticised for its complexity and risks of political bias in reference setting (EC, 2021h). The 2023 revision of the LULUCF regulation (Article 4) simplified the accounting rules, requiring that the budget for 2026 to 2029 be defined based on the GHG inventory data submitted in 2025, and that compliance with this budget be assessed based on the data submitted in 2032, which corresponds to the gross-net method described above. This means direct human-induced removals and natural CO_2 uptake not directly caused by human activities will be accounted for. The discrepancies between MRV for accounting towards national GHG inventories – which is a tool to measure progress to national GHG targets – and MRV for removal certification are justified by the different purposes of the two MRV systems, particularly the potential use cases of certified removals. However, with the proliferation of certified removals (Nolan et al., 2024) and the shift to gross-net accounting under the LULUCF regulation, some degree of complementarity between the two systems may become not only helpful but also necessary, as presented in Section 6.7.

6.4 Reflecting storage duration

6.4.1 Need

MRV systems need to manage the storage duration and reversal risks of each removal method and reflect the different degrees of equivalence between temporary and permanent removals, and between removals and emission reductions. These aspects will determine payment structures and societal trust in the use and policy implications of removal credits.

The quality of a removal method is affected by the storage duration and risk of reversal. Typical storage durations of temporary removal methods – particularly those within the land sector – can range from years to centuries depending on the methods and management practices, and are more vulnerable to reversal through human- and natural-induced processes. These factors also show high variability and uncertainty over time, and maintaining carbon storage in vegetation and soils requires continuous maintenance, monitoring and verification.

As a result, certification MRV rules need to provide clarity for each removal method regarding their assumed or required storage duration, frequency of MRV, and the certificate validity in connection with reversal liability mechanisms (see Chapter 13). The quality of MRV will define payment structures (Thorsdottir et al., 2024) and inform collective decisions of society (Prado and Mac Dowell, 2023) regarding, for example, the legality of the use of the credits from certified removal activities for different purposes, and the trustworthiness of the relevant policies. MRV systems can help to mitigate some of the risks linked to shorter duration of storage and reversal, but cannot eliminate them. Given the challenges this presents for establishing equivalence with permanent removals or emission reductions, Chapter 4 and 13 of this report include further reflections on the appropriate role of temporary removals in the EU's GHG budget, and the necessary mechanisms to reduce the risks of reversal and to improve equivalence while considering the impacts of changing climate.

6.4.2 Status and policy gaps

6.4.2.1 Distinction between permanent and temporary removals

Temporary and permanent removals are treated separately in the CRCF. Permanent removals require carbon to be stored for several centuries.

The CRCF regulation recognises the fundamental differences between permanent and temporary removals (Chapter 4) and requires them to be kept distinct from each other. It provides the following definition of permanent removals:

> *'permanent carbon removal' means any practice or process that, under normal circumstances and using appropriate management practices, captures and stores atmospheric or biogenic carbon for several centuries, including permanently chemically bound carbon in products, and which is not combined with Enhanced Hydrocarbon Recovery* (Article 2 (9))

Temporary removals include carbon storage in products and biogenic pools. The definition of carbon farming covers temporary removals and emission reduction jointly; such conflation risks obscuring removals' role in the EU's climate mitigation efforts.

The regulation also defines types of temporary removals. Article 2(11) requires 'carbon storage in products' to result in at least 35 years storage of atmospheric or biogenic carbon with the possibility of on-site monitoring of the carbon stored and certified throughout the monitoring period. Other types of temporary removals, notably those in the land sector, are collectively defined as:

> *'carbon farming' means any practice or process carried out over an activity period of at least five years, related to the management of a terrestrial or coastal management and resulting in capture and temporary storage of atmospheric and biogenic carbon into biogenic carbon pools, or the reduction of soil emissions.* (Article 2(10))

These definitions set the expectations regarding the storage duration of removals, from 'several centuries' in case of permanent removals, to 'at least five years' in temporary removals. The definition of carbon farming covers temporary removals and emission reduction jointly; such conflation risks obscuring removals' role in EU's climate mitigation efforts **(policy inconsistency)**. This risk is partly mitigated by separate definitions of relevant measurement units, namely soil emission reduction units and carbon farming sequestration units. The three types of units under the CRCF framework – reduction, temporary removals and permanent removals – should follow distinct MRV requirements and their respective uses be clearly defined (see, for example, Thorsdottir et al., 2024)**.**

6.4.2.2 Management of reversals

The CRCF regulation recognises the reversal risks linked to the different removal methods and requires operators to take preventive action to mitigate those risks and monitor that carbon is continuously stored.

The monitoring rules, including the length of the monitoring period, will be tailored for each removal method (Article 6 CRCF Regulation). The specific rules to monitor and mitigate risks of reversal occurring during the monitoring period are already set out for the permanent removals under the CCS directive and the EU ETS directive. The rules for temporary removals remain to be laid out in the certification methodologies. The new rules will also set out liability mechanisms to be activated in case of reversals (Article 6(2) CRCF Regulation).

Under the CRCF regulation, the validity of the certified unit depends on the expected duration of the storage, and the different risks of reversal associated with the given activity. This means that the validity of CRCF certificates for permanent removals extends to several centuries. The validity of temporary removals (i.e. carbon farming sequestration and carbon storage in some products) ends together with the relevant monitoring period, for instance at least 5 years for carbon farming removals and at least 35 years for carbon storage in products. After that, the stored carbon is assumed to be released into the atmosphere. Operators may prolong the monitoring period, and hence also the certificate validity of temporary removals several times so that their duration extends to decades (recital 17, CRCF Regulation).

The CRCF regulation signals the need for preventive measures to minimise the risk of reversals and liability mechanisms, as well as rules on *the risk of failure of the liability mechanisms*, such as collective buffers and up-front insurance mechanisms. These will be set through the delegated acts to the CRCF regulation, considering that the applicable liability mechanisms in respect of geological storage and CO_2 leakage, and relevant corrective measures are set under the EU ETS and the CCS directives. The CRCF regulation strives in this respect for regulatory consistency between the certification methodologies and the rules concerning permanently chemically bound carbon products set out in a delegated act under the EU ETS directive (EC, 2024f). This delegated act does not include specific MRV requirements for permanent capture and utilisation in products however (**ambition gap**); it merely stipulates that the amount of CO_2e bound in the product during the utilisation process should be measurable and links the permanence of storage to the *normal use* of the product including any normal activity taking place after the end of the life of the product. "Multiple normal use and end of life pathways," need to be taken into account in determining the permanence of storage (Article 3, EC, 2024a), but no further requirement is specified in the delegated act.

MRV costs per unit of GHG storage are expected to be higher for temporary removals than for permanent removals due to the monitoring specificities and the frequency of verification audits.

It will be important to ensure that the monitoring rules are tailored to the specific removal method with its associated risks, and informed by relevant experience in EU and international contexts. Monitoring periods should be long enough and checks (i.e., independent verification audits) frequent enough to detect changes with sufficient certainty, as well as to reduce uncertainties linked to climate-related risks (see FAO, 2023). It is therefore expected that MRV costs will be higher for temporary removals than for permanent ones over longer time horizons (Prado and Mac Dowell, 2023). It remains to be seen if the monitoring period the CRCF methodologies require is of sufficient duration and if they find the right balance between the frequency of the audits, compliance costs and administrative burden. For example, in the case of biogenic carbon storage in construction materials, keeping track of storage duration and life-cycle emissions, while important from the environmental integrity perspective, could be very cumbersome in practice.

6.5 Safeguarding wider sustainability

6.5.1 Need

Although the primary value of removal activities lies in their ability to capture and durably store atmospheric GHG, a comprehensive evaluation of their broader side effects and to steer them towards sustainability is essential to removals' successful scale-up.

Removals are linked to sustainability-related risks and opportunities beyond climate mitigation, as they are likely to have impacts on the EU's climate resilience, land, water and marine resources, circular economy, pollution, biodiversity and ecosystems, social safety and other sustainability and distributional aspects, as described in Chapters 3 and 5. Viewing the climate effects of removals in isolation from their wider environmental and social context risks neglecting or even damaging other ecosystem services, highlighting the need for the comprehensive inclusion of sustainability criteria in removals certification (CREDIBLE, 2024). Scientists highlight the need to steer the future development of removals technologies towards justice and sustainability now, while the shape of future configurations is still malleable (Nawaz et al., 2024b) ensuring removals contribute to just transition. This necessitates carefully designed MRV systems able to reflect the impacts of removal activities beyond GHG emissions, so as to support informed decision-making and holistic approaches to implementing removals (Smith et al., 2024).

6.5.2 Status and policy gaps

Under the CRCF regulation, removal activities are required to comply with EU laws, including the CCS directive and the RED II/III, and where possible be consistent with the sustainable finance taxonomy, which establishes safety, sustainability and technical criteria for various removal methods and associated sectors.

To be certified under the CRCF framework, removal activities have to demonstrate compliance with a range of applicable EU laws, such as the CCS directive and RED II, and the 'do no significant harm' principle, where possible in line with the sustainable finance taxonomy regulation (EU, 2020). The CCS directive together with its guidance documents aims to ensure safe CO_2 storage in geological formations (see also Chapter 9). As regards to BECCS, RED II/III sets rules for assessing the sustainability of biomass used in bioenergy applications (EC, 2023p) (see also Chapter 7).

In private finance, the sustainable finance taxonomy is underpinned by a delegated act on climate change mitigation and adaptation, which includes technical screening criteria for CO_2 transport and storage, as well as for research and development related to DACCS. Other technical screening criteria with relevance to removals include those on forestry, wetland restoration, biogas and biofuel production, landfill gas capture and utilisation, cement manufacturing and the construction of new buildings (EC, 2023p). The minimum sustainability requirements are to be set out in the CRCF methodologies, and their alignment with the taxonomy's technical screening criteria for the 'do no significant harm' principle is not guaranteed – Article 7 of the CRCF regulation mandates it only 'where appropriate' without further specification, leaving much room for interpretation **(ambition gap)**.

The CRCF regulation mandates that removal activities do no significant harm and optionally contribute to various *co-benefits*. Only carbon farming is required to deliver a co-benefit. The regulation merely signals the need to prevent unsustainable biomass demand by limiting bioenergy plant expansion for CCS, and relies on untested sustainability safeguards set in RED II/III.

The CRCF regulation requires that removal activities do not cause significant harm. It will be important that the certification methodologies setting out the minimum sustainability safeguards for each removal method are at least aligned with the technical screening criteria under the taxonomy regulation and go beyond them to reflect removals specific risks and opportunities (see Chapter 3) while overcoming any shortcomings of the taxonomy's do-no-significant-harm criteria (UBA, 2023; Hummel and Bauernhofer, 2024) such as the lack of integration with the environmental impact assessment legal framework (Dusík and Bond, 2022).

It lists sustainability objectives that removal activities *may* contribute to. Only carbon farming is required to benefit the protection of biodiversity and ecosystems (EU, 2024d, p. 39). The lack of a binding requirement for removal activities to run a climate risk assessment and include relevant adaptation measures is a major **policy gap**, especially risky in the case of temporary removals (see also Chapters 3 and 7). The list of sustainability objectives, called 'co-benefits' as set out in Article 7 of the CRCF regulation, includes:

- climate change mitigation beyond the net removal benefit and net soil emission reduction benefit;
- climate change adaptation;
- sustainable use and protection of water and marine resources;
- transition to a circular economy, including the efficient use of sustainably sourced bio-based materials;
- pollution prevention and control;
- protection and restoration of biodiversity and ecosystems, including soil health, as well as avoidance of land degradation.

The robustness of CRCF sustainability safeguards depends on removal activities' compliance with auxiliary laws such as RED II/III and the CCS directive. It is unclear why the CRCF regulation does not mention compliance with the environmental impact assessment directive as a precondition for certification. The directive requires project permitting to be conditional on conclusions from an assessment of its expected environmental impacts, a process that engages local communities. Moreover, reliance on RED II/III sustainability and GHG criteria of biomass may be risky, unless EU policies learn from the certification challenges following the adoption of renewable energy directive in 2009 (EU, 2009a); see also Sections 6.6 and 7.3. The EU should scrutinise the robustness of the RED II/III sustainability and GHG criteria and enact measures limiting unsustainable demand for biomass raw materials. This could help prevent the financial benefits of the CRCF from leading to the expansion of biomass-fired plant capacity beyond what is necessary for CCS operations.

While the CRCF regulation sustainability safeguards are yet to be operationalised, they should measure and disclose the impact of removal activities, foster community benefits through transparency and revenue sharing, and require and document safeguards to uphold the 'do no significant harm' principle, including climate change adaptation.

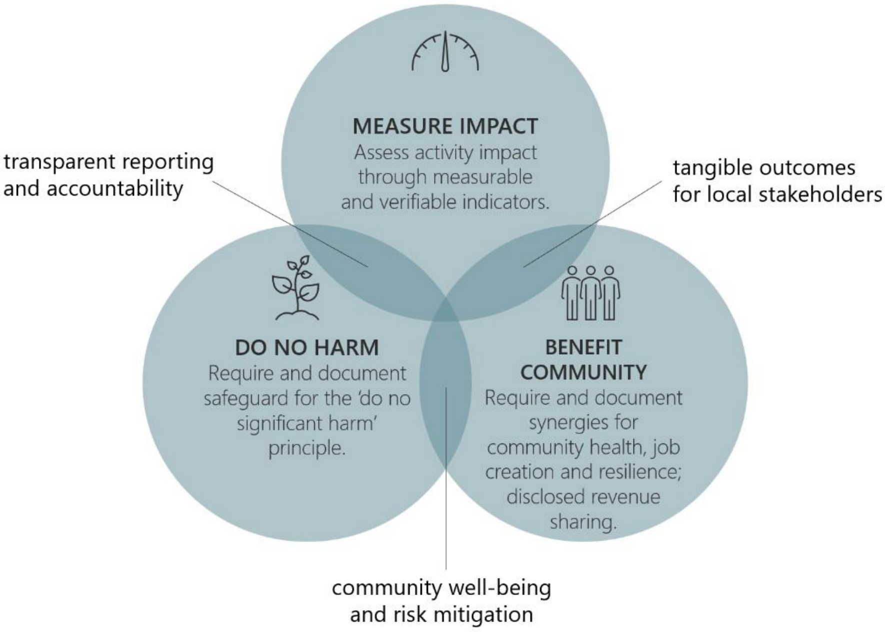
Beyond environmental sustainability, the CRCF regulation lays a basis for social safeguards. According to its Article 8, the certification methodologies are required to contribute to food security, avoid speculative land acquisition, and take into account the competitiveness of farmers and foresters in the EU in a sustainable manner, particularly for small-scale operators. The need to prevent negative effects on rural communities, and respect the rights of local communities and indigenous people affected by the activities is mentioned in the preamble to the regulation (EU, 2024d).

The CRCF regulation also recommends that operators report any side effects that contribute to the sustainability objectives set out in Article 7, and, by going beyond the sustainability requirements, could enhance the economic value of certified units and lead to higher revenues for the operator (EU, 2024d).

Since impacts vary depending on the removal method, sustainability requirements will depend on a specific certification methodology. It is uncertain what sustainability indicators will be defined as minimum requirements and how they will be quantified. Concerns raised by public and private bodies, such as the German Environment Agency (2023) and Carbon Direct and Microsoft (2023), as well as the principles behind the Equity and Environmental Justice Index developed to support removal policy in the United States (U.S. DOE, 2024), could inspire the upcoming CRCF methodologies so that, as shown in Figure 18, they:

- measure impact by assessing activity impacts through measurable and verifiable indicators;
- benefit communities by documenting synergies and trade-offs for community health and local job creation, and by disclosing project revenues shared with community members and local partners;
- do no harm by documenting safeguards to respect or go beyond the 'do no significant harm' principle, including by adapting activity to the adverse impacts of climate change and avoiding maladaptation.

Figure 18 Guiding design objectives underpinning sustainability criterion to be developed in the certification methodologies



Source: Advisory Board

6.6 Enhancing data and processes

6.6.1 Need

Building trust in carbon markets and wider climate policies requires MRV systems that provide reliable data for impact assessment, use transparently developed science-led methodologies and ensure credible verification to prevent integrity risks.

This section addresses three horizontal needs for MRV systems that contributes to investors' and the public's trust in future carbon markets:

(a) Access to reliable and comparable data, to understand the impacts of removals and maximise their benefits, and to make the best use of the available public and private data streams supplied in response to various EU policies, including the LULUCF and CRCF regulations, the CAP, and nature conservation laws. Measuring changes to forests in a timely manner is necessary for understanding forest policy effectiveness and driving progress towards the LULUCF sink target.

(b) Science-led methodologies developed transparently through participatory decision-making, to be in line with the EU principles of the rule of law and transparency and to respond to technological and societal developments and the wider context including changing climate. Addressing the scientific and political challenge of establishing robust MRV schemes requires appropriate measures and processes (Burke and Schenuit, 2023).

(c) Credible verification as part of the MRV and market oversight to avoid the integrity risks known from deceptive or misleading sustainability certification and offsetting (Chan et al., 2023; Kaplan et al., 2023).

6.6.2 Status and policy gaps

6.6.2.1 Access to reliable and comparable data,

Effective MRV of land sinks in the EU is hindered by inconsistent and outdated data collection methods. The EU should roll out harmonised, advanced approaches to data collection and handling supported by the adoption of the Forest and Soil Monitoring Laws.

The governance regulation, the revised LULUCF regulation and the CRCF regulation encourage the use of the most sophisticated method for collecting data, known as the tier 3 method recommended in the 2019 Refinement to the 2006 IPCC guidelines for national GHG inventories (IPCC, 2019). Their use is not mandatory however **(ambition gap)**, and in practice not yet widespread.

The quantification approaches in Member States under the national GHG inventory reporting and LULUCF regulation have so far been based on rough, lower-tier approaches, calculating carbon balance for each land type using average emission/removal factors. Forest-monitoring data is incomparable across the Member States and often incomplete and inaccurate (FISE, 2024; Lier et al., 2022). Satellite monitoring of forest cover beyond the EU is also insufficient, which, combined with low transparency regarding the origin of biomass for energy and the conversion pathways in reporting within the NECP process (EC, 2023b; Sikkema et al., 2021), constitutes a major obstacle to the MRV of biomass-based projects such as BECCS. It is further exacerbated by substantial time lags between the emissions' occurrence and the reporting of data (Korosuo et al., 2023). In parallel very large carbon gains and losses from soils are unreported:

> *'accurate estimates of emissions and removals, based on good information on land use activities and local emission factors, cover at most 37% of EU cropland, because most Member States use default IPCC methods. As long as soils remain such a 'blind spot' of climate policies, it is challenging to design effective policies and incentives.'* (EC, 2021h).

Technologies, including remote sensing and AI-enabled methods exist and evolve dynamically into support policy needs. The legal framework aimed at collecting better data and turning them in policy-relevant information is not yet in place, however, causing a major policy gap. Today, forest inventory monitoring systems differ from Member State to Member State, as each country has its own forest inventory system with its own methodology to set up national forest inventories. The new EU Forest Strategy for 2030 stressed the need for 'strategic forest planning in all Member States, based on reliable monitoring and data, transparent governance and coordinated exchange at Union level' (EC, 2021f). The proposed forest monitoring regulation and the Soil Monitoring and Resilience Directive (EC, 2023l, 2023i) aim to address this gap and should be adopted without further due in support of ambitious improvements of the land observations systems' data collection and use.

Article 4 of the CRCF regulation requires removals to be quantified in an accurate, complete, consistent, comparable and transparent manner, in accordance with the latest available scientific evidence. It also requires the monitoring to be based on a 'combination of on-site measurements with remote sensing or modelling'. The exact rules will be set in the certification methodologies. The foreseen 'Union registry' is a step in the right direction regarding data quality. As it supports CRCF data comparability in line with the 'findable, accessible, interoperable, and reusable' principle, which is good practice in data management (Advisory Board,). Transparency of data and methodologies, including open access to them, are important for the growth of carbon markets (Burke and Schenuit, 2024, 2023).

6.6.2.2 Science-led and trustworthy methodologies

The CRCF regulation's mandate for updates to certification methodologies at least every five years is important to incorporate technological advancements and scientific evidence. However, gaps remain in the systematic application of impact assessments with public consultations and climate neutrality consistency checks of relevant EU delegated acts, undermining transparency and democratic legitimacy.

As mentioned in Section 6.3, the CRCF regulation mandates regular, at least five yearly revisions of the certification methodologies to reflect the latest technological developments and scientific evidence. This is a welcome, flexible provision that should be implemented dynamically. Leaving outdated methodologies, in particular the standardised baselines, to linger risks hampering innovation and progress in the sustainable scale-up of removals as part of the EU's wider climate ambition (see, for example, Michaelowa et al., 2019).

Given the risk of incentives for project developers to 'game project parameters in order to gain more [removal] units' in additionality testing of removal activity (Michaelowa et al., 2019), as well as other perverse incentives, for example during verification (see Section 6.2.2), good governance should play a central role in the development of and updates to the certification methodologies (see also Chapter 10). To ensure market and public trust in removals, the development of the key delegated acts under the CRCF regulation should be based on impact assessments together with public consultation and climate neutrality consistency checks should be applied to, as further explained in Chapter 10.

6.6.2.3 Credible verification as part of the MRV and market oversight

The CRCF framework mandates third-party verification of removal activities by accredited certification bodies, but concerns about regulatory capture and poor verification persist. The lack of an oversight mechanism for the CRCF-triggered market should be addressed early on to ensure the trustworthiness and independence of certification processes.

Under the CRCF framework, the verification of removals within the certification process consists of third-party auditing of the activity, starting with the initial certification audit before its implementation. This process is intended to be conducted by independent, accredited certification bodies, which issue certificates of compliance to operators (EU, 2024d). It follows the same approach as in biomass sustainability certification under the RED, which has been criticised for insufficient transparency and ambition (European Ombudsman, 2022; Mai-Moulin et al., 2021; Moser and Leipold, 2021; Vogelpohl, 2021), and is still largely untested (see Chapter 7). In addition, Grubert and Talati (2024) warn against the risk that a removal market in which removal credits at a unit level are traded will incentivise poor verification due to the financial rewards associated with selling credits at a lower cost than competitors. They further argue, drawing from historical instances of regulatory capture, that the process of establishing robust verification standards is likely to face pressure from within the removals industry (Grubert and Talati, 2024). In light of these concerns, combined with integrity issues within various voluntary carbon markets (Badgley et al., 2022), the CRCF should include strong safeguards of the integrity of conduct of both private and public actors, including the independence and trustworthiness of the certification bodies. The market to be triggered by the CRCF regulation does not yet have an oversight mechanism attached to it **(policy gap)**. A need to fill this gap is mentioned in the CRCF regulation. Given the integrity risks mentioned above a market oversight mechanism should be set up early on.

6.7 Addressing the complementarity of activity-level MRV and national GHG accounting

6.7.1 Need

Appropriate GHG accounting can help to prevent decreased climate ambition. Nested accounting could improve the accuracy and transparency of national GHG inventories, particularly for land sector removals.

In the latest State of Carbon Dioxide Removals report, Smith et al. (2024) raise the following, still largely unanswered, question and consider it critical to the integrity of removals: *'How can greenhouse gas accounting be designed across scales e.g. nesting of voluntary removals in national accounting schemes to prevent decreased ambition?'*. The authors further link the risk of decreased ambition to the issue of double counting, which can refer to double *issuance* (e.g. certifying a single removal under two programmes), double *use* (e.g. using a removal credit as an offset twice), or double *claiming* (e.g. claiming of a removal by two entities without appropriate nesting) (Smith et al.,2024). The nested accounting approach collects data at the smallest unit of analysis (e.g. removal activity within nested jurisdictions) and then reflects them in higher aggregation levels such as national GHG inventories submitted to international frameworks (Supervisory Body, 2024, Article 6.4). Nested accounting could therefore help to shed light on the contribution of removals to climate pledges under the UNFCCC. Without nesting, a subset of these removals (e.g. afforestation/reforestation) may be certified as removals yet hidden from view if counted towards net GHG emission reductions, where emissions and removals are summed in their respective sectors (Lamb et al., 2024).

Besides avoiding the challenges linked to double counting, addressing complementarity between the MRV systems could help to improve the quality of national GHG inventories thanks to the provision of more granular and accurate data than those currently used in their compilation, especially in case of land sector removals (EC, 2022d).

6.7.2 Status and policy gaps

The national GHG inventory and the CRCF operate on separate MRV and accounting paths. The CRCF certified removals will contribute to the EU's NDC; the CRCF regulation does not allow their use in third-party NDCs or international compliance schemes.

National GHG inventory data compilation and the CRCF follow separate MRV paths and accounting levels. The framework for EU emissions and removals reporting and accounting for the inventories is set out in the governance regulation. The activity-level data collected as part of the certification are not directly reflected in the inventories, although Article 4 of the CRCF regulation encourages the data collection and reporting methods to be compatible with those required under the governance regulation. Due to the accounting separation, this current approach does not in principle decrease the EU's climate ambition, as the double counting of the same removal happens at two separate accounting levels and serve different purposes. It is in essence what the international energy agency's GHG R&DD programme (IEAGHG, 2024) refers to as dual accounting or co-claiming: a situation of parallel accounts where emissions and removals count once against the GHG inventory of the private entity that purchases removals and once against the national GHG inventory of the country where the removal occurred.

Regarding the end use of removal certificates in the international context, the CRCF regulation requires all removals certified under its framework to contribute to the achievement of the EU's NDC and the EU's climate objectives. This restriction supports the European Climate Law requirement to balance EU domestic emissions and removals by 2050, effectively excluding the EU from reliance on removals delivered in non-EU jurisdictions to achieve the net-zero target. In addition, the separation in which the

CRCF certified removals do not contribute to third party NDCs or international compliance schemes is intended to avoid double claiming of removals in EU and non-EU jurisdictions (Article 1, CRCF regulation). Furthermore, the CRCF allows the use of CRCF certificates to contribute to corporate climate targets of non-EU based entities, as long as they do not fall under the 'international compliance scheme' category. This means that CRCF certificates can be traded or purchased by buyers from outside the EU. The CRCF coexists with other removal certification schemes and is ready to recognize them should they apply and meet the conditions. The CRCF could also be recognised by other certification schemes.

Article 6 of the Paris Agreement lays down opportunities to pursue cooperative implementation of the NDCs. Any upcoming revision of the CRCF regulation should not jeopardise the EU's ambition to achieve net zero through balancing of its domestic emissions and removals, or the Paris Agreement ambition for Article 6 to uphold the overall mitigation in global emissions.

Regarding both accounting for and end-use of certified removals under the UNFCCC, there has been very little experience so far. Article 6 of the Paris Agreement lays down opportunities to pursue cooperative implementation of the NDCs, including through trading carbon credits between governments (Article 6(2)) and a UNFCCC-governed carbon-crediting programme (Article 6(4)). The implementation of these articles was enabled in late 2024 and will feed into the potential revision of the CRCF regulation to align it with Article 6 of the Paris Agreement. This future alignment appears to be targeted primarily towards private end-users of the certificates (point 40 of the preamble to the CRCF regulation). It is not clear, however, how the review could affect the possible ways to achieve national and EU climate targets. Any upcoming revision of the CRCF regulation should not jeopardise the EU's ambition to achieve net zero through balancing of its domestic emissions and removals, as set out in the European Climate Law, or the Paris Agreement ambition for Article 6 to uphold the overall mitigation in global emissions (see also Chapter 10).

Activity-level removal MRV should be leveraged to improve the accuracy of national GHG inventories and support global climate ambition. The EU should ensure certified removals visibility in national GHG inventories and reflect on how to further address risks and opportunities stemming from insufficient transparency in removals reporting and accounting.

Some authors warn against the risk of mitigation deterrence that could arise from insufficient transparency in removals reporting and accounting. For example, it may be challenging to adequately account for all emissions in removals' value chains, including cross-border biomass trading, if the net carbon benefit quantification boundaries and wider sustainability safeguards are not adequately set and applied (IEAGHG, 2024). In case of temporary removals, Paul et al. (2023) suggest that corporations could mislead the public with their offsetting claims (e.g. marketing their products as climate neutral when relying on temporary removals). In addition, the German Environment Agency (Umweltbundesamt, 2024) points to the risks of using the same CRCF certificates twice for compliance purpose: corporations claiming compliance with their transition plans and progress obligations under the green claims directive (EC, 2023j) and the Directive on corporate sustainability due diligence[17] (EU, 2024b), and Member States using them to comply with their national obligations, such as transport fuel decarbonisation goals under RED II/III (EU, 2018a).

[17] The directive sets out an obligation for large companies to adopt and put into effect, through best efforts, a transition plan for climate change mitigation aligned with the 2050 climate neutrality objective of the Paris Agreement as well as intermediate targets under the European Climate Law (EC, 2024k).

In addition to consequential accounting (see Section 6.2) and possible end-use restrictions (see Part C), transparency emerges as an essential principle in linking activity- and inventory-level accounting and reporting. Notably:

- integrated assessments could help to reveal the cross-sectoral effects that can arise from the deployment of a portfolio of removal methods (IEAGHG, 2024);
- the upcoming IPCC guidance will help further with harmonised and transparent removals and emission accounting and reporting under the UNFCCC (IPCC, 2024);
- finally, the CRCF will enable advanced data collection methods and access to granular data that could enhance the accuracy of the GHG inventories.

The national GHG inventory has already been enhanced with emission reduction data, through the harmonisation of the EU ETS data reporting and the inventory reporting approved by the UNFCCC, for example, the MMR regulation (Article 73). National GHG inventories rely on the EU ETS data, which are considered to have improved the overall quality of GHG inventories. Furthermore, Smith et al. (2024) suggest the REDD+[18] activities as a source of useful insights regarding complementarities between activity- and inventory- level accounting. The three could be supported by practitioners and scientific communities working together to align estimates of the land sector carbon fluxes, as part of a wider effort to increase compatibility between reporting conventions, national targets, and benchmarks estimated by global models (Gidden et al., 2023).

Considering the above, and in anticipation of a major scale-up in certified removals, the EU should ensure removals visibility in national GHG inventories and reflect on how to further address the risks and opportunities stemming from complementarities between removal activity-level MRV and national GHG inventory reporting and accounting.

6.8 Summary of EU policy assessment

Table 14 summarises the policy assessment carried out in this chapter, by providing an overview of the status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024).

Table 14 Summary of the EU policy assessment of Chapter 6

Policy	Status	Gaps and inconsistencies
EU ETS directive **Delegated act on permanently chemically-bound carbon products**	Counts certain products as storing carbon permanently.	Lack of specific MRV requirements for permanent capture and utilisation in products. → **ambition gap**
Governance Regulation/LULUCF Regulation	Encourages use of tier-3 data collection methods	Not yet mandatory, and in practice not yet widespread. → **ambition gap**

[18] REDD+ is the UNFCCC framework to protect forests as part of the Paris Agreement. The abbreviation stands for 'reducing emissions from deforestation and forest degradation and the role of conservation, sustainable management of forests, and enhancement of forest carbon stocks in developing countries.' Under the framework, eligible countries can receive results-based payments for forest-based emission reductions.

Policy	Status	Gaps and inconsistencies
CRCF regulation	Defines permanent and temporary removals. Sets MRV quality criteria for removals. Rules to ensure sufficient oversight of the trading of certified units to be defined in the delegated acts.	Carbon farming definition conflates emission reduction and removals. → **policy inconsistency** Specific rules and methodologies for MRV and to ensure appropriate market oversight still need to be elaborated in delegated acts. → **policy gap** Adherence to the "do no significant harm" principle is only required "where appropriate", which is not further specified and thus leaves substantial room for interpretation. → **ambition gap** Lack of a binding requirement for removal activities to run a climate risk assessment and include relevant adaptation measures. → **ambition gap**
Better Regulation	Requires impact assessments including public consultations of initiatives likely to have significant economic, environmental or social impacts or which entailing significant spending, and where the European Commission has a choice of policy options'	EU delegated acts of binding and general application not accompanied by impact assessments → **implementation gap**

7 Reversing the decline of the land sink in a changing climate

- **Adaptation can counteract the decline of land sink.** The EU needs to urgently bolster the mainstreaming of climate adaptation to reduce impacts on, and enhance resilience of, the declining soil and biomass carbon stocks, as well as safeguard communities reliant on these sectors.

- **Healthy ecosystems are essential.** Healthy ecosystems are essential for climate-resilient carbon stocks and removals, even if both synergies and trade-offs exist between biodiversity and climate policy objectives. The Nature Restoration Law aims at tackling some of the persisting challenges in funding, governance and land-use policy fragmentation, and should be rigorously implemented to overcome the so-far limited progress in ecosystem protection and restoration.

- **Bioenergy use needs to be balanced with other priorities.** The decrease in the LULUCF sink is partly linked to increasing bioenergy use in the EU. Sustainable deployment of BECCS requires the EU to balance overall biomass demand with environmental limits by improving resource efficiency and biomass sustainability. Current policies, including REDII/III, do not sufficiently encourage an efficient biomass value chain, and face implementation challenges which undermine efforts to achieve sustainable bioenergy and BECCS deployment towards net zero.

- **Agriculture has removal potential.** Agricultural land, which accounts for 38% of total EU land use, has significant potential for carbon sequestration through improved soil management. The CAP offers opportunities for enhancing land sinks but remain misaligned with net zero, supporting high-emission agricultural practices and lacking strong incentives for land sink enhancement.

- **Implementation is lacking.** The European Climate Law requires mainstreaming climate resilience and adaptation, but progress is hindered at implementation. Land-relevant EU policies remain fragmented and lack sufficient funding and long-term planning to be aligned with the EU climate goals. The EU should integrate its land-related policies into a coherent framework supported by the Soil Monitoring and Resilience Law and the Forest Monitoring Law. The framework should guide sectoral measures towards sustainable biomass use and land management that enhance EU land sinks and foster climate adaptation.

7.1 Introduction

The EU's land sink has been decreasing dramatically in the past decade. To achieve its climate goals for 2030 and 2050, the EU needs both to protect and enhance existing sinks and to establish new ones in the LULUCF sector through ambitious land management interventions.

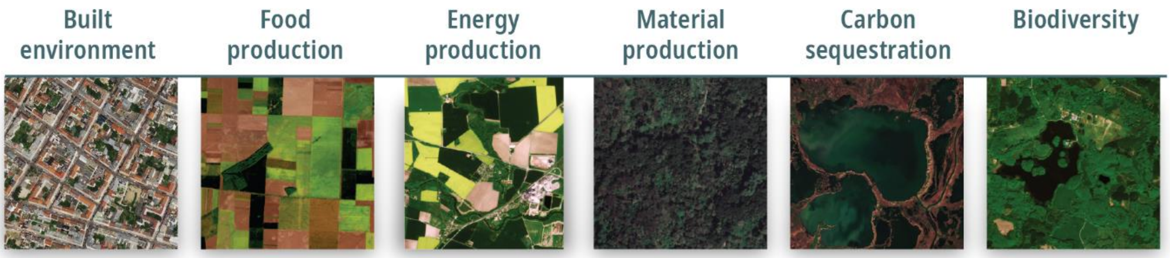
The LULUCF carbon sink has decreased over the period 2014-2022 (see Chapter 2). The latest inventory data from 2022 shows net removals in the LULUCF sector of 236 $MtCO_2$ in 2022, i.e., around of 7% of the EU's GHG emissions in 2022 (EEA, 2024e). Recent assessments by the Advisory Board and others (EEA, 2023e; JRC, 2024c; Korosuo et al., 2023) have warned that the LULUCF sector is off track and even heading in the wrong direction compared to its 2030 net-removal target. By 2050 activities in the wider land sectors are projected to become both the largest source of GHG emissions, notably from agriculture, and the largest GHG sink, mainly thanks to forested land (Korosuo et al., 2023). Some estimates show that the EU's LULUCF sink, mostly in forest land, could grow to 400 $MtCO_2$ by 2050 (EC, 2024i) (see also Chapter 2).

In addition to terrestrial ecosystems, ocean and marine ecosystems are a critical natural sink also being degraded by climate impacts. However, because of uncertainties about the potential of current ocean-related removal methods and associated risks (see Chapter 2 and 3), this chapter focuses on the land sink.

Biomass consists of organic matter, which contains carbon. Such biogenic carbon can be used in bio-based supply chains that may include removals.

Biomass resources include living and dead plants, animals and microbial organisms, present on the land and in the freshwater and marine environment. Living or dead biomass can be used as a carbon storage medium lasting for years, decades or even centuries (e.g. in soils); it can be used in bio-based products where biogenic carbon can be used as a replacement of fossil sources (e.g. fuel); chemicals, plastics, biotechnology; or as a replacement for materials that are carbon-intensive to produce (e.g. some construction materials). Bio-based supply chains differ in terms of substitution effects and the time of carbon release to the atmosphere. Depending on the latter, biomass could be considered a temporary or even permanent removal in the case of waste from bio-products' is collected to feed BECCS (see Section 7.3).

Figure 19 Competing land uses



Sources: Images from the European Space Agency

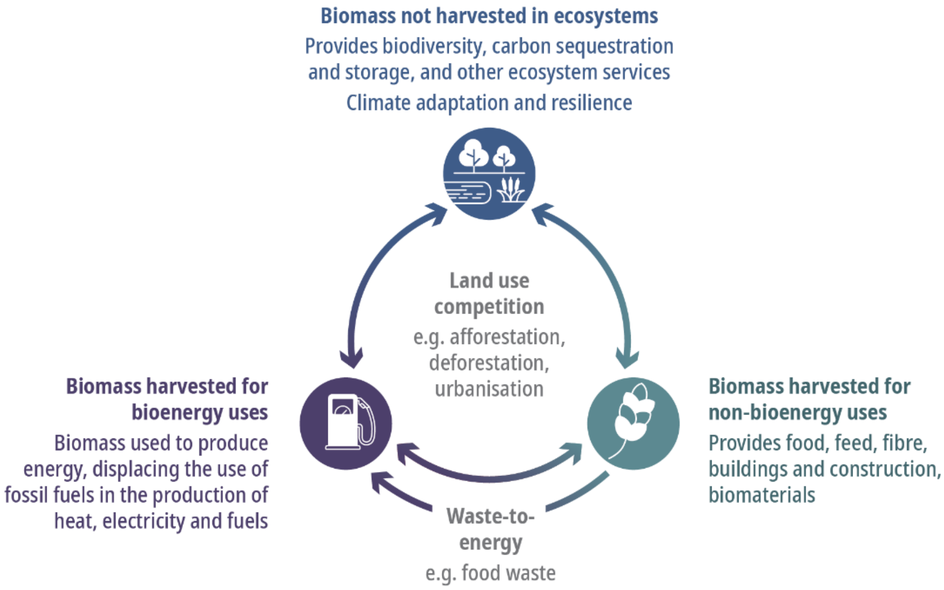
Many removal methods rely on the availability of finite land and biomass resources that are already under pressure from competing demands.

To serve the 450 million inhabitants of the EU, different types of human activities are competing for its 4 million km^2 of land, including the built environment, the production of plant food and livestock feed, energy generation, materials and the maintenance and conservation of ecosystems. While some land sector removal methods require land use change (e.g. afforestation), others do not (e.g. agricultural soil carbon sequestration on croplands). Depending on current and future land use changes in the EU, the removal potentials of these methods vary. Moreover, the future removal from biochar and BECCS will depend on the availability of biomass, which is in high demand across the EU's economy, including in the food, energy, and construction sectors.

Increased competition for land between food production and biomass for other uses can lead to land-use changes, such as deforestation, and create trade-offs between carbon sequestration and other ecosystem services.

The availability of all biomass used in the EU's economy is bound by the pace of the natural growth rates and varies across agricultural crops, grassland livestock species and woody biomass (see Figure 20). The production and harvest of biomass, depending on the land use, livestock production type and soil management practices, can have impacts on natural habitats, biodiversity, water and air quality, and both CO_2 and non-CO_2 GHG emissions.

Figure 20 Types of biomass use



Source: (EEA, 2023e)

Note: the following section identifies the trade-offs in policies related to agriculture and biomass. More specifically, the following policies that affect removals in agriculture are explored: CAP, LULUCF (biomass), CRCF (carbon farming), Soil Monitoring Law

The EU's biomass supply and carbon cycle is increasingly affected by climate change.

As explained in Chapter 3 in more detail, droughts, heatwaves, floods, storms, wildfires, pests and other disturbances caused or amplified by climate change affect the growth of vegetation and increase mortality (EEA, 2024a; IPCC, 2022a), and hence affect the sequestration capacity of forests, soils and wetlands, and the production of biomass for wood products and bioenergy with and without CCS. In addition to the carbon budget, the EU is limited by a biomass budget, the amount of biomass that can be grown in a year. Regionally, natural hazards such as wildfires, windstorms and insect outbreaks may turn some forests from carbon sinks into sources of GHG emissions. In several European countries, the LULUCF sector has become a net source of CO_2 during such exceptional events (EEA, 2024a).

Forest management practices across the EU have often prioritised a limited number of tree species, leading to simplified forest structures and a lack of diversification (European Forest Institute, 2023). However, tree species diversity positively influences forest biological productivity (Liang et al., 2016), which is critical for both climate adaptation and mitigation. Forests with high species diversity demonstrate resilience to hazards such as fire, wind and pests (Astrup, 2018; Jactel et al., 2018) reducing associated emissions when such disturbances occur. Because these hazards tend to increasingly occur in a cascading succession and compound each other (Pescaroli and Alexander, 2018), traditional hazard-specific management options may be overwhelmed, further underlining the urgency of broadly adopting adaptive forest management strategies (Morin et al., 2018).

Multiple EU policies affect demand for and supply of land and biomass resources. These policies influence different land uses and create synergies with and trade-offs for the sustainable scale-up of removals.

The LULUCF regulation requires the EU to achieve 310 $MtCO_2$ net LULUCF removals in 2030. This target is set within a mixed policy context that places many direct and indirect requirements on land resources, for example, through an increase in afforestation and avoiding the conversion of wetlands and peatlands (Advisory Board, 2024). Only some parts of the EU's agriculture, forestry, energy, environment and climate policies support increases in carbon stocks in the land sector. To help manage the impacts of such fragmented EU land policies, several EU policies have been proposed or adopted recently, notably:

- the Forest Monitoring regulation (EC, 2023l);
- the Soil Monitoring and Resilience directive (EC, 2023i);
- the deforestation regulation (EU, 2023g);
- the Nature Restoration Law (EU, 2024f);
- the revised renewable energy directive (RED III) (EU, 2023d).

Several strategic documents guide EU policy in this area, including the EU's strategies on: forests, soil, bioeconomy, biodiversity, farm-to-fork and adaptation to climate change.

Sections 7.2-7.5 present selected considerations regarding the potential of EU policies to contribute to scaling up removals while reinforcing other EU policy objectives such as biodiversity protection, fossil fuel subsidies' phase-out, food security, health, circular economy and climate resilience.

7.2 Protecting, restoring and expanding nature and land sinks

7.2.1 Need

Healthy and biodiversity-rich ecosystems can provide significant climate resilience, and carbon sequestration and storage benefits. Integrated land use planning can help maximise benefits and minimise trade-offs of competing policies and objectives for land and biomass.

As highlighted in Chapters 2 and 4, delivering temporary removals through ecosystem restoration can have multiple benefits: supporting climate mitigation goals by helping to limit short-term temperature overshoots, reducing risks from climate hazards, while also helping to address the ongoing global biodiversity crisis. Healthy ecosystems not only provide significant potential for carbon sequestration and storage, but are also more resilient to the effects of climate change, which can reduce the risks of reversal events (IPCC, 2022a). With the sequestration effects of practices like afforestation generally taking longer to materialise (Chapter 2), it is also urgent to restore existing ecosystems to contribute to reversing the decline in the land sink, and to maintain and restore critical ecosystem services.

EU policies on nature and biodiversity that support ecosystem conservation and restoration also have benefits for carbon storage and sequestration. However, as Chapter 3 outlines, these synergies are not always guaranteed, and specific trade-offs may arise between climate and other ecosystem functions in certain contexts. For example, large-scale afforestation with monocultures replacing species-rich grassland can deliver removals at the detriment of biodiversity (Verkerk et al., 2022; Woziwoda and Kopeć, 2014). Conversely, restoration of native grassland or heathland ecosystems can require the removal of trees and scrub, leading to emissions and reduced carbon sequestration and storage on the affected land (EEA, 2020). For adaptation purposes, nature restoration is indeed found to be one of the measures with the largest potential and fewer trade-offs (Reckien et al., 2023). These synergies and trade-offs can be partly managed through the rules on quality if removals (see Chapter 6). Integrated land use planning can contribute to managing these trade-offs at the landscape level. Sustainable land use planning requires a participatory, multi-level governance process to identify synergies and trade-offs in land use decisions, and to ensure coherence between competing policies and objectives for land and biomass (IPCC, 2022j).

7.2.2 Status and policy gaps

The EU nature directives establishing the Natura 2000 network form the core of the EU's biodiversity policies, providing EU-wide legal protections for many carbon-rich ecosystems.

Since their adoption in 1979 and 1992 (respectively), the birds and habitats directives (the 'EU nature directives') have placed legal requirements on Member States to designate and protect sites containing listed species and habitats. Natura 2000 sites cover 18% of land and 10% of marine waters in the EU, with around 60% of the network's terrestrial area comprised of forests, grasslands and heathlands (EEA, 2023d).

Among the habitats listed in Annex I of the habitats directive, the Natura 2000 network provides legal protections for many particularly carbon-rich marine and terrestrial habitats, including maerl and seagrass beds, wetlands, forests, grasslands or temperate heath and scrub (EEA, 2022). On average, carbon stocks on sites within the Natura 2000 are 43% higher than those outside (Beresford et al., 2016), with several estimates indicating that approximately 5.5-17.8 Gt of carbon (or 20-65 Gt CO_2e) is stored within Annex I habitats in the EU (EC, 2016; IEEP and WWF, 2021). Collectively, these Annex I habitats also have considerable carbon sequestration potential, and some estimates have suggested that, if fully restored to a healthy condition, they could sequester in the order of magnitude of 300 $MtCO_2e$ per year (IEEP and WWF, 2021). Nevertheless, according to the EEA:

> *'uncertainties in quantitative estimates of carbon storage and sequestration in many ecosystems are high, making it difficult to quantify the impact of nature restoration on climate change mitigation policies in Europe. This calls for further biogeographical differentiation and validation with data from monitoring and measurements, and for better spatial delineation of habitats across Europe's land and seas'*. (EEA, 2022, p. 2)

Despite the potential positive effects of EU nature directives, the conservation status of carbon-rich ecosystems in the EU is still largely poor and deteriorating. Pressures on biodiversity come from agricultural and forest management practices, as well as urbanisation and climate-induced risks.

Although the assessment of the EU nature directives shows positive effects for many species and habitats (EEA, 2023d), still the general objectives of the directives have not yet been met and it is not possible to predict when they will be fully achieved **(implementation gap)**, partly due to insufficient monitoring (EC, 2016, EEA, 2023a). In the most recent assessment of the status and trends in the Natura 2000 network (EEA, 2020), just 14% of habitat assessments showed a good conservation status, and 27% of non-bird species are 'good'.

Among terrestrial habitats considered to be carbon-rich, 'bogs, mires and fens' (over 50%) and 'grasslands' (49%) had the highest proportions of assessments showing a bad conservation status, with trends that are mostly deteriorating. Agricultural practices and urbanisation were generally the largest source of pressures reported across all habitat types. Forestry activities, including harvesting and felling, as well as drainage of wetlands are the main sources of pressure on these habitats, and among the largest pressures for several species (e.g. arthropods, mammals, fish and non-vascular plants). Climate change impacts, including through temperature and precipitation changes, have been recognised as a growing threat to most habitats and species covered by the EU nature directives. Trends that have been extensively highlighted by other authors (EEA, 2024a; Pilli et al., 2021).

Funding and governance challenges as well as the lack of restoration safeguards have limited the EU nature directives' effectiveness.

Policy and academic assessments have highlighted several implementation challenges to achieving the objectives of EU nature and biodiversity policies, including insufficient funding, governance, and restoration safeguards. In particular, several authors have highlighted how insufficient or inadequately-targeted funding has limited the impact of the EU's biodiversity and nature policies to date (Hermoso et al., 2022; ECA, 2020; Kettunen et al., 2017; ECA, 2013), with various estimates identifying funding gaps at both EU and national levels. One study for the European Commission (EC et al., 2022a) estimated that delivering on the EU's overall biodiversity objectives would require funding of approximately EUR 48 billion annually between 2021-2030, compared to EUR 30 billion currently estimated to be available from the EU and Member States, a funding gap of EUR 18 billion. Other studies focusing specifically on the maintenance and restoration of Annex I habitats have estimated total annual funding needs of between EUR 7.4 billion (EC et al., 2023) and EUR 10.6 billion (EC et al., 2022b).

Governance challenges during the process of designating Natura 2000 sites have delayed or otherwise compromised their implementation **(implementation gap)**, with this process the subject of numerous infringement proceedings taken by the European Commission against Member States (Beunen et al., 2013; Bonsu et al., 2019; Frederiksen et al., 2017) (EC, 2016). This challenge has been linked to both policy-level and localised trade-offs between biodiversity and other policy objectives, mostly in agriculture (Hristov et al. 2020; ECA 2020; Pardo et al. 2020; Pe'er et al. 2020), biomass and bioenergy (EEA, 2023e; Söderberg and Eckerberg, 2013), as well as infrastructure and investments (EC, 2016).

Several studies have argued that the original EU nature directives fail to make a clear distinction between 'conservation', with management measures focused on maintaining a stable status quo, and 'restoration', which involves measures aimed at improving the condition and functions of degraded ecosystems. Described as a lack of strong, binding restoration norms, this includes the absence of clear legal targets for restoration and a lack of focus on connectivity (Mendes et al., 2023; Hoek, 2022; van Teeffelen et al., 2014).

EU biodiversity and forest strategies have increasingly promoted land management that delivers on multiple EU policy objectives including land sink protection and removals. The newly adopted Nature Restoration Law reinforces these strategic priorities by including binding targets for ecosystem restoration.

As part of the European Green Deal, the EU biodiversity strategy for 2030 (EC, 2020c) was adopted to respond to the "state of crisis" facing nature and biodiversity. In addition to a renewed commitment to better implementing existing environmental legislation, it set quantified targets to protect and restore terrestrial and marine ecosystems, many of which are also likely to enhance the carbon sink (Table 15). The EU forest strategy for 2030 (EC, 2021i) builds on those targets while formulating principles to incentivise sustainable forest management and resource use. The EU forest strategy promotes the widespread adoption of synergetic management measures in existing forests that improve productivity, biodiversity, carbon sequestration and climate adaptation. It calls for these practices to be incentivised through 'payment for ecosystem services' schemes, for instance under the CAP and the CRCF framework.

The recently-adopted Nature Restoration Law could reinforce the non-binding EU biodiversity and forest strategies by enshrining specific, quantified, and time-bound biodiversity and restoration targets into EU law (Cliquet et al., 2024; Hoek, 2022). Article 1 of the Nature Restoration Law requires that Member States implement measures to restore at least 20% of the EU's overall land and marine areas by 2030, and all ecosystems in need of restoration by 2050. The law sets binding ecosystem restoration targets for listed land and marine habitats, as well as separate targets covering specific habitats or species. While these targets do not directly create obligations for individual land managers, Member States will be required to put in place necessary measures to reach these targets, including public and private incentive schemes, monitoring and reporting. Under Article 14 of the law, Member States are to develop national restoration plans to identify and quantify these restoration measures.

Table 15 Targets contained in the Nature Restoration Law

Land, freshwater and coastal	For terrestrial Annex I habitats not in good condition, 30% must be under restoration measures by 2030 (prioritising Natura 2000 habitats), 60% by 2040 and 90% by 2050.
Marine	For most marine habitats not in good condition, 30% must be under restoration measures by 2030, 60% by 2040 and 90% by 2050.
Urban ecosystems	No net loss of urban green space and tree canopy cover by 2030, and an increasing trend thereafter
Rivers and floodplains	Restore 25,000km of rivers to free-flowing status by 2030 through removal of obsolete artificial barriers
Pollinators	Reverse decline in pollinator populations by 2030, and achieve an increasing trend thereafter
Agricultural ecosystems	Implement restoration measures to enhance biodiversity in agricultural ecosystems, achieving an increasing trend by 2030 in two out of three indicators: a) grassland butterfly index; b) organic carbon stocks in cropland mineral soils; c) share of agricultural land with high-diversity landscape features
(Agricultural) Peatlands	Restore or rewet organic soils in drained peatlands under agricultural use: 30% of areas by 2030 (of which one quarter rewetted); 40% by 2040 (one third rewetted); 50% by 2050 (one third rewetted)
Forests	Increasing trend in the forest bird index, as well as six out of seven forest ecosystem indicators (e.g. standing deadwood, soil carbon stocks, species and age diversity) Contribute to planting 3 billion trees by 2030, prioritising native species

Source: (EU, 2024f)

The Nature Restoration Law is expected to deliver dual benefits for the EU's climate mitigation and biodiversity objectives if adequately implemented and funded.

Robust and well-resourced implementation of the Nature Restoration Law is expected to deliver dual benefits for climate mitigation and biodiversity, particularly from the restoration of peatland, coastal wetland and forest habitats (EC et al., 2023; IEEP and WWF, 2021). Given the importance of many of these habitats for carbon sequestration and storage, the Law has been described as a crucial contribution towards the EU's 2030 LULUCF targets (EC, 2024v). Member States' submission of national restoration plans serves as the framework for implementation of restoration measures, and should be accompanied by monitoring and reporting on progress towards targets (including GHG emissions), making use of the EU's spatial surveillance capacities and robust in-situ methods (EU, 2024f).

Under the 2021-2027 multiannual financial framework, the European Commission has committed to dedicate 7.5% of the total EU budget over the period 2021-2027 to biodiversity objectives as of 2024, and to increase this to 10% in 2026 and 2027 (EC, 2024c), with the available EU-level funding amount to average EUR 13.8 billion (EC et al., 2022a). To mobilise this level of funding, the European Commission has increasingly highlighted opportunities to tap into sectoral funding streams by mainstreaming and prioritising nature-based solutions, in agriculture, adaptation, urban areas, fisheries, water and energy infrastructure. EU 'missions' – such as those on adaptation, an EU soil deal, and restoring oceans and waters – also provide an opportunity to mainstream these objectives in other EU policies, and to increase the available funding for these types of ecosystem restoration projects and research (EC, 2021g).

Although the European Commission is required to report on biodiversity spending through its green budgeting tracking mechanism (EC et al., 2022a), this follows a similar methodology used for tracking climate spending. The Advisory Board (2024) has previously highlighted weaknesses in this methodology, particularly that it risks overstating the impact of EU programmes towards EU environmental climate and environmental objectives. Several stakeholders have called for the EU to establish a dedicated 'nature restoration fund', or similar funding instruments, to ensure sufficient funding to support the implementation of the Nature Restoration Law and biodiversity policies. This could also contribute to the EU's LULUCF objectives by funding relevant ecosystem restoration projects (EC, 2024x; EEB et al., 2024).

No explicit policy mechanism details how national land use decisions contribute to the achievement of diverse policy objectives. National nature restoration plans can help address this gap by setting processes to identify and manage policy trade-offs and synergies.

The development of national restoration plans is an opportunity to improve coherence between multiple land use objectives, requiring Member States to identify ecosystem restoration practices that have synergies and trade-offs with climate and other objectives. According to Article 14 of the Nature Restoration Law, plans are bound to identify synergies in restoration measures with climate change mitigation, climate change adaptation, land degradation neutrality and disaster prevention, as well as agriculture and forestry (see Chapter 3). These plans could therefore increase EU policy coherence, for instance between the nature restoration and the CAP.

The EU's CRCF framework encourages removals activities that deliver biodiversity benefits. Challenges remain in accurately tracking environmental spending and promoting nature-based solutions.

As presented in Chapter 6, the CRCF framework sets minimum sustainability criteria for biodiversity, explicitly excluding practices that produce harmful effects for biodiversity, such as forest monocultures, and mandating that a carbon farming activity must always generate at least a biodiversity co-benefit including soil health and avoidance of land degradation. It also states that sustainability requirements should consider the impacts on biodiversity both inside and outside the EU (EU, 2024g). The CRCF framework may also unlock financing for ecosystem restoration that involve removals, particularly in peatland and forest restoration (Günther et al., 2024). Although, as noted in Chapter 6, there are still uncertainties as to which practices or ecosystem restoration projects would be eligible for certification under the CRCF.

7.3 Managing biomass demand for energy including BECCS

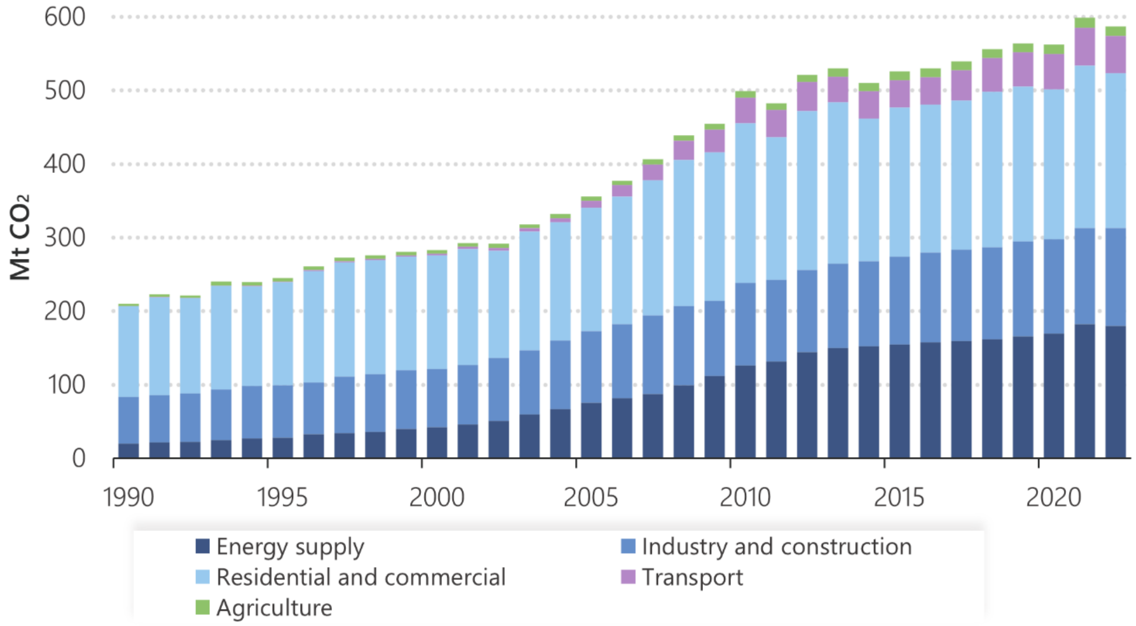
7.3.1 Need

Bioenergy satisfies around 60% of EU renewable energy demand and its share in the EU's overall energy generation mix is increasing. Rising forest biomass demand, largely for energy use, has led to increased harvesting, reliance on imports and sourcing from unknown origins.

The EU used 1.2 billion tonnes of biomass (measured in dry matter) in 2017, of which 50% was used for food, feed and bedding for livestock, 22% for bioenergy and 28% for materials (EEA, 2023e). Demand for biomass for energy (direct combustion of biofuels, mainly in the buildings, energy supply, and industry sectors) has been growing since 1990 (see Figure 21). In 2021, bioenergy, mostly from primary woody biomass, made up nearly 60% of renewable energy used in the EU. In 2022, almost one third of gross heat production in the EU came from biomass combustion. In the power sector, biomass was 15% of the total gross renewable electricity mix and nearly 6% of the total gross electricity production (Eurostat, 2024b). In transport, biofuels produced from food and feed crops continue to have the highest share of all renewable energy carriers (3.9% of total energy consumption in transport in 2021 (EC, 2023).

Between 2009 and 2017, the EU's demand for woody biomass increased by over 25% (193 million m^3), mainly due to an increase in demand for energy use (121 million m^3) (Advisory Board, 2024; JRC, 2022). Nearly half of the increased demand was met by increased harvesting, with another 22% coming from unknown sources which could also include harvesting. Only a third of the increase is known to have been met from secondary supply such as residues and post-consumer wood (JRC, 2022). The EU is a net importer of woody biomass[19], mainly wood pellets and roundwood (EU, 2024). Wood pellet imports from non-EU countries more than doubled between 2009 and 2023 (Eurostat, 2023; USDA, 2024).

Figure 21 Annual CO_2 emissions from combustion of all types of biomass for energy purposes in different sectors in the EU-27



Source: EEA based on European Commission (2023)

Notes: CO_2 emissions from biomass combustion are reported as a Memo Item in national GHG inventories and are not included in national GHG emissions total

The EU's reliance on bioenergy and BECCS to reach net zero raises concerns about sustainability due to the impacts of biomass extraction on land use, water, biodiversity and carbon sinks. Sustainable BECCS deployment requires limiting primary biomass demand, enhancing technology

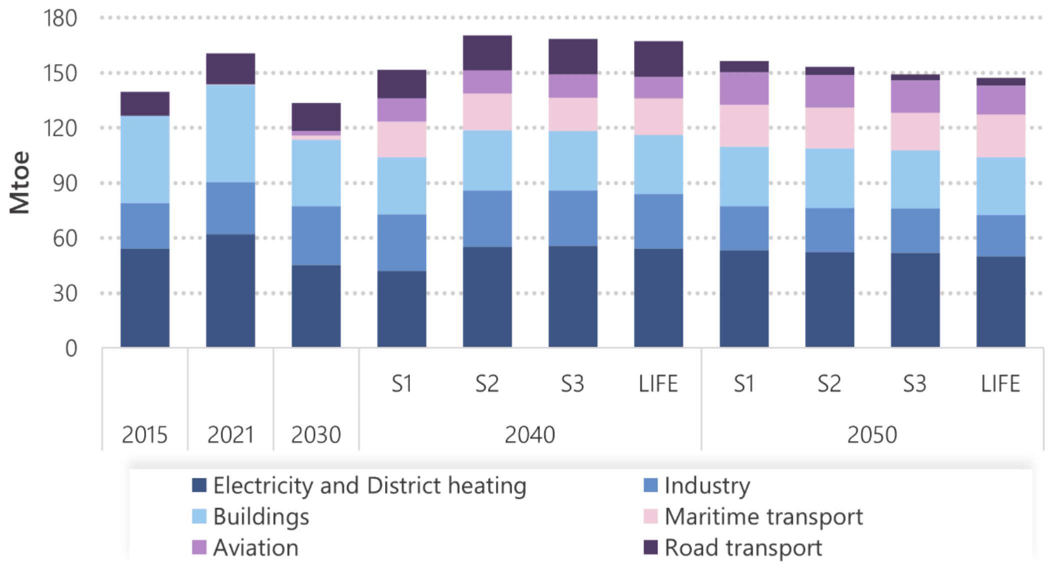
[19] Imported woody biomass accounted for 19% of the EU's total primary bioenergy in 2021. Russia and the United States were the biggest exporters of woody biomass to the EU until the Russian war of aggression that led EU to ban woody biomass imports from Russia and increase its supply from the United States. EU imports of United States wood pellets increased from 1,781,000 tonnes in 2021 to 3,125,000 tonnes in 2022 (USITC, 2024; EU, 2024).

efficiency, and ensuring that overall bioenergy use contributes to net GHG reductions without exacerbating environmental pressures.

The increasing trend of bioenergy use continues in the European Commission's scenarios underpinning the EU's 2040 climate target communication[20]. The expected increase is linked to uptake in advanced liquid biofuels and biomethane as part of enhanced value chains for biogenic carbon (see also Section 7.4), while direct consumption of solid biomass has been modelled to decline. Accordingly, the expected final bioenergy demand in electricity and district heating generation would decrease from the current level by 2040[21] (EC, 2024i).

The focus on advanced fuels with more circular use of biomass is underpinned by the European Commission's modelling choice to cap the gross available energy from biomass at 9 EJ until 2050, which is 40 % more than 2021 levels (EC, 2024i). The modelled cap reflects the environmental risk level applied for 'primary bioenergy use' by the Advisory Board in its analysis for the EU 2040 target recommendations, although it exceeds the 7.5 EJ bioenergy level that was found in the 5-7 scenarios aligned with the recommended 90-95% reduction target (Advisory Board, 2023). The European Commission's assessment includes specific feedstock caps in its assumptions: 1.2 EJ for harvestable stem wood, 0.8 EJ for forest residues, and 0.4 EJ for imported biomass. These caps are not prescriptive; the Commission acknowledges that the supply of biomass for energy could exceed the modelled levels, depending on future energy demand and the actual uptake of e-fuels and DACCS towards 2050 (EC, 2024i). In general, projections suggest that biomass demand driven by climate and energy policies will often surpass the sustainably available domestic supply (EEA, 2023e; Material Economics, 2021); see Figure 22.

Figure 22 Final demand for bioenergy by sector and scenario in European Commission's scenarios



Source: (EC, 2024i)

Notes: Final demand for bioenergy includes here bioenergy used in final energy consumption sectors and as input to the electricity and district heating. It does not consider transformation process losses in producing biofuels, biogas or biomethane. Scenarios

[20] A 38% increase in bioenergy generation by 2040 from 2019 levels and a 22% increase after 2040 from the same baseline (2,424 TWh and 1,183 TWh of gross available energy from biomass in 2040 and 2050 respectively) (EC, 2024i).

[21] 721 TWh in 2021 to 630-650 TWh in 2040 and 581-602 TWh in 2050.

S1, S2, and S3 build on the continuation and upscaling of the current trends driving decarbonisation towards 2030, with different degrees of ambition regarding GHG emission reduction in 2040, and LIFE builds on an assumption of more sustainable lifestyles.

The 2040 impact assessment assumes BECCS in the power sector to capture and store up to 33 $MtCO_2$/y in 2040 and no more than 56 $MtCO_2$ per year in 2050 (or a maximum of 60 $MtCO_2$ when storage in bio-based products is included) (EC, 2024i), which corresponds to, respectively, around 18% and 31% of emissions from large-scale bioenergy plants in 2021. This assumption matches the expectations of some researchers that BECCS will not necessarily lead to an increase in biomass use when applied to existing installations (Lefvert and Grönkvist, 2024). In parallel, up to 22 Mt of biogenic CO_2 from industrial biomethane production is projected to be captured and applied in e-fuels production as CCU by 2040 (EC, 2024i)

The impacts of biomass extraction on land, water, carbon sinks, and biodiversity result in uncertainty regarding the scale at which BECCS can be sustainably deployed to achieve negative emissions (IPCC, 2022). The EU's reliance on large-scale BECCS for negative emissions may increase pressure on planetary boundaries for freshwater use, land-use change, biosphere integrity, food security and biogeochemical flows (Heck et al., 2018; Koponen et al., 2024). BECCS installations require energy for post-combustion CCS processes (Babin et al., 2021; Bui et al., 2018; Capocelli and De Falco, 2022). Besides energy, BECCS is associated with high life cycle water demand (Kumar et al., 2023; Rosa et al., 2021b; Wu and Zhai, 2021). In addition, bioenergy production, especially from primary sources, increases demands on land, as well as nitrogen and phosphorus inputs (Fajardy et al., 2019). Some bioenergy processes offer efficiency gains by creating removal opportunities beyond BECCS, for example, biofuel production through pyrolysis that creates biochar (Volpi et al., 2024).

Bioenergy can lead to either increased or reduced GHG emissions, depending on four factors: (a) the scale of aggregate biomass demand, (b) the efficiency of conversion and removal technologies, (c) what fuel it displaces and (d) how/where the biomass is produced (IPCC, 2022d). The following section assesses EU policies relevant to each of the four factors.

7.3.2 Status and policy gaps

7.3.2.1 The scale of aggregate biomass demand

Zero-rating of emissions from biomass under the governance regulation, EU ETS, and renewable energy policies incentivises bioenergy deployment in the EU. The CRCF encourages BECCS as certifiable permanent removal activities, providing further incentive for bioenergy deployment.

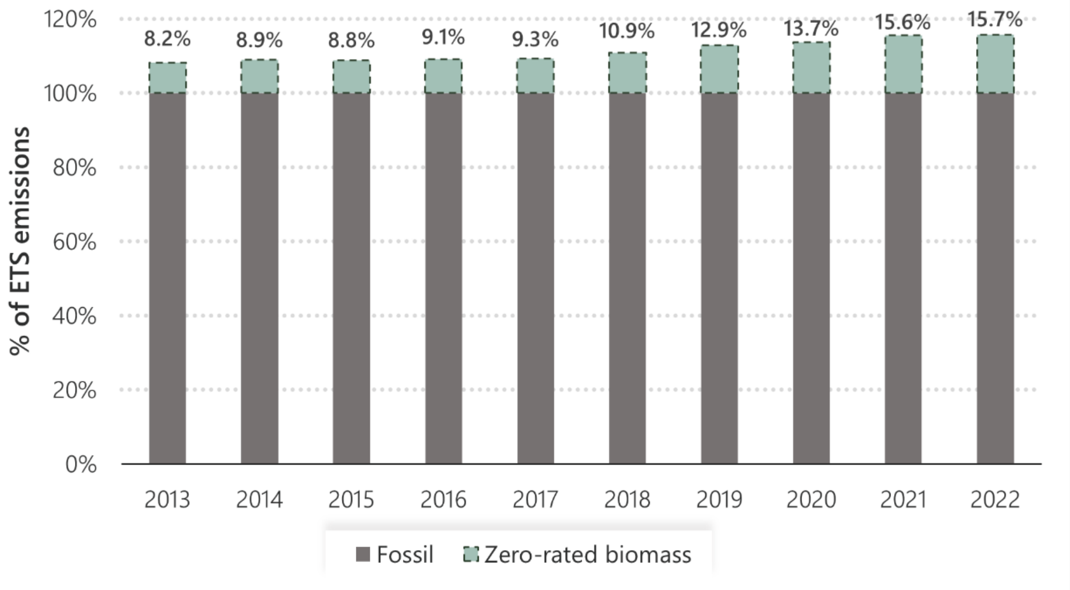
The current policy and economic incentives behind the growing deployment of bioenergy stem from the EU ETS directive (EU, 2003) and RED II/III. Certified sustainable biomass counts towards the EU's renewable energy targets and, under the EU ETS, CO_2 emissions from its combustion are zero-rated; in other words, utility operators do not need to surrender allowances for these emissions. The zero-rating of biomass combustion in energy sector is also a premise in GHG inventories under the governance regulation and, by extension, under the CRCF regulation: BECCS can deliver certified negative emissions if it meets predefined sustainability and other quality criteria.

In 2022, nearly all emissions from the combustion of biomass under the EU ETS were zero-rated, as the compliance with the sustainability criteria under REDII was not yet required in practice[22]. They amounted to ca. 173 $MtCO_2e$ (EC, 2023n), which represents nearly all CO_2e emission from biomass combustion in public electricity and heat production in the EU in 2021 (179 $MtCO_2e$) reported under the UNFCCC (EU,

[22] Until 1 January 2023, national authorities could have allowed installations to zero-rate emissions from biomass without demonstrating compliance with the RED II criteria for sustainability and emissions savings (EC, 2023n).

2023e). The use of biomass in EU ETS installations is increasing rapidly (EC, 2023n), as presented in Figure 23 below. These shares are expected to drop in the future, due to (a) the stricter compliance requirements with sustainability criteria under RED II/III and (b) the exclusion from the EU ETS of installations running almost exclusively on biomass.

Figure 23 Biomass emissions in EU ETS installations (% of total emissions in the EU ETS)



Source: EC, 2023b, p.23

Note: Labels not shown if fuel never reaches a share above 3% of the total

The zero-rating approach has been criticised as simplistic and offering perverse incentives (Cherubini et al., 2011; Pulles et al., 2022). Scientists from the European Academies Science Advisory Council highlight that an exclusion from carbon pricing effectively subsidises biomass combustion although direct emissions of CO_2 per unit of electricity generated from combustion of biomass in large-scale bioenergy plants can be higher than when fossil fuels are used, due to inefficiencies when converting biomass to electricity and complex and lengthy biomass supply chains (EASAC, 2022a). Moreover, according to the International Energy Agency, the soundness of the reporting of removals from BECCS is based on an assumption of comprehensive reporting in the LULUCF sector (see also Section 6.2) (IEA, 2011). As explained by (Field et al., 2020): 'net GHG mitigation is not an automatic outcome of any bioenergy system [...] which is an avoidable pitfall if policy makers and the bioenergy industry are mindful of [it] and design land use policies and bioenergy systems with intent accordingly'.

A sustainability cap applied in the modelling mentioned above does not have a direct equivalent in terms of policy restrictions on the overall quantity of EU's bioenergy demand. However, the CRCF regulation signals some safeguards in this respect. At an installation level it highlights that the financial benefits related to the certification should not be used to increase the capacity of a bioenergy plant beyond what is necessary for the operation of the CCS. However, this is only reflected in a recital (recital 28) which means there are no legally binding requirements in place so far **(ambition gap**, see also Chapter 6). At a broader level, the CRCF regulation requires the European Commission's to review the regulation considering, among others, its 'environmental impacts of increased biomass use' (recital 40, EU, 2024).

The EU's reliance on BECCS hinges on scaling DACCS and other non-biomass removal technologies, which remain undervalued in policy modelling that often overestimates bioenergy's

role in net-zero pathways. While circular economy and energy demand policy measures aim to ease biomass pressures, uneven incentives for biomass use versus land carbon sink persist.

Future demand for BECCS depends on incentives to scale up DACCS and other non-biomass permanent removals, including investment in innovation and additional non-biomass renewables to meet DACCS energy needs. Other non-biomass removal options offer further opportunities to diversify the EU's removal portfolio (see Chapter 3). The potential of non-biomass removal methods is often not captured in policy-relevant modelling, and the role of bioenergy and BECCS in the net-zero transition tends to be overestimated compared to alternative technologies (Adun et al., 2024; Luderer et al., 2022): for example, when modelling assumptions do not consider comprehensive sustainability criteria or when expected DACCS costs are prohibitively high (Béres et al., 2024; Lux et al., 2023).

Finally, to release the pressure on biomass supply, the EU seeks to foster a circular economy and a decrease in the demand for energy and materials demand, notably through RED II/III and the energy efficiency directive. While it is understood that the lower the EU's energy and material demand, the lower the need for removals and bioenergy (EC, 2024i), the incentives for using biomass for energy purposes persist in the absence of a EU policy driven financial incentive for land managers to reduce emissions and increase removals in the LULUCF sector (Advisory Board, 2024).

7.3.2.2 Efficiency of conversion and removal technologies

The scalability and sustainability of bioenergy in the EU face challenges due to inefficient conversion processes, inconsistent data reporting, and slow deployment of advanced pathways. Policies such as RED III and the energy efficiency directive promote cascading biomass use and resource efficiency, but current cross-sectoral governance is not strong enough to maximise synergies and mitigate trade-offs in bioenergy and BECCS deployment.

The various chemical and biological conversion pathways to convert diverse biomass feedstocks into multiple final energy carriers differ in terms of resource intensity, that is, the amount of resource use (e.g. for example energy and water) used in the conversion process for each unit of output (IPCC, 2022m). In the EU, the energy efficiency of some biomass combustion processes, notably in the residential sector, is low due to inappropriate pretreatment of feedstock and outdated equipment (Sikkema et al., 2021), and the data regarding conversion efficiencies of bioenergy installations are not consistently reported at national level (EC, 2023b; Sikkema et al., 2021). The roll-out of advanced biofuels is slower than expected, and cases of fraud in this bioenergy segment have recently been confirmed (ECA, 2023) **(implementation gap)**. While fossil fuel subsidies persist (Advisory Board, 2024), biofuels are not yet economically viable in the EU and need additional policy measures to secure sufficient production (ECA, 2023).

The European Commission recognises the need to ensure the sustainable, water-efficient production and consumption of food, materials and bioenergy, but it is still uncertain how such resource efficiency will be achieved across the EU in practice (EC, 2024i). Efficiency of bioenergy installations is subject to the energy efficiency directive, and in case of large-scale industrial installations, also the industrial emissions directive. While inducing operators to comply with the best available techniques, the industrial emissions directive does not yet include any specific requirement regarding efficiencies of carbon capture process **(policy gap)**. Under RED II/III support for electricity-only installations excludes new or renewed support for electricity-only installations; a measure reflecting low energy conversion efficiency of such installations (EU, 2023d).

System's efficiency-led cascading use of biomass is encouraged under the REDII/III, in which biomass is put to good use by prioritising uses with higher added value and lower environmental impact, before it is burnt for energy purposes (EEA, 2023e). Systems that offer the benefits of long-term biogenic carbon storage (e.g. in buildings) are encouraged at EU level, notably in the sustainable carbon cycles communication (EC, 2021e), the 2030 forest strategy (EC, 2021d), the revised construction product regulation (EU, 2011), the CRCF regulation (EU, 2024g), regulation on deforestation-free products (EU, 2023g), the revised LULUCF regulation (EU, 2023f), and the new European Bauhaus (EC, 2021j). These policies encourage among others eco-design and traceability of wood which can maximise the potential benefits of its cascading use (Bais-Moleman et al., 2018).

In addition, according the CRCF regulation the captured biogenic emissions from waste to energy plants could benefit from the certification of removals (EC, 2024b). The waste framework directive (EU, 2008b) set-out the waste hierarchy in which the priority is prevention, followed by preparing for re-use, recycling, other recovery (e.g. energy recovery) and, as a last resort, disposal. This implies limits to CCS on the biogenic fraction of waste incineration, as it could be applied only to truly unavoidable and non-recyclable waste. This approach could be considered as part of the wider strategy recommended by the IPCC in which a cross-sectoral agenda for bio-based production within a circular economy and international governance helps to maximise synergies and limit trade-offs of bioenergy and BECCS deployment (IPCC, 2022a), which is currently lacking at the EU level (see, for example, JRC, 2024). Globally, further efforts are needed to identify and develop efficient pathways at a system-level, for example through sequencing of value chain steps with appropriate management of supply chains of biomass (IPCC, 2022a). This process may include exploring the lifecycle emissions and resource efficiency of clusters (IEA, 2023a) and systems involving bio-CCS or CCU such as harvested wood products, bioenergy, biochar systems and biohydrogen (Rosa and Mazzotti, 2022; Woolf et al., 2016).

7.3.2.3 Fuel substitution

EU policy does not sufficiently support targeting of biomass to sectors with limited potential for electrification to substitute for fossil fuels.

Biomass is well suited to substitute fossil fuels in uses less amenable to electrification due to the versatility of its application. It can be converted to multiple energy carriers, not only electricity but also liquids, gases, hydrogen and solid fuels, as well as other value-added products (IPCC, 2022m). Biofuels can also substitute for other renewables. Given the sustainability limits to biomass supply, and to avoid crowding out other types of renewables, bioenergy serves best those sectors where alternatives to direct electrification are limited. For instance, in power and heat generation non-bioenergy solutions such as wind and solar energy and heat pumps are often available. Balancing intermittent renewable energy can, to a large extent, be covered by technologies and system solutions other than biomass, such as hydro power, battery storage, hydrogen, and demand side response.

As mentioned above, RED III (EU, 2023f) prioritises the material use of biomass over energy use, and excludes new or renewed support for electricity-only installations. It also introduces a dedicated target for advanced biofuel deployment in transport sector. It does not further differentiate between end uses based on the availability of other renewable energy or other mitigation option **(ambition gap)**. RED III and the wider EU policy framework encourage biomethane as an alternative to fossil gas, which may risk extending the use of fossil fuels and associated methane leaks (Advisory Board, 2024). Overall, in the current legal context, considering the lack of a carbon price signal in the LULUCF sectors and the substantial incentive through zero-rating of bioenergy under the EU ETS, biomass is not always deployed where it is most beneficial from a socioeconomic and technological efficiency perspective. This market failure is reflected in the European Commission's 2040 target communication, which notes that bioenergy should be prioritised in sectors where the potential for electrification is limited, such as air or maritime transport (EC, 2024i).

7.3.2.4 Biomass sustainability

The EU's forest carbon sink is decreasing due to higher biomass demand, slower forest growth, and climate change-induced impact. EU policies aim to protect forest carbon but do not yet consistently address broader environmental and climate risks, and the potential of BECCS.

Despite regional differences, overall the decline in the EU's forest carbon sink is linked to increased demand for woody biomass combined with stable or reduced forest growth and climate change hazards like fires or droughts (Biber et al., 2020; Advisory Board, 2024; Hyyrynen et al., 2023). Focusing on the EU territory, current forest management practices are projected to increase harvesting and decrease the net annual increment, both of which are driven by ageing forests. As a result, the forest carbon sink in the EU could decrease to 240 MtCO_2 in 2030 and 207 MtCO_2 in 2050 (Korosuo et al., 2023; Pilli et al., 2022).

The risk of affecting forest carbon sinks is reflected in the European Commission's scenarios in which the demand for biomass in 2040 is met increasingly with advanced/second generation biofuels including herbaceous crops such as miscanthus, rather than woody biomass (EC, 2024i). In addition, EU policies, notably the LULUCF regulation, encourage protection of forest carbon stocks. As described in Sections 7.1 and 7.5, however, EU policy does not yet address the mitigation, productive, and adaptive capacities of land in an integrated manner, despite the benefits of such integration (Advisory Board, 2024; Field et al., 2020). There is no pricing of emissions and other externalities linked to biomass extraction from land **(policy gap)**. To minimise the externalities and help to avoid the conflict between decarbonisation and other sustainable development goals, the EU applies sustainability and GHG criteria for biomass for energy (Bhaduri et al., 2018; IPCC, 2022m). The EU policies applying sustainability criteria and GHG criteria to biomass for energy include: RED III (EU, 2023d), the CRCF regulation (EU, 2024g), the FuelEU maritime regulation (EU, 2023h), and the ReFuel aviation regulation (EU, 2023i) (see Table 16). Due to the novelty of these acts, so far there is little experience of their actual implementation.

Table 16 Sustainability requirements for biofuels in EU legislation

Safeguards linked to	**REDII/III** art.3, 26,29	**CRCF** Reg. art. 7,8,4	**FuelEU Maritime** art. 10,4	**ReFuelEU Aviation** art. 3,4
GHG savings	Explicit	Explicit	Explicit	Explicit
Feedstocks from highly biodiverse areas	Explicit	Explicit	Explicit	Explicit
Feedstocks from high carbon stocks	Explicit	Explicit	Explicit	Explicit
Food crops/high indirect land use change risk	Explicit	Explicit	Explicit	Explicit
Harvesting operations	Explicit	Explicit	Explicit	Explicit
Monitoring and management of agricultural land	Explicit	Explicit	Explicit	Explicit
Accounting of land-use change emissions	Explicit	Explicit	Explicit	Explicit
Do no significant harm principle	No explicit	Explicit	No explicit	No explicit
Sustainability co-benefits	No explicit	Explicit	No explicit	No explicit
Cascading use of biomass	Explicit	Explicit	No explicit	No explicit
Lifecycle emissions	No explicit	Explicit	Explicit	Explicit

Legend ■ Explicit safeguards in place
■ No explicit safeguards in place

Source: Advisory Board

The sustainability and GHG criteria for biomass under RED II/III, and by extension under the CRCF regulation, face challenges due to inconsistent implementation, insufficient transparency, and fragmented data and terminology across the EU, raising concerns about the sustainability of biomass use. To address the decreasing LULUCF sink and integrity risks of BECCS projects, the EU should address the perverse policy incentives and the lack of emission pricing for biomass extraction, while implementing robust safeguards and lifecycle assessments under the CRCF framework.

The sustainability and GHG criteria for biomass set out in RED II in 2018 apply de facto only since 2023, and the RED III provisions need to be transposed by Member States by mid-2025. The CRCF regulation provides overarching sustainability safeguards applicable to certified BECCS projects (see Chapter 6). It does not only require the RED II compliance, but also goes beyond it through clauses on doing no significant harm, sustainability co-benefits, and entire value chain emissions of removal projects; the detailed methodologies are still under way (EU, 2024g). Consistent implementation of the adopted rules may be challenging, however, for several reasons, including:

- the uncertain integrity of the existing sustainability and emission criteria as well as the certification schemes under RED, as pointed out by the European Court of Auditors (ECA, 2016), the European Ombudsman (European Ombudsman, 2022), researchers (Mai-Moulin et al., 2021; Moser and Leipold, 2021; Vogelpohl, 2021), and NGOs (e.g., biofuelwatch et al., 2023);
- lack of consistency between REDIII, ReFuelEU, FuelEU maritime, and the CRCF regulation (**policy inconsistency,** see Table 16 above) and the resulting risks to the sustainability of the biomass supply (EEA, 2023e);
- insufficient transparency regarding the origin of biomass for energy and the conversion pathways in reporting within the NECP process **(implementation gap)** (EC, 2023b; Sikkema et al., 2021);
- incomparable and patchy forest monitoring data at the EU level, preventing accurate assessments and comparisons (FISE, 2024; Lier et al., 2022);
- substantial time lags between the occurrence of emissions and reporting of the data (Korosuo et al., 2023);
- a lack of common terminology, vagueness and a lack of standardisation in the EU and national sustainability frameworks for bio-based products and bioenergy (Moosmann et al. 2020).

So far, according to the European Environment Agency:

> *'despite the [sustainability] criteria, data have shown that the LULUCF sink continues to decrease in the EU and bioenergy use is increasing. This triggers a debate about the extent to which biomass extraction for human use is sustainable, efficient biomass use, and the sustainability of biomass raw materials.'* (EEA, 2023e, p. 20).

Apart from a policy-relevant debate looking at the robustness of the existing safeguards, accounting of actual removals and emissions of BECCS as well as resource intensity and side-effects across project lifecycle (IEA, 2023a) in line with the CRCF regulation emerges as an important safeguard to avoid integrity risks stemming from policies incentivising permanent removals.

Finally, as highlighted in Chapter 4, there is no pricing of emissions and other externalities linked to biomass extraction from land; which in in combination with the zero-rating rules, results in bioenergy being exempted from any carbon price while counting towards binding targets under RED II/III. The Advisory Board previously recommended to initiate extension of the emissions pricing regime to the agricultural/food and LULUCF sectors to incentivise further climate action in these areas (Advisory Board, 2024).

7.4 Farming carbon on agricultural land

7.4.1 Need

The EU's agricultural land can contribute to removals directly by sequestering carbon in soils and living biomass through a variety of management practices. Improved data is needed to more accurately assess their impacts.

Despite a slight decrease in total agricultural land area since 2005 (Advisory Board, 2024), agriculture still accounted for approximately 38% (157 million hectares) of the EU's total land use in 2020, according to the latest official statistics. In addition to managing two-fifths of the total land area of the EU, farms manage land as wooded areas (5.9 %) and as other farmland not used for agriculture (2.2 %) (Eurostat, 2022).

Currently, EU agricultural soils emit more CO_2 than they remove. The overall level of net CO_2 emissions from agricultural land declined from almost 70 $MtCO_2$ in 2005 to 41 $MtCO_2$ in 2022 (EEA, 2024c). Remaining emissions are highly concentrated in cultivated organic soils[23] (e.g. drained peatlands mainly located in northern Europe), even though organic soils account for only 2% of the total EU agricultural area (EASAC, 2022b; JRC, 2024c). The carbon losses from soil cultivation and drainage are exacerbated by climate change, notably due to increasing drought frequency and decreasing water resources (EEA, 2024).

As a major user of land, the EU agricultural sector can contribute to removals directly by sequestering CO_2 in agricultural soils and biomass. Key practices include agroforestry and a range of soil carbon management practices such as cover cropping, certain crop rotation changes and enhanced grassland management (see Chapter 2 for a more detailed description). As part of the wider issue with the quality and availability of land monitoring data highlighted previously (see Section 7.3 and Chapter 6), soil carbon losses and sequestration potential are not fully captured by current monitoring systems. Only a fraction of EU land— at most 33% for forests and far less for croplands — is accurately monitored for soil carbon changes. As a result, national GHG inventories fail to adequately reflect soil carbon changes, with likely unreported losses in croplands and unreported gains in grasslands and forests (Bellassen et al., 2022). Data from peatlands, particularly from heavily degraded ones, are also relatively limited (Evans et al., 2022). Apart from soil carbon fluxes, significant quantities in biomass flows remain unreported (EEA, 2023).

The agricultural sector can also support removals indirectly by providing biomass for removals (e.g. through BECCS) or by freeing up agricultural land for land uses with high sequestration potential (e.g. wetland restoration and afforestation).

In addition to increasing removals on agricultural land, the agricultural sector can contribute to removals indirectly by supplying biogenic carbon to replace fossil sources in CO_2 value chains (Ravichandran et al., 2024). For example, agricultural biomass can be used as a feedstock for biochar production, or as input for BECCS facilities (see also Section 7.3). In turn, crop yield can be increased by the use of biochar as a soil amendment, depending on the type of soil (Chapter 3). Agricultural waste products could also be used as feedstock for biogas production through anaerobic digestion. When that biogas is then upgraded to biomethane, it releases a relatively pure stream of biogenic CO_2, that could be captured and then stored either temporarily in bio-based products (i.e. as a form of CCU) or permanently in

[23] In 2022, EU crop- and grasslands on organic soils accounted for only 2% of the total crop- and grassland area, but jointly emitted 69 $MtCO_2$. Crop- and grasslands on mineral soils (98% of the total area) delivered a net sink of 38 MtCO2 in 2022, resulting in 41 MtCO2 of net emissions for all crop- and grasslands (EEA, forthcoming).

geological formations, in which case it results in removals. Finally, the agricultural sector can support removals indirectly by freeing up land for land uses with higher sequestration potential such as wetland restoration and afforestation, with a longer-term potential to become net sinks (see Chapters 2 and 3). Given the high land-intensity of livestock farming and their contributions to GHG emissions, reductions in the production and consumption of livestock products could free up substantial areas of land for land uses with high sequestration potential (Advisory Board, 2024).

7.4.2 Status and policy gaps

The primary EU policy instrument that governs land sector emissions and removals in the agricultural sector is the LULUCF regulation, which is assessed in more detail in Section 4.4.2. The remainder of this section provides an assessment of other EU policies that are specifically relevant for land sector emissions and removals in the agricultural sector, which include the CAP, specific provision in the CRCF regulation, the soil deal for Europe and the farm to fork strategy.

Despite providing some opportunities to maintain and increase carbon stocks, the CAP is currently overall misaligned with the need to enhance the EU's land sector carbon sink.

The key policy impacting EU agricultural land is the CAP. As previously highlighted by the Advisory Board, whereas the current CAP does provide some opportunities to enhance the land sink in the agricultural sector, it is not fully aligned with EU climate goals and does not sufficiently protect and enhance the EU's land sinks (Advisory Board, 2024). Opportunities include minimum requirements under the enhanced conditionality, which could maintain and enhance land sector carbon stocks. Currently, enhanced conditionality includes the requirement to maintain permanent grassland (GAEC1), protect wetlands and peatlands (GAEC2), and to ensure minimum soil cover (GAEC6). Furthermore, through eco-schemes, Member States can encourage farming practices that enhance land sector removals, such as agroforestry, rewetting of wetlands and peatlands, and the establishment, maintenance and extensive use of grasslands (EC, 2024w). Despite these opportunities, several shortcomings of the CAP undermine its potential to maintain and enhance the EU's land sector carbon stock. Firstly, several other payment schemes – including the direct basic payments – continue to support GHG and land-intensive agricultural practices, such as the cultivation of organic soils and livestock production, both directly and indirectly (Kortleve et al., 2024), thereby discouraging changes in land use that could enhance the land sink (e.g. afforestation and wetland restoration) (Advisory Board, 2024) **(policy inconsistency)**. Furthermore, due to the voluntary nature of the eco-schemes and the lack of incentives for Member States to implement these in an ambitious way, their eventual impact is uncertain **(ambition and implementation gaps)**. Previous assessments have warned that the national strategic plans under CAPs would only deliver limited mitigation outcomes at best (Advisory Board, 2024). A more recent assessment for the European Commission (EC, 2024) estimated that the current CAP strategic plans could deliver 31 $MtCO_2e$ of net reductions per year, of which 22 $MtCO_2e$ in the LULUCF sector, but stressed that this is a rough estimate based on a range of high-level assumptions. Finally, the EU has recently diluted some of the minimum requirements under the enhanced conditionality framework, which could undermine their capacity to maintain and enhance the EU's land based sink (EC, 2024e) **(ambition gap)**.

In January 2024, the Advisory Board recommended using the upcoming revision of the CAP to better align it with the EU climate targets, which could include (i) setting a standalone GHG reduction objective, (ii) moving towards mandatory good practices that support GHG reductions and soil carbon increases and (iii) shifting CAP support away from GHG intensive agricultural practices towards lower-emission products, removals, environmental services and economic diversification (Advisory Board, 2024). The Advisory Board intends to publish a dedicated report on how to further enhance mitigation and adaptation action in the EU agri-food sector in 2025 (Advisory Board, 2024). This policy direction was echoed in the strategic dialogue on the future of EU agriculture that highlights the urgent need to transition towards a climate resilient agriculture, in response to increasing climate variability, to ensure sustainability and resilience (EC, 2024).

The CRCF regulation certifies carbon farming activities for soil emission reduction and CO_2 capture, and emphasises integrating policies like the CAP to reduce sectoral trade-offs and align economic outputs with sustainability goals, offering financial rewards and support for farmers.

As presented in Chapter 6, the CRCF regulation recognises two types of carbon farming activities: (i) soil emission reduction and (ii) practices that result in atmospheric and biogenic CO_2 capture and temporary storage in biogenic carbon pools. Both are certifiable under the CRCF framework. The certification of carbon farming practices creates opportunities for farmers' income through the sale of any resulting credits (e.g. in voluntary markets), but comes with challenges when considering the sequestration uncertainties and the competing economic purposes of land. Nevertheless, EU agricultural stakeholders underline that the EU has a strategic autonomy interest in preserving arable land for agricultural use (EC, 2024x). This interest is partly reflected in removals quality criteria embedded in the CRCF regulation (see Chapter 6), notably those related to the quantification of net carbon benefit and sustainability. Finding synergies and limiting trade-offs between land and biomass economic outputs and carbon sequestration should become an objective for the EU policy integration, as further explained in Section 7.5. The CRCF regulation invites such policy integration by pointing to the CAP and national state aid as some of potential sources of (i) financial rewards to farmers delivering removals as well as (ii) support to the provision of removal-related advisory services and capacity building.

The EU's Soil Deal for Europe mission aims to promote healthy soils including by increasing soil carbon, but faces challenges regarding data availability and quality, funding misalignment, fragmented policies, and the lack of binding standards across Member States.

Under the Horizon Europe programme, the EU pursues currently five missions, including one dedicated to soils. The main goal of the "Soil Deal for Europe" mission is to support the transition towards healthy soils through research and innovation funding, 100 labs and showcases to be set up by 2030, development of a harmonised framework for soil monitoring, and public awareness raising. One of the eight objectives of the mission is to conserve organic carbon in soils (EC, 2021g). An assessment of EU missions conducted in 2023 showed promising results and several areas for improvement (EC, 2023e). In the context of "Soil Deal for Europe" the mission is successful in, among others, establishing first living labs, integrating the mission in strategic plans under the CAP, and increasing soil literacy see. e.g., (Prepsoil, 2024). The areas for improvement include: availability and quality of data for evaluating progress, funding gaps and misalignment of resources at local, regional, and national levels, limited clarity on how to effectively include citizens in decision-making processes, fragmented soil-relevant policies, and the absence of binding requirements or standardized criteria for soil health management across Member States (EC, 2023f).

The Farm to Fork Strategy promotes soil carbon sequestration, circular bioeconomy, and reduction of food waste and highlights harmonisation issues across monitoring frameworks under CAP, LULUCF, CRCF, and the Soil Deal for Europe. It is not reflected in binding legal basis, which constitutes a major policy gap.

The Farm to Fork Strategy (EC, 2020b) launched the carbon farming initiative, encouraged practices enhancing soil carbon sequestration and laid the ground for the CRCF framework. It also promotes circular bioeconomy including biogenic carbon capture and utilisation, and advanced bio-refineries to produce bioenergy, biofertilizers, and bio-based chemicals. The strategy recognizes data gaps in monitoring soil carbon stocks and fluxes, as well as measurement and reporting of nutrient losses (e.g., nitrogen and phosphorus), and notes a lack of detailed data to support the transition to a circular economy, particularly concerning the tracking of biogenic carbon flows. It points also to challenges in harmonising data definitions, spatial and temporal resolution, and integrating datasets from various sources. The objectives of the Farm to Fork Strategy to reduce fertiliser use by 20% and increase the share of organic farming to 20% have carbon benefits, but risk reducing yields and therefore increasing demand for land either in the EU or abroad, were the demand for agricultural products not reduced in parallel. The Farm to Fork Strategy lacks a binding legal framework to support the achievement of its objectives. For example, the strategy sets an objective to reduce food waste per capita by 50% by 2030, but the proposed amendments to the Waste Framework Directive fall short of achieving this (Advisory Board, 2024).

While advanced geospatial data systems already support EU land monitoring, fragmented definitions, methodologies, and resolutions undermine their utility, a challenge that should be tackled thanks to the adoption of the proposed Soil Monitoring and Resilience Law.

The data challenge highlighted in the Farm to Fork Strategy are shared and affect all agriculture-related policies and measures, including the CAP, the LULUCF regulation, the CRCF framework, and the Soil Deal for Europe. As mentioned in Chapter 6 and Section 7.3 above, EU has a few existing and proposed measures to ensure that sufficient quality data is available to monitor land sinks the EU. Geospatial data is particularly useful for tracking land use changes and supporting land sector removal efforts at inventory and activity levels e.g., for LULUCF and CRCF reporting. EU's land monitoring data sources include:

- land cover datasets from the Copernicus Land Monitoring Service,
- biomass stock estimates from the ESA Climate Change Initiative,
- fire emissions from the European Forest Fire Information System,
- land cover/soil carbon data and maps e.g., Land Use and Coverage Area frame Survey,
- atmospheric GHG data from the Copernicus Atmospheric Monitoring Service, and
- data systems supporting CAP e.g. Integrated Administration and Control System and Land Parcel Identification System.

The Integrated Administration and Control System contains parcel-based agricultural activity data relevant for both CAP and LULUCF policy. It is subject to annual quality assessment which increases its reliability. The Land Parcel Identification System identifies agricultural land ready for production based on farmers' declarations and contains interoperable data facilitating its potential re-use (EEA, forthcoming).

While technical capacities to monitor land uses and GHG fluxes are already advanced and are further improving, the use of available data sources (including the Integrated Administration and Control System and Land Parcel Identification System) faces challenges due to a lack of harmonisation between definitions, resolutions, and methodologies they apply (JRC, 2024b, EEA, forthcoming). This implementation gap is partly reflective to the EU and national policies themselves, still largely fragmented when it comes to land. Experts and practitioners have been calling for tailored, timely data delivery and improved collaboration between Earth observation experts, inventory institutions, and policymakers (EEA, 2024).

7.5 Integrating policies and enhancing climate resilience of land and local communities

7.5.1 Need

Climate change is undermining the LULUCF sector's carbon sink capacity due to intensified disturbances such as wildfires and droughts. The EU needs policies to mainstream adaptation in land management. Policy integration and long-term planning are essential to protect, restore and enhance the EU's land sink.

As explained in Chapter 3 and Section 7.1, the impacts of climate change undermine the LULUCF sector's capacity to function as a carbon sink. Climate change is intensifying disturbances such as wildfires, storms, droughts and pest outbreaks, reducing the carbon sequestration potential of biomass and soils and threatening their ecosystem services. In this context, the European Climate Risk Assessment highlighted the need for adaptive land management practices and integrated long-term strategies and measures that align with EU-wide policies (EEA, 2024a). The integrated approach requires embedding climate resilience objectives into sectoral policies and practices to create synergies while addressing climate risks during the policy design phase (Hegger et al., 2017). There is also a need to prevent maladaptation, which occurs when adaptation measures inadvertently increase vulnerability to climate change, shift or create new risks (EEA, 2024a). Promoting community-based adaptation approaches, incorporating local knowledge and ensuring the equitable distribution of benefits and burdens are crucial to avoid maladaptation (Buck et al., 2022).

Integrating adaptation measures for removals in land sector policies and measures can lead to multiple additional benefits (Chapter 3). Policy instruments that give credit for the carbon removed through adaptive measures can create a positive feedback loop by strengthening adaptive capacity and providing financial incentives for adaptation projects. In addition, changes in forest cover have mostly positively impacts on the local climate through biophysical effects like albedo, evapotranspiration and surface roughness, potentially leading to regional cooling (Verkerk et al., 2022), although there is uncertainty about the relative influence of afforestation in temperate zones, which might see warming (Perugini et al., 2017). The integrated land policies in the EU are therefore context dependent. Specific removal methods also carry some risks, including increasing differences in relative vulnerability between groups that door do not adopt these methods, and increased exposure to certain hazards with which local communities might be unfamiliar (Chapter 3).

Policy integration is a complex process aimed at improving coherence and coordination across policy sectors and levels of government (Knill et al., 2020). Climate adaptation can guide the integration of EU land-related policies alongside the need to balance the competing demands on land and biomass resources and achieve climate, biodiversity, and socio-economic objectives (see Sections 7.3 and 7.4).

7.5.2 Status and policy gaps

EU policies affecting land and biomass have so far been fragmented and have insufficiently addressed declining carbon sinks, climate risks and biodiversity loss.

Current land-related policies are fragmented, limiting their effectiveness in addressing challenges such as declining carbon sinks, climate adaptation and biodiversity loss. Policy integration has been recently advanced by the Nature Restoration Law (EU, 2024f) and is reflected in the bioeconomy strategy(EC, 2018), but remains insufficient in other key policies including the CAP and RED II/III (see Section 7.2-7.4). As introduced in Section 7.3, the requirement of cascading use of biomass is not yet sufficiently stringent and operationalised, and conflicting demands arise from inconsistent land use and energy policies. Moreover, there is only limited evidence from the implementation of the LULUCF criteria embedded in Article 29 of RED II/III (Böttcher et al., 2019). Lack of pricing of emissions and other externalities linked to biomass extraction from land, in combination with the zero-rating rules, indicate EU policy inconsistencies resulting in undue pressures on land and biomass resources. The pressures are exacerbated due to the weak compliance mechanisms in the LULUCF regulation as well as its short time horizon i.e. 2030 (Advisory Board, 2024).

The upcoming update of the EU bioeconomy strategy and the reform of the CAP is an opportunity for further land-related policy integration and could be used to enhance the EU's ability to protect land carbon sinks, promote the most efficient biomass use in line with the cascading principle, and ensure that land use decisions deliver synergies across environmental and economic goals.

The European Climate Law requires the integration of climate adaptation across policies to build resilience by 2050, but significant gaps remain unaddressed.

The European Climate Law mandates 'continuous progress in enhancing adaptive capacity, strengthening resilience, and reducing vulnerability' (Article 5). It requires Member States to adopt and implement national adaptation strategies and plans, taking into account particularly vulnerable sectors such as agriculture, water and food systems, along with the need to promote nature- and ecosystem-based solutions. The law's implementation is supported by the EU adaptation strategy which lays out policy steps to mainstream climate adaptation in EU policy, aiming to create a climate resilient society by 2050 (EC, 2021b). This strategy emphasises integrating adaptation, including through nature-based solutions, into a wider range of policy areas.

The mainstreaming is reflected in the Nature Restoration Law (EC, 2023h), where climate adaptation is one of the key objectives and which requires national restoration plans to 'identify synergies with climate change mitigation, climate change adaptation, land degradation neutrality and disaster prevention and prioritise restoration measures accordingly' (p. 31). The Nature Restoration Law has entered into force in August of 2024, and the first draft nature restoration plans are due in mid-2026.

The CRCF regulation specifies that removal activities are to maintain a neutral impact or create co-benefits aligned with sustainability objectives, including climate adaptation. However, it does not require that removal activities actively contribute to climate adaptation, which is a an **ambition gap** in EU policy given the need to reduce reversal risks (see, for example, German Environment Agency (2023) and Chapter 6).

The revised LULUCF regulation (EU, 2023f) recognises that Member States should integrate adaptation measures into national policies and therefore requires that national compliance reports cover the synergies between climate mitigation and adaptation, including policies and measures to reduce the vulnerability of land. Moreover, the regulation requires that Member States take into account the 'do no significant harm' principle when developing their compliance plans (Korosuo et al., 2023; Bastos et al., 2016). Member States are also required to integrate land use considerations into their NECPs and CAP strategic plans, ensuring alignment with the targets set out in the revised LULUCF regulation and the effort sharing regulation. The updated NECPs are expected to integrate adaptation and nature restoration measures into their LULUCF and agriculture sectors (EEA, 2024a). In its EU-wide assessment, the European Commission stated that most of the draft updated NECPs do not show sufficient ambition and action on land and that very few Member States showed a concrete pathway to reach their national LULUCF targets (implementation gap) (EEA, 2024e); see also Chapter 10.

Moreover, further efforts are necessary to address the complexity of risk ownership, as most climate risks are co-owned by the EU and its Member States, demanding clear responsibilities and a coordinated response across multiple governance levels (EEA, 2024a). Addressing this governance bottleneck requires more ambitious and transformative action to fully mainstream adaptation, ensuring that climate risks are considered from a policy's inception and not solely during its implementation (Griscom et al., 2017; EEA, 2024a). Unclear risk ownership and reliance on voluntary commitments has led to weak implementation of EU adaptation mainstreaming measures **(policy gap)** (see also EEA 2024e). Climate change adaptation should become a binding requirement across EU land-related policies, including the CRCF regulation (see also Chapter 6).

Implementation of national adaptation measures is challenged due to the undervaluation of nature-related positive externalities, and by a lack of long-term planning.

Effective implementation of national adaptation strategies faces significant challenges due to the undervaluation of nature-related co-benefits **(policy gap)**, as highlighted in the European Climate Risk Assessment (EEA, 2024a). It is therefore positive that the EU taxonomy recognises interlinkages between actions significantly contributing to climate change adaptation and to restoration of biodiversity and ecosystems (EU, 2023a). In addition, economic valuation of natural capital and ecosystem services (Eurostat, 2021), as well as EU's emerging approach to biodiversity certification and nature credits (EC, 2024m) can further promote nature-based solutions, and support EU efforts to scale up removals sustainably.

National policies often fail to adopt an integrated, multifunctional approach to soils and forests, focusing narrowly on objectives like carbon sequestration or energy efficiency while neglecting biodiversity and ecosystem resilience (see e.g., Beland Lindahl et al., 2023; Vrebos et al., 2017). For example, most forest plans in the EU operate on short cycles (e.g. ten years), limiting their ability to address long-term climate change impacts, such as shifts in species distribution and extreme weather events (EC, 2023l).

To align with the European Climate Law and the Nature Restoration Law, land-related policies need to adopt a long-term perspective targeting climate neutrality, resilience and ecosystem restoration by 2050 and beyond. Accurate, forward-looking data and projections are essential to mitigate climate-induced risks and improve disaster response to threats like wildfires and pests.

EU land monitoring faces significant shortcomings. The proposed Forest Monitoring Law and the Soil Monitoring and Resilience Law should be adopted so that they help address these shortcomings through harmonised definitions, rules and monitoring frameworks.

As explained in Chapter 6 and Sections 7.3 and 7.4, current EU land-monitoring practices show significant shortcomings, particularly in the timeliness and accuracy of data used in national GHG inventories. These inventories frequently rely on outdated data, delaying policy decisions and feedback on forest management (Korosuo et al., 2023; Maes and et al., 2023). Existing monitoring systems under the Copernicus Emergency Management Service – such as the European Drought Observatory, European Forest Fire Information System, and the European Flood Alert System – provide valuable early warnings of droughts, wildfires and floods. However, these monitoring systems often lack the depth and precision required for fully informed decision-making, and lack harmonised reporting rules and definitions (EEA, 2024a). Most Member States lack regular soil inventories, creating a significant blind spot in understanding soil carbon dynamics (EEA 2024e). Enhanced methodologies building on Earth observation with ground data can bridge this gap, offering real-time insights into the dynamics of the forest carbon sink. These upgrades, mandated under the revised LULUCF regulation and supported by forthcoming legislation on forest and soil monitoring and resilience, are critical for reversing the ongoing decline in the EU land sink, especially on forested land (Bastos et al., 2022; Korosuo et al., 2023) (see Chapter 6). The proposed Forest Monitoring and Soil Monitoring Laws should be adopted without further ado.

Increased climate and compounded impacts in the land sector make adaptation measures more costly and conditions more dangerous to workers. The foreseen initiative of the European Commission's Climate Resilience Dialogue aims to leverage catastrophe insurance EU-wide to increase recovery after disasters, which requires significant funds.

Increased climate hazard risk is an obstacle for the sector's ability to adapt. Besides catastrophic events, manual workers that work outside, such as in agriculture and forestry, are also increasingly exposed to high temperatures and there is currently no overarching EU legislation on workers protection which defines a maximum temperature (ECCRD 2024). In agriculture, the CAP already allows for the use and public support of an array of instruments, including insurance, mutual funds and disaster relief programs, but subsidies for risk premiums are not available in every EU country (Schwarze and Sushchenko, 2022). EU funds for disaster relief are limited and represent only a small proportion of the overall costs of such events (EIOPA, 2023). The Climate Resilience Dialogue at the initiative of the European Commission was set up to discuss ways to narrow the climate protection gap (Climate Resilience Dialogue, 2024). A proposed EU-wide catastrophe insurance scheme would be key for risk diversification and pooling benefits across regions, complementing private and national insurance schemes, but does not yet exist **(policy gap)**. However, it would require a meaningful fund to enable swift pay-outs that would make it a credible risk transfer solution for tackling major events (EIOPA, 2023).

Funding for adaptation in the LULUCF and agriculture sectors falls far short of the needs. EU funding allocations and eligibility criteria should increase the weight attributed to climate adaptation.

Adaptation in the wider land sector is addressed through several EU policy instruments below, including the European Agricultural Fund for Rural Development, the European Regional Development Fund, and the Cohesion Fund (EEA, 2024a), as well as the CAP eco-schemes described in Section 7.4.2. Between 2014 and 2020, it is estimated that adaptation activities received annual allocations ranging from EUR 14 billion to EUR 62 billion through EU Structural and Investment Funds (Nesbitt et al., 2019). The summary of CAP strategic plans for 2023-2027 (EC, 2023n) shows that less than 2% of CAP spending is allocated to risk management tools. These investment volumes fall short of the European Investment Bank (EIB, 2021) estimates of the total annual adaptation investment needs, approximately EUR 500 billion annually. In addition, tracking specific expenditures for climate adaptation remains a challenge due to the European Commission's methods, which often fail to distinguish between mitigation and adaptation objectives. This lack of transparency is further reflected in Member States' reporting (Advisory Board, 2024).

Funding allocations and eligibility criteria should increase the weight attributed to climate risk management and contributions to meeting EU’s adaptation needs. For example, promoting the update of climate-resilient crop varieties, supporting investments in water-efficient irrigation systems, and encouraging afforestation and reforestation activities that enhance carbon sequestration and biodiversity could be prioritised through these funding mechanisms (EEA, 2024b).

7.6 Summary of EU policy assessment

Table 17 summarises the policy assessment carried out in this chapter, by providing an overview of the status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report ‘Towards EU climate neutrality: progress, policy gaps and opportunities’ (Advisory Board, 2024).

Table 17 Summary of the EU policy assessment of Chapter 7

Policy	Status	Gaps and inconsistencies
LULUCF regulation	Mandates Member States to integrate adaptation and mitigation measures, with a target of 310 $MtCO_2$ net removals by 2030 including through binding country-level LULUCF budget.	Insufficient and fragmented ambition in the implementation of the LULUCF regulation by Member States, with only few of them including concrete pathways to reach their national LULUCF targets in their NECPs → **implementation gap**
RED II/III	Includes cascading use of biomass principle. Excludes new or renewed support for bioelectricity-only installations. Allows support for biomethane as an alternative to fossil gas. Includes a target for advanced biofuels in transport.	Cascading principle is not yet sufficiently applied. → **ambition gap** No other measures targeting biomass to uses less amenable towards electrification. → **ambition gap**
CRCF regulation	Need to restrict capacity increases of bioenergy installations linked to financial rewards from certification. Certifies carbon farming activities and integrates adaptation and sustainability criteria into removal practices.	The need to restrict capacity increases of bioenergy installations is only signalled in the preamble, there are no binding rules in place. → **ambition gap** Does not mandate climate adaptation. → **ambition gap**
Industrial Emissions Directive	Requirement for operators to comply with the best available techniques.	Does not yet include any specific requirement regarding efficiencies of carbon capture process. It therefore does not prevent BECCs projects with low capture efficiencies which might undermine the land sink through biomass use. → **policy gap**
Governance regulation	Requires reporting of biomass use for energy, including its impacts on net carbon sinks.	NECPs provide insufficient assessment of (i) the potential impacts of expanding bioenergy, as envisaged in several plans, on carbon sinks, and resources, and (ii) efficiency of bioenergy compared to other sources of renewable energy, and (iii) ambition and action on land and national pathways to reach their LULUCF targets. → **implementation gap**

Policy	Status	Gaps and inconsistencies
Common agricultural policy	Provides some opportunities to enhance land sector carbon stocks through eco-schemes and conditionality.	Misaligned with climate goals, supports high-emission practices, and voluntary eco-schemes lack incentives for ambitious implementation. → **policy, ambition and implementation gaps**
Soil Monitoring and Resilience Directive	Aims to harmonise soil health definitions and create a coherent monitoring framework.	Not yet adopted. → **policy gap**
Forest Monitoring and Resilience Regulation	Supports long-term planning and resilience-building in forest management.	Not yet adopted. → **policy gap**
Birds and habitats directives	Supports the protection of carbon-rich habitats.	Insufficient monitoring, and governance challenges during the process of designating Natura 2000 sites, general objectives of the directives have not yet been met. → **implementation gap**
Other		No pricing of GHG emissions and other externalities linked to biomass extraction from land sector. → **policy gap** Inconsistencies between the different criteria in RED II/III, the CRCF regulation, REFuel EU aviation and FuelEU maritime. → **policy inconsistency** Unclear risk ownership between EU and MS to fully mainstream adaptation, ensuring that climate risks are considered from a policy's inception and not solely during its implementation. → **policy gap** Nature-based benefits remain undervalued. → **policy gap** The Farm to Fork Strategy lacks a binding legal framework to support the achievement of its objectives. → **policy gap** Lack of EU-wide catastrophe insurance to increase recovery after disasters in the agriculture and forestry sectors. → **policy gap**

8 Accelerating innovation and raising public awareness

- **A diverse portfolio of removal methods can help accelerate and manage trade-offs.** To stay competitive and prosperous, the EU needs to scale up a diverse portfolio of removal methods combining solutions with significant mitigation potential across different technology readiness levels.

- **Public support is needed in all four stages of innovation.** Advancing removal methods from low readiness levels towards maturity, requires policymakers to apply targeted policy mixes along the four main stages of the innovation process:

    1 emergence – support for foundational research to evaluate feasibility, environmental impacts, and mitigation potential,

    2 early adoption – targeted support to bridge funding gaps and establish early-market incentives, fostering initial uptake,

    3 diffusion – support in scaling up, including the development of supply chains, skill-building, and market integration,

    4 stabilisation – long-term regulatory predictability to support the formation of large-scale projects that are financially sustainable.

- **Current innovation funding is insufficient.** EU funding into innovation for removals, so far mainly supported by Horizon Europe and the Innovation Fund, remains fragmented and insufficient to enable a rapid and sustainable scale-up of removals.

- **Public awareness requires increased efforts.** Societal engagement and knowledge diffusion through information sharing are necessary to increase public awareness of removals' role in achieving EU's policy objectives and to inform policies and projects.

8.1 Introduction

Achieving net-zero and net-negative emissions requires accelerating the early adoption of removals and intensifying innovation activity to drive down costs and support deployment.

A rapid and sustainable scale-up of removals is needed to achieve emission reduction pathways consistent with the Paris Agreement and will play a key role in achieving the objectives of the European Climate Law (as discussed in Chapter 1).

Scaling-up of removals in line with the EU Climate Law poses a significant challenge, particularly for permanent removals where the current global removal volume, at an estimated 1.3 MtCO_2, is miniscule (Smith et al., 2024). Dedicated support policies supporting innovation and deployment can drive technological advancement and experience-based learning, with the potential to drive significant cost reductions. In the case of technologies like solar photovoltaic and batteries, this has led to cost reductions and deployment rates that have consistently surpassed projections Krey et al. 2019). The early adoption and scaling-up of technologies, which drive down cost, can mean faster transitions could be more cost-effective as processes driving cost-reductions are accelerated (Way et al. 2022). Though patterns of innovation and the pace of technological progress differ across technologies (Malhotra and

Schmidt, 2020), meaning the potential for cost reductions also varies across technologies (see Chapter 2). To scale up CDR, innovative activity needs to intensify to improve the efficiency and sustainability of different methods (Smith et al., 2024).

To effectively scale up removals, there is a need for a diverse portfolio of methods, each associated with idiosyncratic strengths and limitations.

Removal methods are currently at varying stages of maturity, cost-effectiveness and monitoring feasibility (see Chapter 2). This diversity supports the need to promote a range of solutions tailored to their technological potential, as each removal method varies in technological readiness, cost-effectiveness, sequestration capacity, storage duration and associated risks (see Chapter 2). Furthermore, deploying a diverse portfolio of removal methods mitigates the risks associated with over-reliance on a single approach (IPCC, 2022m), including differences in storage duration, risks of reversal, technological challenges, and environmental limitations.

The successful scaling of GHG mitigation technologies requires a robust innovation system, supported by targeted policies, financial mechanisms and investments, and stakeholder collaboration. While some technologies are already being deployed, others remain in early development stages, necessitating substantial investment in research, demonstration and infrastructure. Moreover, ensuring equitable access and social acceptance is vital to avoid controversies that could hinder progress and to facilitate input into the policy design and implementation processes. The following sections explore the current state of GHG technologies, the stages of their development, and the policy and financial gaps that need to be addressed to unlock their full potential in contributing to the EU's climate objectives.

8.2 Increasing the readiness of diverse removal methods

8.2.1 Need

Achieving net-negative emissions requires accelerating the innovation process to improve efficiency and reduce costs of deployment for low-readiness methods.

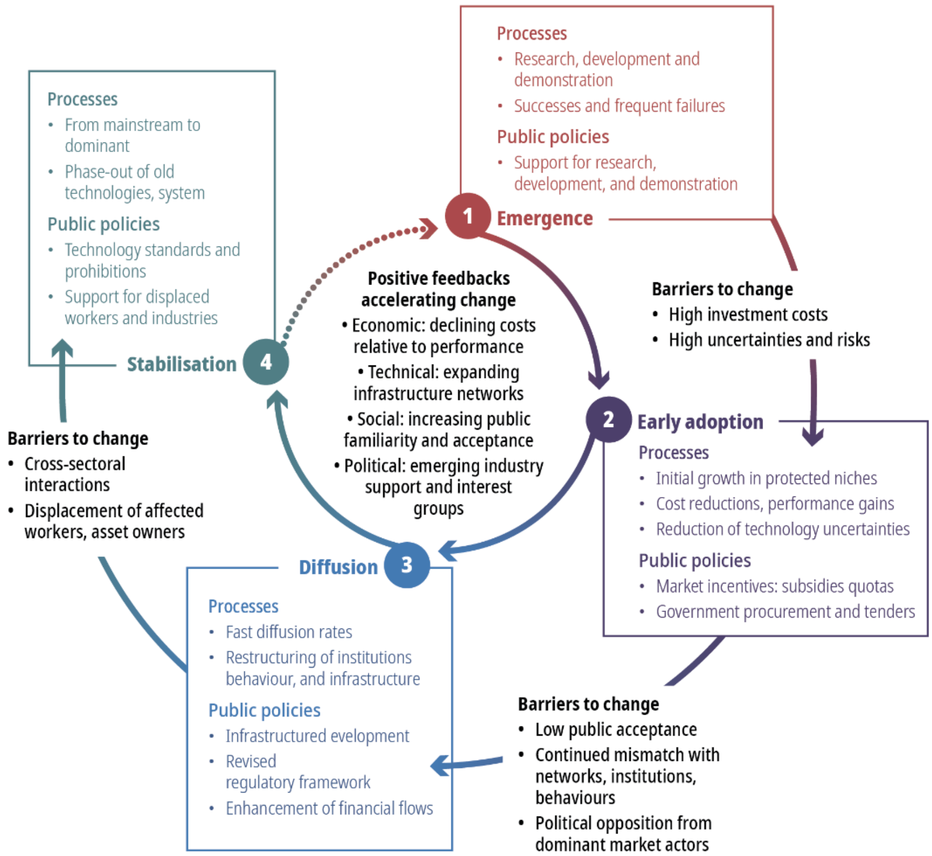
Removal methods are at different stages, and barriers that policies need to address are often context specific, related to the applications of these technologies (see Chapter 3). Achieving net-negative emissions requires the rapid scaling of removal methods, some of which are currently in their early stages of development (Chapters 2 and 3). Therefore, there is a need to accelerate the innovation process, improving efficiency and reducing operational costs for methods at low readiness levels. The successful development of these technologies depends on shifts in knowledge, behaviour, institutions and markets, which requires targeted policy mixes (Geels, 2018; Nemet et al., 2018b). The innovation process and the necessary shifts in policy mixes (see Figure 24) can be summarised in four distinct stages: emergence, early adoption, diffusion and stabilization (IPCC, 2023e). Each stage has specific needs that are further explored below.

1. **The emergence stage of removal methods, characterised by low readiness levels and high uncertainties, requires targeted research and policy mixes to catalyse breakthrough effects.**

The emergence stage includes removal methods at low TRLs which are in the early stages of the innovation process and require further research to better understand their environmental impacts and mitigation potential.

The focus should be on technologies with the potential to deliver breakthrough effects and generate positive spillovers across multiple sectors, such as advancements in MRV of removals. Breakthrough effects can reshape existing markets, create new ones and drive the emergence of new technological trajectories (Capponi et al., 2022). For instance, integrating satellite imagery with artificial intelligence can enhance the monitoring of removal processes, offering more accurate, timely and cost-effective inputs (Pham and Saner, 2021; Mercer and Burke, 2023). The potential for these spillover effects should considered, particularly when the initial investment case appears weak but large spillover effects could justify policy intervention (Stephan et al., 2021; Kolesnikov et al., 2024). To support the development of removal methods from the emergence stage to early adoption, policy mixes should address the elevated investment costs and uncertainties associated with pilot projects. Such policy mixes can include research grants, public-private partnerships and reverse auctions, among other possible demand-pull policies (IPCC, 2023e).

Figure 24 Stages of socio-technical transition processes



Source: IPCC (2023e)

2. **The early adoption stage of removal methods focuses on reducing uncertainties, improving removals' performance and enabling incremental improvements.**

The second stage of the innovation process, early adoption, includes removal methods that are at low to middle TRLs. Progressing towards the next stage, diffusion, requires reducing technological uncertainties, lowering operating costs and enhancing removal performance. A critical aspect of early adoption is induced innovation (i.e. the process in which demand-pull forces drive innovation and adoption), aided by incremental improvements in design and production processes, as learning tends to occur faster for technologies that are modular such as DACCS (Izikowitz, 2021; Grubb et al., 2021; Wilson et al., 2016). Effective policy mixes at this stage of the innovation process should provide market incentives such as subsidies and market quotas, and should leverage public procurement through tenders (Geels et al., 2017; IPCC, 2022m).

3. **The diffusion stage focuses on deploying infrastructure, skills development and creating value chains, and necessitates institutional changes.**

The third stage, diffusion, includes removal methods at mid to high TRLs. During the diffusion stage, the policy focus should shift from direct financial support during the early adoption stage towards infrastructure deployment and fast knowledge diffusion. This includes scaling-up deployment to drive down costs, strengthening skill development and creating value chains and capacity building (IPCC, 2023e). This stage is often the most visible as it gives rise to structural changes in institutions (Köhler et al 2019).

4. **The stabilisation stage involves the standardisation and large-scale deployment of removal methods. Many temporary removal methods are at this stage; however, their scalability is constrained by MRV challenges, land competition and a lack of incentives.**

The fourth stage is stabilisation, where removal methods and supporting systems are standardised (Andersen and Gulbrandsen, 2020). Many of land-sector removals are already deployed globally, but their scalability is limited by factors such as MRV, a lack of incentives, land competition and long-term permanence (see Chapters 2 and 3).

8.2.2 Status and policy gaps

Removal methods can be classified into three categories – early stage, medium readiness and high readiness – based on their deployment maturity.

Removal methods can be grouped in three broad categories, according to their readiness for deployment. Early-stage technologies include technologies that are primarily in the research and development stage to determine their feasibility and potential (Nemet et al., 2018a). The medium-readiness category includes technologies that are currently deployed at a small scale and require further development to prove their effectiveness and reduce costs (IPCC, 2023e). High-readiness technologies are already established, deployable at scale and already reported in GHG inventories. However, even these mature technologies can face challenges, such as high MRV costs in the case of land-sector removals.

Early-stage removal methods include methods such as ocean fertilisation, ocean alkalinisation and enhanced weathering, are in early development stages, and require further research to address environmental uncertainties and feasibility.

Despite the theoretical potential of ocean fertilisation and ocean alkalinisation, both methods remain at a very early stage of development (IPCC, 2022e). Their potential for large-scale deployment is constrained by significant environmental uncertainties, including risks to marine ecosystems from changes in marine chemistry and impacts on biodiversity (Vivian and Savio, 2024) and legal barriers (see Section 3.4.4). As discussed in Chapter 3, further research is needed to assess the ecological and biogeochemical consequences of both methods.

Enhanced weathering is a removal method at an early readiness level, which requires more research to address uncertainties related to feasibility, environmental risks, and long-term effectiveness (IPCC, 2022e). Environmental concerns, such as potential impacts on biodiversity and water quality, have not been adequately researched (Fuss et al., 2018). Significant energy demand may also limit or even cancel out removals under certain conditions (Rigopoulos et al., 2018; Rinder and von Hagke, 2021).

Research on methane removal methods is currently at an early stage. Current policies on removals primarily target CO_2, likely leaving methane removal efforts underfunded and understudied (Pozvek et al., 2024).

Medium readiness removal methods include methods such as DACCS, BECCS and biochar, and face challenges, including funding gaps and high costs.

The transition of innovative technologies, such as removals, from demonstration to commercialisation, is notoriously difficult and is referred to as the 'valley of death' (Nemet et al., 2018a). Public funding can help de-risk medium-readiness technologies, providing financial support for demonstration projects that showcase the technology's capabilities in real-world settings. A significant funding gap exists in the EU for climate projects at the demonstration stage; this gap also affects the development of removal methods (Advisory Board, 2024). Medium-readiness removal methods each also face specific challenges.

Major barriers to the deployment of DACCS at scale include high energy requirements, high costs (see Chapter 2) and infrastructural constraints for permanent geological storage (see Chapter 9). A few small-scale projects currently exist in regions like the United States and Iceland. The largest operational facility, Mammoth in Iceland, has a nameplate removal capacity of 36,000 tonnes of CO_2 annually (Climeworks, 2025). This is far below the scale required for significant climate impact, though a large-scale project, with a capacity of 0.5MtCO_2 of removals per year, is in late stages of inception and expected to come online in 2025 (IEA, 2025; OnePointFive, 2025).

BECCS is assessed at a similar level of technology readiness to DACCS by the IPCC, though assessments differ and some recent studies find that certain BECCS technologies are more mature (see Chapter 3). While BECCS is operational at small scales, mainly in countries such as the Denmark, the Netherlands and Sweden, significant barriers to scaling up remain. These include the availability of sustainable biomass to avoid negative impacts on carbon sinks and biodiversity (see Chapter 7), the efficiency of the energy conversion process (IPCC, 2022e), and the infrastructure needed for large-scale deployment (see Chapter 9).

In the case of biochar, the main challenges for scaling up deployment relate to the lack of large-scale field studies, variability of feedstock costs, uncertain financial rewards, which disincentivise farmers from adopting it, and the lack of large pyrolysis facilities in Europe, which constrain production capacity (Kenneth Möllersten, 2022; Fridahl et al., 2023).

High-readiness removal methods include soil carbon sequestration, agroforestry, afforestation, reforestation and improved forest management, but the EU policy framework currently provides limited incentives for their deployment and they see limited support under the CAP.

As described in Chapter 2, the LULUCF sector is the only sector which currently delivers substantial volumes of removals, and the only one where removal options are in a mature stage and can be deployed at a large scale at relatively low costs in the near term. Removal methods at a high readiness level include methods such as soil carbon sequestration, nature restoration, afforestation, reforestation and improved forest management. However, as described in more detail in Chapters 0, 5 and 7, the EU policy framework currently only provides limited incentives for their scale up:

- The LULUCF regulation sets binding targets for Member States to increase the net sink in the LULUCF sector, but relies on national measures to achieve these targets. So far, it has not resulted in sufficient action at national level to deliver the overall EU target of 310 MtCO_2 net removals by 2030 (see Section 4.4.2).
- The absence of an EU pricing instrument that prices emissions and rewards removals in the LULUCF sector, in combination with incentives for biomass use and agrifood policies, have skewed financial incentives away from providing removals and towards land uses and practices that undermine the net sink in the LULUCF sector (see Section 4.4.2).

- The CAP allows Member States to incentivise practices with carbon sequestration potential, but its impact depends on the extent to which Member States use this possibility (see Section 7.4).
- The Nature Restoration Law requires Member States to take measures which are also expected to increase net removals in the land sector, but its impact is currently uncertain and will depend on Member States' implementation and funding (see Section 7.2.2).
- Direct EU support for removals through other funding mechanisms has been limited so far (see Section 5.2.2)

8.3 Increasing RD&D spending to improve competitiveness

8.3.1 Need

Financial support needs to be strategically allocated through targeted funding to address barriers across all stages of the innovation process.

Early-stage technologies often carry high levels of risk and uncertainty, making them less attractive to private finance (EC, 2023f). Public funding is critical during this phase to support research and innovation activities, addressing the inherent risk-reward imbalance that deters private sector investment (Mazzucato, 2015). Public funding support is necessary in the transition from demonstration to commercialisation to de-risk removal methods and attract private investment. This support should include the development of supply chains, essential infrastructure, and assistance with navigating permitting and regulatory approval processes (see Chapter 9).

To enhance the effectiveness of public interventions in innovation at the early stage, there is a need to actively strengthen collaborations between public institutions and the private sector. More research, development and demonstration (RD&D) institutional development and support is needed for removals, learning from experience and evaluation on other technologies (Mazzucato and Semieniuk, 2017). Recognizing this, over the past two decades there has been an increase in the level of public funding for energy RD&D (Meckling et al., 2022; Goldstein et al., 2020a; Howell, 2017; Doblinger et al., 2019; Pless, 2024).

For the EU removal sector to be competitive, the EU needs to increase public and private funding of innovation.

To stay competitive in GHG emission removal methods, the EU needs to provide sufficient funding towards innovation. Overall EU spending towards innovation is below the target of 3% of GDP, whereas countries like China and the United States have increased their RD&D intensity, potentially putting the EU at a disadvantage in strategic sectors like climate mitigation technologies (Advisory Board, 2024; Draghi, 2024). More than 30% of top scientific publications originate in the EU, but there is a lag in innovative solutions for clean technologies (Advisory Board, 2024).This is in part due to a significant funding gap for projects aiming to overcome the 'valley of death' towards commercial deployment at scale. Public funding on innovation has also stagnated over the last decade, at 0.8 % of the EU-27's GDP in 2021 compared with 0.8 % of the EU-27's GDP back in 2011, despite the increasing needs for cleaner technologies across all sectors (Advisory Board, 2024).

8.3.2 Status and policy gaps

Slow and complex EU funding mechanisms risk limiting competitiveness in the fast-paced removal market.

The Advisory Board has previously highlighted the need to increase support for innovation in climate mitigation technologies to address funding gaps from the lack of available venture capital. This was also emphasised in the recent Draghi report (Advisory Board, 2024; Draghi, 2024). Public funding instruments can be slow to react to the rapidly evolving global clean technology landscape (Advisory Board, 2024; Meckling et al., 2022), which can lead to missed opportunities and could hinder the EU's ability to compete in the removal market. Moreover, EU funding instruments can be administratively complex, which can hinder access for smaller enterprises (Advisory Board, 2024; Draghi, 2024). This section assesses the available EU funding instruments for removals in more detail (summarised in Table 18).

Horizon Europe, the EU's primary research and innovation funding programme, supports diverse climate initiatives but allocates limited direct funding to removal methods.

Horizon Europe is the EU's primary funding programme for research and innovation, with a total budget of EUR 95.5 billion for the 2021-2027 period. Horizon Europe provides support to a wide range of TRLs and thematic areas, and diverse policy intervention tools. It plays a significant role in supporting climate mitigation technologies, including technologies for CO_2 removal. It is challenging to determine the amount of funding provided for removals, with funding for CO_2 removal projects often provided within broader research categories. A high-level assessment by the Advisory Board indicates that under the Horizon Europe Cluster 5, on climate, energy and mobility, EUR 1,040 million of funding was budgeted for CCS/CCU projects (EC, 2025a) that removal projects may have benefitted directly or indirectly from. Temporary removal methods may have benefitted from some of the EUR 423 million of funding made available from 2021-2024 under the Horizon Europe mission 'a soil deal for Europe'. It is unclear to what extent this funding will support removals, with direct funding for removals likely to be only a small part given the broader scope, though some removal projects have directly benefitted. For example, an estimate budget of EUR 12 million was made available to support carbon farming living labs with the aim of conserving and increasing soil organic carbon stocks (EC, 2025d). Funding relevant for removals may have also been available under the Horizon Europe Cluster 4 (for industry CCS/CCU projects) and 6 (for projects focused on land, forestry, oceans and agriculture) but this was not assessed.

The lack of dedicated funding for removals makes it challenging to assess the level of direct funding provided under Horizon Europe. While the Advisory Boards high-level assessment indicates in the region of EUR 1 billion of the 2021-2024 budget could broadly be relevant for removal methods, direct funding for removals, methods, which along with CCS for activities with no or limited mitigation alternatives should be prioritised over other fossil-CCS, will be a small subset of the total and likely falls short of the levels needed to drive a scale-up of removals **(ambition gap)**. An analysis of Horizon Europe funding by Carbon Gap, a non-profit organisation promoting the need for removals, found that around 1.1% (around EUR 181 million) of the 2021-2022 budget and 0.9% (around EUR 127 million) of the 2023-2024 budget was allocated towards removal projects (Carbon Gap, 2024). A recent call for proposals, opened in September 2024, provides a welcome step with dedicated support for DACCS and BECCS, however, with a budget of only EUR 15 million the funding amount is small (EC, 2024l).

The LIFE programme offers limited direct support towards removal methods.

LIFE is the EU's funding programme supporting green innovations and cleantech solutions related to the EU's environment, climate action, nature conservation and energy objectives. Its primary purpose is to support a clean, circular and climate-neutral economy in line with the objectives of the European Green Deal. With a budget allocation of EUR 5.4 billion for 2021-2027, the programme is open to companies of all sizes, public authorities, and civil society organisations in the EU, typically offering funding to projects in the range of EUR 1 - 10 million. Although LIFE supports a multitude of research streams that promote eco-innovative technologies, there is a lack of dedicated support for removal methods. A high-level assessment[24] of the fund's dashboard for 2010-2020 shows that in the region of EUR 1.4 billion of funding may have been provided for nature-based projects that indirectly, and possibly in a handful of cases directly, relate to removals. Over the same period, around EUR 15 million of funding was provided to support CCS projects that may benefit permanent removals.

The European Innovation Council and European Investment Fund play a role in supporting innovation, but stronger coordination is needed in supporting removal methods.

The European Innovation Council plays a significant role in fostering innovation within the EU, with a particular focus on supporting breakthrough innovation. The EIC's mission is to bridge the gap between early-stage research and commercialisation. The EIC Accelerator, one of the three main instruments of the European Innovation Council, is specifically designed to support companies in this transition. While the European Innovation Council has directly supported at least once removal projects, with a contribution of EUR 2.2 million to a biochar project (EC, 2022a), there has been limited funding for removals to date **(implementation gap)**. The council's budget, while substantial at EUR 10.1 billion, is still significantly lower than comparable agencies in the United Kingdom and United States, (Draghi, 2024) To enhance the organisations impact, it could reinforce coordination with the European Investment Fund, part of the European Investment Bank Group, and strengthen the venture capital funding environment in Europe (Advisory Board, 2024; Draghi, 2024) **(implementation gap)**

The European Investment Fund is dedicated to supporting small and medium-sized enterprises and fostering innovation. The fund has a significant role in supporting innovations, such as removal methods, by providing access to venture capital and guarantees, and empowering public institutions and national promotional banks to provide more capital to innovative and strategic investments in their early stage. The fund's investments are structured across six thematic strategies, one of which addresses climate.

The Innovation Fund reports funding for CCS and CCU together, which obscures the fund's impact on scaling up removals.

The EU's Innovation Fund uses revenues from the EU ETS to support decarbonisation efforts, including in energy-intensive industries. In 2022, the fund received approximately 10% of ETS revenues, which is a significant limitation given the substantial funding required for the transition to climate neutrality (EEA, 2023g). The total funding available will depend on the carbon price. Assuming an average price of EUR 75 per tCO_2 results in an estimated total of EUR 40 billion of revenues from 2020 to 2030 going to the Innovation Fund to cover the development of a wide range of mitigation technologies, including removals. Demand for funding consistently surpasses available resources at the fund, with each call being oversubscribed and evaluation results showing good quality projects have been rejected because of a lack of available funding (EC, 2025e).

Since 2020, a high-level assessment[25] of the funds project portfolio suggests it has supported around 26 projects related to CCS, totalling about EUR 3.3 billion (EC, 2025c). Removals are not explicitly listed as a separately reported area on the funds key statistics (EC, 2024n). A lack of dedicated funding for removal methods, which along with CCS for activities with no or limited mitigation alternatives, should be prioritised over other fossil-CCS, could limit the type of removal projects that can apply for funding, as removal projects are evaluated in broader categories **(ambition gap)**. The fund's monitoring dashboard shows limited direct support for removals, such as the EUR 180 million awarded to the

[24] EU contributions were identified from the LIFE project database using keywords relevant for removals, e.g. 'forest', 'land conservation policy', 'wetlands'. This assessment should be treated as indicative.

[25] EU contributions were identified from the Innovation Funds project database using keywords relevant for removals, e.g., "CCS", "carbon capture", "biochar". This assessment should be treated as indicative.

Stockholm BECCS project, and support for the other projects predominantly focussed on CCS and CCU projects (EC, 2025e).

The Connecting Europe Facility plays a role in supporting cross-border CO_2 infrastructure to support permanent removals.

The Connecting Europe Facility is an EU funding instrument designed to support trans-European networks, focusing on transport, energy and digital infrastructure. It can support removal methods by funding cross-border CO_2 infrastructure necessary for methods like DACCS and BECCS. Through the revised TEN-E regulation, the Connecting Europe Facility supports investments in CO_2 transport and storage networks. A high-level assessment of the Connecting Europe Facility's project portfolio[26] indicates that between 2021-2023 in the region of EUR 600 million was allocated towards supporting CO_2 infrastructure (EC, 2025b).

The NER300 programme failed to realise any CCS projects due to technical complexity, high costs, rigid funding rules and adverse market conditions.

The NER300 programme, established under the EU ETS, was intended to fund large-scale demonstration projects for CCS and renewable energy technologies. It was named after the 300 million emission allowances that were sold from the new entrants' reserve of the EU ETS. The evaluation of the NER300 programme by the European Court of Auditors (ECA, 2018) highlights that no successful CCS projects were realised under NER300, despite the ambitious goal of facilitating up to 12 CCS demonstration projects by 2015, with innovative renewable energy technologies also falling short of their intended impact. Only one CCS project was awarded EUR 300 million under the second call for proposals, which was not completed. The key barriers identified include adverse investment conditions, fluctuating carbon market prices, and inadequate regulatory frameworks. The report's recommendations called for enhanced internal coordination among European Commission services and clearer accountability structures to ensure better coherence in supporting such projects.

The Strategic Energy Technology Plan's has a significant role in fostering collaborations among governments, industry and research organisations.

The Strategic Energy Technology Plan is an initiative launched by the EU in 2007 with the aim of accelerating the development and deployment of low-carbon energy technologies. It aims to promote collaboration between governments, industry and research institutions to drive down costs and increase the effectiveness of clean technologies for widespread adoption (EC, 2023n). Activities are clustered into 10 actions for research and innovation, one of which is CCS. Although the plan itself is not a direct source of funding, it strengthens collaborations across different stakeholders.

The Recovery and Resilience Facility supports the green and digital transitions by funding innovation, although only few Member States have included removal methods projects in their recovery and resilience plans.

The Recovery and Resilience Facility is the European Union's primary financial tool to support Member States in recovering from the COVID-19 pandemic while driving long-term growth through the green and digital transitions. As part of the EU's broader NextGenerationEU recovery plan, the facility allocates substantial funding for innovation in green technologies, including removal methods. Member States are encouraged to integrate these technologies into their national recovery and resilience plans, receiving financial support to develop large-scale projects that reduce GHG emissions (EC, 2022b;

[26] EU contributions were identified from the Connecting Europe Facility project database using keywords relevant for removals, e.g. "CCS", "CO_2 transport". This assessment should be treated as indicative.

Domorenok, 2024). A high-level assessment[27] of indicates some Member States included projects related to removal methods in their recovery and resilience plans. Since 2021, in the region of EUR 4,845 million of funding has been allocated for CCS and carbon management measures, which may benefit permanent removals, and EUR 2,920 million allocated for various ecosystem and biodiversity measures, which may benefit temporary removals (EC, 2023n).

In the context of meeting the EU's climate goals, the Advisory Board previously recommended the EU consider continuing the approach of the current recovery and resilience facility beyond 2026 (as discussed in Section 5.2.2). The framework is financed by common debt and supports the EU budget to boost EU public investment, strengthen the EU's sovereignty and accelerate the climate transition. This could also provide further funding to support the scale-up of removals and the necessary infrastructure.

Table 18 Overview of the existing and past EU funding instruments available to potentially support innovation in temporary and permanent removals

Programme	Period	Type of removals	Funding stream	Funding (EUR, million)
Horizon Europe	2021-2027	Permanent	Climate, energy and mobility – CCU and CCS projects, including DACCS, BECCS	1,040
Horizon Europe	2021-2027	Temporary	Horizon Europe mission 'a soil deal for Europe'	423
EU LIFE	2010-2020	Permanent	Funding for CCS projects	15
EU LIFE	2010-2020	Temporary	Funding for various projects involving forests, wetlands, agroecosystems etc.	1,414
Innovation fund	2021-2024	Permanent	Funding awarded to CCS and carbon management projects up to 2024	3,291
Recovery and Resilience Facility	2021-2026	Permanent	Funding allocated for CCS and carbon management measures	4,845
Recovery and Resilience Facility	2021-2026	Temporary	Funding allocated for various ecosystem and biodiversity measures	2,920
Connecting Europe Facility	2021-2023	Permanent	Funding for carbon capture and storage infrastructure	572
NER300	2013-2020	Permanent	Funding awarded to one CCS project, which was terminated.	300

Source: Advisory Board estimates

Note: Funding amounts presented here are indicative, based on a high-level assessment of instrument budgets and project portfolios. Figures reflect the total funding made available that could potentially support removals. As discussed in section 8.3.2, while some of this funding may directly or indirectly benefit removals, it is likely that removals only accounted for a small share of

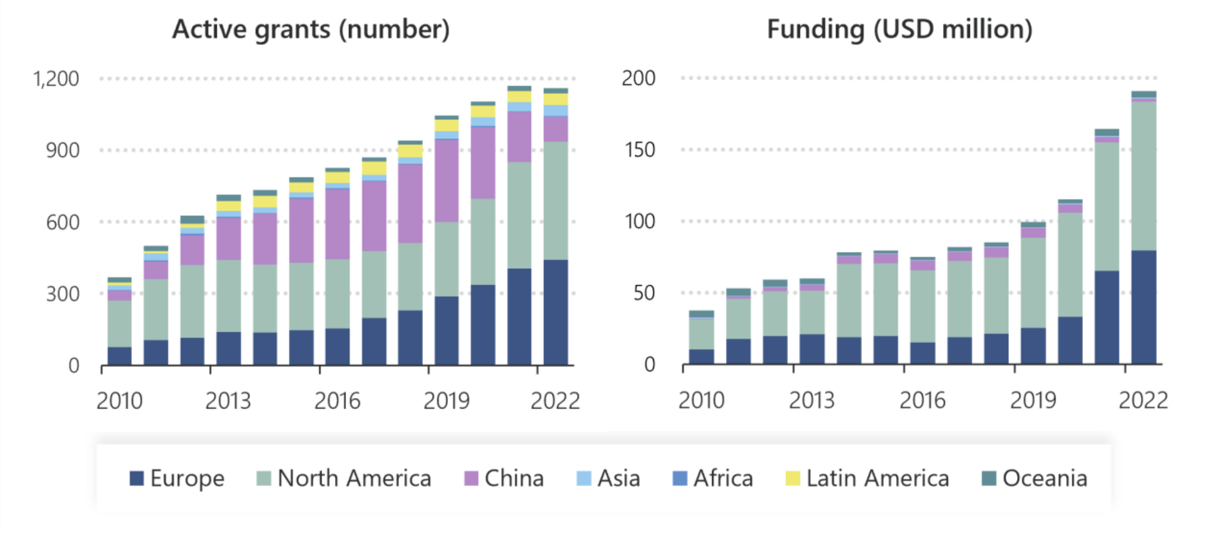
[27] EU Recovery and Resilience Plans were reviewed to identify funding streams that potentially support removals. For example, EUR 275m was allocated to Denmark to support energy efficiency, green heating and CCS. Thus, not all funding is relevant for removals and figures should be treated as indicative of the total funding volumes of which removals are likely only a subset.

the funding. Where possible specific funding calls that are relevant for removals have been identified but, in some cases, broader categories have been used, where only a subset of the funding volumes are relevant for removals

The EU, despite recognising removals as a priority, lags behind the United States in research grants and funding, risking its competitiveness in a growing market.

The EU lags behind the Canda and the United States in terms of funding grants allocated to RD&D for removal methods, as shown in Figure 25, even though the EU has acknowledged removals as a fundamental RD&D priority. The pattern is similar with regards to the amount of funding for RD&D in removals. North America, in contrast, has led the way in investment in removals over the last decade (Smith et al., 2023). This disparity in funding could have significant implications for the EU's competitiveness in the emerging removal market, as the United States attracts a bigger share of venture capital investment and could reinforce its leading position in the industry (JRC, 2022) Consequently, the EU risks falling behind in technological advancements and commercialisation of removal solutions.

Figure 25 Active grants and funding for research in removals by region



Source: Smith et al. (2024), Key Indicator 2.2 (and related funding data) in Chapter 2

Note: The authors note several limitations to the estimates provided in this figures, which suggest these are likely underestimates, including uncertainties on the comprehensiveness of funding data for some regions, such as Latin America, Africa, and Asia

8.4 Enhancing knowledge diffusion and public awareness

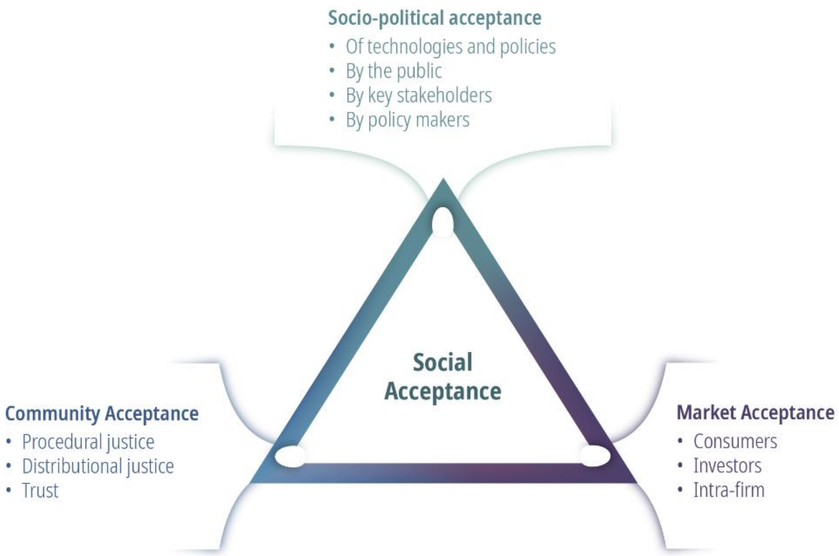
8.4.1 Need

Public awareness, trust and engagement are critical for the successful deployment of removal methods, requiring inclusive communication and public participation.

To develop and deploy removals sustainably, public perceptions, which may differ depending on people's specific contexts, values and beliefs, need to be understood and addressed (Smith et al., 2023). The awareness and perception of removals impact the political attitude towards removal projects and policies (IPCC, 2022e). Public awareness of the opportunities and risks linked to removals, as well as removals' role in the transition to net zero, is generally low in the EU. Perceptions differ across Member States, removal methods and the origin of gases to be removed (Low et al., 2024; Merk et al., 2023). Countries have different socio-political preferences for different removal methods (Schenuit et al., 2023). For example, failed CCS projects in the past as well as news related to integrity issues in some offsetting schemes, including under the clean development mechanism, have hampered public trust in project developers, support to CCS and carbon offsetting (IPCC, 2022m).

At local and regional scales, removal projects will need to consider local community engagement and procedural justice (Erans et al., 2022). According to the 'triangle of social acceptance' framework (Figure 26), social acceptance of climate technologies is determined by the perceptions and actions of stakeholders, operating on three main dimensions: socio-political, market and community acceptance (Wüstenhagen and Menichetti, 2012). Reaching social acceptance is critical for the deployment of removal methods, and this requires knowledge diffusion to build public awareness and public participation in decision making processes . In addition, public engagement will be needed in policy implementation to ensure that all the relevant knowledge and preferences are considered (Nawaz et al., 2023).

Figure 26 The "triangle of social acceptance"



Source: Adapted from (Wüstenhagen et al., 2007)

A fair and effective scale-up, supported with multidisciplinary research on public perceptions and public participation, is needed to ensure social acceptance in the application of different removal methods.

Explicit attention to equity and justice is relevant to both social acceptance and fair and effective climate policymaking (IPCC, 2023a). Safeguarding of the three tenets of climate justice, distributional, procedural and restorative, will involve both legislative and judiciary bodies at the national and EU level (McCauley and Heffron, 2018). They are expected to play a key role in creating and maintaining public trust in future climate policy measures, and will contribute to alleviating tensions (e.g. between democratic participation and technological efficiency) that may arise at the cross-over of different governance approaches (Petrovics et al., 2024).

Healey et al. (2024, 11) point to the importance of assessing each possible deployment of CO_2 removals as 'unique and complete sociotechnical proposition, inseparable from its environmental and political context'. Sharing technical, institutional, and social experiences from pioneering projects can help to accelerate the learning curve in the implementation of removal projects. Early research on public perceptions of removals indicates that the acceptability of the different removal methods can vary between socioeconomic groups, and public awareness and participation is critical in building democratic and trustworthy applications of these methods (Fuss et al., 2018; Bellamy and Raimi, 2023). Further multidisciplinary research on public perception of removals needs to inform project and programme development (Lezaun et al., 2021; Bellamy and Raimi, 2023; Otto, 2016).

8.4.2 Status and gaps

The industrial carbon management strategy emphasises the importance of public awareness and engagement, proposing actions such as engaging communities, fostering public debate and integrating public input into policy making.

The industrial carbon management strategy, which covers a broader range of activities than industrial CCS, dedicates a section to public perception and recognises that public understanding and awareness of industrial carbon management solutions is required to ensure certainty for investors and viable business cases (EC, 2024w). The strategy outlines a series of actions for the European Commission and Member States to take to boost public awareness and trust of removals. These include:

- specifying operating conditions for CO_2 transport and storage projects that can reward local communities;
- working with industry to increase knowledge and awareness of, and public debate on industrial carbon management;
- monitoring public opinion on industrial carbon management, including through Eurobarometer surveys;
- using existing forums to stimulate public debate and increase public understanding and awareness of industrial carbon management;
- contributing to the public debate at the national and local level by sharing data and experience from projects it supports, including under the Innovation Fund and the TEN-E;
- including public perception topics in EU research-funding programmes on industrial carbon management;
- engaging public authorities, project developers, non-governmental organisations and civil society before, during and after the policymaking and project implementation.

These actions echo the growing body of scientific publications on the importance and benefits of engagement with local communities and cooperative governance in climate infrastructure projects (Smith et al., 2024). They also reflect the conclusions of the industrial carbon management forum working group dedicated to the public perception of CCU and CCS (CIRCABC, 2015). The recognition of the importance of public awareness and engagement is an important step. The effectiveness of the industrial carbon management strategy will depend on how it and the outlined actions are implemented. However, it has not been possible to assess policy gaps or inconsistencies with the evidence available.

8.5 Summary of EU policy assessment

Table 19 summarises the policy assessment carried out in this chapter, by providing an overview of the status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024).

Table 19 Summary of the EU policy assessment of Chapter 8

Policy	Status	Gaps and inconsistencies
Horizon Europe	Supports a broad scope of research and innovation projects, including for climate action.	Limited focus on scaling removal methods. → **ambition gap**

Policy	Status	Gaps and inconsistencies
ETS Innovation Fund	Provides support for innovative low-carbon technologies, including CCS, CCU and removals.	Limited focus on scaling removal methods. → **ambition gap**
Other	The European Innovation Council aims to foster innovation, with a particular focus on supporting breakthrough innovation. The European Investment Fund provides dedicated support to small and medium-sized enterprises.	Insufficient focus on scaling up removal methods; limited funding compared to other national counterparts; strengthened coordination between EIC and EIB Group could improve removal access to early-stage finance. → **implementation gap**

9 Securing the CO_2 infrastructure's availability and resilience

- **BECCS and DACCS are dependent on the availability of CO_2 transport and storage infrastructure.** Two permanent removal methods, BECCS and DACCS, rely on CO_2 transport and storage infrastructure, which is only emerging at EU level. Apart from these methods, the CO_2 infrastructure can serve emission reductions and CCU.

- **Investments in storage capacity need to be accelerated.** By 2030, an estimated EUR 9.2-12.2 billion is needed to meet the EU's target of 50 million tonnes of annual operational CO_2 injection capacity and develop corresponding CO_2 transport infrastructure, with further investments needed for carbon capture and long-term operation and expansion of the infrastructure. Policy, regulatory and price signals are currently too weak to stimulate investment.

- **EU rules for CO_2 infrastructure are not yet fit for purpose.** The EU lacks rules prioritising infrastructure for removals and addressing disparities in CO_2 storage access. The EU does not have a comprehensive map of its CO_2 storage potential and does not yet measure CO_2 infrastructure buildout and contribution to reaching net zero by 2050 while ensuring resilience of the assets to climate change.

- **Enhanced EU-level coordination is needed.** The EU should coordinate efforts to secure sufficient availability of CO_2 infrastructure to support permanent removals and reduction of emissions from activities with currently no or limited mitigation alternatives.

- **Coordination builds on a harmonised regulatory framework.** Coordinated efforts include setting up a harmonised and predictable regulatory framework to ensure efficiency, environmental integrity, climate resilience and safety for CO_2 infrastructure while expediting permitting and addressing public concerns. Storage potential mapping, cross-border planning and progress tracking could help ensure access to CO_2 storage infrastructure where it is needed.

- **EU funds are key in the early phases of establishing the infrastructure.** EU funds will play a critical role in supporting pioneering projects and catalysing the roll-out of CO_2 transport and storage infrastructure enabling permanent removals.

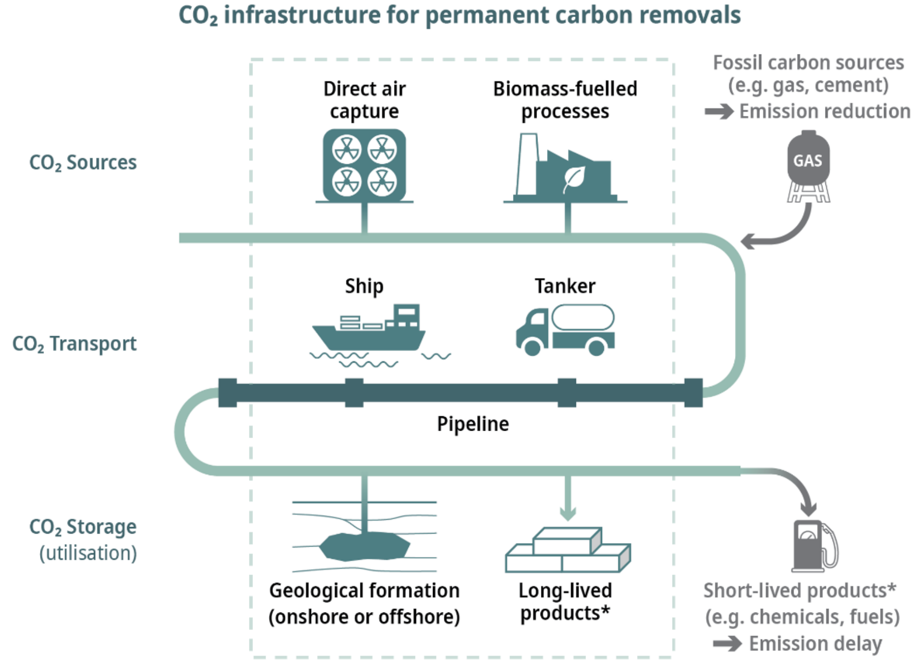
9.1 Introduction

The EU's transport and storage CO_2 infrastructure is not ready for the scale up of permanent removals necessary for the achievement of net zero and net negative. To accelerate CO_2 infrastructure development, the EU needs to overcome several challenges. These include high investment costs, policy issues, regulatory gaps, and organizational barriers.

As permanent removals through CCS technologies reach early stages of market roll-out, they face several obstacles that are common to nascent markets. These obstacles vary depending on the type of CO_2 infrastructure - capture, transport, and storage assets (see

Figure 27) - and include high investment costs as well as regulatory, technological, organisational, and market barriers (EC, 2024i)

Figure 27 Types of infrastructure across CO_2 value chains



Source: Advisory Board

Note: *the permanence of removals in certain products depends on the useful lifetime of the product and typical storage duration, as explained in chapter 2.

In 2023, less than 2 Mt/year of CO_2 was being stored geologically in the European Economic Area (EC, 2023c). As of March 2024, there were 77 CO_2 transport and/or storage projects planned, and 4 under construction, for a total estimated storage capacity of more than 70 Mt/year, all intended to be operational in the EU, Iceland and Norway in 2030 or earlier . To reach the EU's target of 50 Mt per year of injection capacity by 2030, and considering the European Commission's estimate that the EU's CO_2 transport network could span up to 7,300 km by that date, overall investment in CO_2 infrastructure excluding capture devices is estimated to reach between EUR 9.2 and 12.2 billion by 2030 (EC, 2024z).

All segments of CO_2 infrastructure are interlinked, which affects investment decisions. Notably storage and transport projects reflect EU emitters' demand for CCS, which in turn depends on, among other considerations, the availability of CO_2 transport and storage (EnTEC et al., 2023). Besides its high financial costs, CO_2 infrastructure is resource-intensive, creating pressures on land, energy and water (IPCC, 2022n), and is exposed to climate risks (EEA, 2024a). It is also associated with economic value benefits linked to future CO_2 management value chains and job creation (EC, 2024z).

Today's high degree of uncertainty hampering investment across the CO_2 value chain is linked not only to future price signals (see Chapter 4) and the availability of non-CCS decarbonisation options (Nilsson et al., 2021) but also to the EU's policy direction, regulatory framework and investment conditions (CCUS Forum, 2023c). EU policy needs to overcome the barriers considered at each stage of large-scale infrastructure roll-out (introduction, expansion, maturity and closure). Given that the EU's upscaling of CCS and removals is in its early stages, the focus of this chapter is on the initial stages in which infrastructure is planned, built and put into operation.

9.2 Enabling CO_2 infrastructure through EU policy direction

9.2.1 Need

EU policy needs to give a strong investment signal to scale up CO_2 infrastructure while preventing mitigation deterrence, ensuring efficient use of resources and a just transition.

Matching EU emission sources with transport and storage capacities through infrastructure projects depends on the EU including legal requirements, compliance markets, and incentives within its CO_2 management policy (e.g., Heffron et al., 2018; Jones, 2023). In the future, removals and CO_2 emission reductions may compete for access to CCS infrastructure. Some emitters stall strategic decisions regarding the way to mitigate the climate risks of their operations due to policy uncertainties, for example weighing the costs and benefits of CCU versus CCS (EC, 2024z). In addition, according to EU plans under the industrial carbon management strategy and 2040 target communication, most CO_2 transport and storage infrastructure that is expected to emerge under current incentives is likely to enable point-source emission reduction rather than removals (EC, 2024z). The modelling results behind EU plans depend on cost assumptions subject to inherent uncertainty, hence leading to uncertainty in determining the composition of cost-effective decarbonised electricity systems, that is, which technologies will dominate future least-cost, climate-neutral energy systems (Duan and Caldeira, 2024; Luderer et al., 2022). In addition, the current development of CO_2 storage sites is unevenly distributed across Europe, raising just transition concerns (Clean Air Task Force, 2024b).

9.2.2 Status and policy gaps

EU policy provides signals regarding the necessity of a fast scale-up of CO_2 infrastructure. However, it does not target CCS infrastructure towards removals and emission reductions from activities with no or limited mitigation alternatives.

Beyond carbon pricing under the EU ETS, EU policy so far has provided signals regarding the overall necessity of CO_2 infrastructure by 2030 and beyond, and the need for more CO_2 storage and transport capacity (EC, 2024z, 2023k; EU, 2024e). It has also laid out several rules safeguarding the environmental integrity of CCS installations (EU, 2009b) and ensuring cross-border collaboration in CO_2 projects (EU, 2022).

The need to target CO_2 capture technologies to emission sources that have no mitigation alternative is mentioned in the EU policy but has no binding force. Yet the menu of non-CCS options to decarbonise heavy industry is expanding (Bataille et al., 2021), and the role of fossil fuels in the power sector by 2040 is expected to be marginal (Advisory Board,). The EU ETS directive (EC, 2003) and other EU laws, such as the TEN-E regulation (EU, 2022), the Net-Zero Industry Act (EU, 2024e) and the CCS directive, do not discriminate against the sources of CO_2 that could be decarbonised without CCS/CCU **(ambition gap)**, such as power generation, despite the signalling that the EU aims to address decarbonisation needs:

> *"hard to abate sectors, such as parts of industry or certain modes of transport, where direct electrification is, currently, technically or economically challenging"*
> (recital 15 of the TEN-E regulation).

In the industrial carbon management strategy, the European Commission envisages that as much as 55 $MtCO_2$ emissions from fossil fuels in the power sector, mostly fossil gas power plants, would need to be captured in 2050[28] ((EC, 2024z). At least 15 large (rated electrical output of at least 300 MW) combustion plants across the EU have recently applied for or received a permit for CCS (EC, 2023m). This suggests

[28] Assuming fossil gas emission factor of 60 tCO_2 per PJ, 50$MtCO_2$ would be emitted to generate 234 TWh of primary energy.

that the reliance of the power sector on CCS and CCU will prolong the life of fossil-fuel assets and methane leakage, despite the fact that there is no necessity for fossil fuel-based electricity in the decarbonised energy supply; for example, the Advisory Board recommends balancing power supply and demand through non-fossil flexibilities (Advisory Board, 2024). With scenarios suggesting minimal use of fossil gas in the power sector by 2050 (Advisory Board,), CO_2 infrastructure can instead reduce residual emissions from activities with no or limited mitigation alternatives. In this context, it is positive that the European Commission proposed detailed CO_2 emission reduction roadmaps co-designed and implemented at sectoral level, taking into account the complexity of industrial processes (EC, 2024z), which is in line with Article 10 of the European Climate Law.

CO_2 infrastructure is crucial for connecting capture sites to storage locations. The prioritisation of CO_2 infrastructure should follow the energy efficiency first principle and be based on environmental impact assessments.

CO_2 infrastructure assets differ in terms of resource-efficiency. CO_2 transport infrastructure connects capture sites with storage sites; the more dispersed capture sites are, the more CO_2 transport will be needed (Holz et al., 2021). Pipelines are generally the most mature and least expensive for large-scale onshore CO_2 transport, with shipping considered the best solution for offshore locations (JRC, 2024b). To minimise costs and disruptions from CO_2 transport, routing needs to be carefully planned. In line with the energy efficiency first principle, repurposing existing gas pipelines should be considered (CCUS Forum, 2023c) (see Section 9.3). To cater for the possibility of dispersed capture sites and reflect the uncertainty surrounding future emitters' needs for CO_2 transport and storage, rail and road CO_2 transport may have some significant advantages over pipelines, especially in the initial phase of market creation (Becattini et al., 2022; Dziejarski et al., 2023; Simonsen et al., 2024). In addition, minimising the dispersion of capture through industrial hubs and clusters can also bring efficiency gains (IEA, 2023a; JRC, 2024b; Wang, 2024).

Efficiency aspects come into play when comparing the resource intensity of different capture techniques and transport modes. For example, the high energy intensity of DACCS implies the deployment of additional energy capacities (Lux et al., 2023). This is only partly compensated for by the efficiency gains offered by the siting flexibility of DACCS, which can facilitate access to CO_2 transport and storage infrastructure. Point source capture has higher efficiency gains than DAC, but requires connection to transport infrastructure (IPCC, 2022n). The energy efficiency first principle and environmental impact assessments apply to CO_2 infrastructure projects as stipulated in the existing EU law. Resource efficiency gains also stem from Member States cooperation with the EU's neighbouring countries, notably Norway and Iceland, underpinned by the European Economic Area, as well as the UK.

Disparities in access to offshore CO_2 storage raise equity concerns among Member States, underlining the importance of developing onshore storage and clustering approaches for a just transition. EU policy, such as the TEN-E regulation and the Net-Zero Industry Act encourage cross-border infrastructure to ensure fair access and align with the EU principles of justice and solidarity.

Given that most storage capacity is expected to be located offshore (EC, 2024z) not all Member States will have the same ease of access to those sites. This raises concerns about a disproportionate burden of decarbonisation for some countries and for a just transition (EnTEC et al., 2023). Given that most storage capacity is expected to be located offshore (EC, 2024z), not all EU Member States will have the same ease of access to those sites, raising concern of disproportionate burden of decarbonisation for some countries and for a just transition (EnTEC et al., 2023). Not all storage methods have the same technological maturity, and, to ensure ease of access to storage places including in countries that are not located close to the North Sea or other suitable basins, further research into and commercialisation of onshore storage also offers an opportunity for a just transition (Dziejarski et al., 2023) (see also Chapter 8).

The Net-Zero Industry Act requires the EU and its Member States to 'make all reasonable effort to develop the necessary CO_2 transport infrastructure, including cross-border infrastructure, while taking into account the economic and environmental benefits of proximity of capture and storage sites' (EU, 2024e). This echoes other parts of the EU policy framework, notably the TEN-E regulation and the funding under the Connecting Europe Facility and the Innovation Fund. Under the TEN-E regulation, one of the criteria for a CO_2 project to become a project of common/mutual interest, reflects the clustering approach, by focusing on 'the efficient use of resources, by enabling the connection of multiple CO_2 sources and storage sites via common infrastructure and minimising environmental burden and risks'.

The list of projects of common interest (PCIs) and projects of mutual interest (PMIs) established in 2023 adds up to an overall planned capacity of up to 103 $MtCO_2$ per year in four onshore storage sites and more than eight offshore locations (EC, 2024z). The cross-border nature of such projects, as well as the pan-European planning and development that underpins the PCI and PMI selection, offers an opportunity to also address the ease of access to CO_2 storage for all Member States, considering local need and conditions in line with the EU's values of justice and solidarity (see Chapter 5).

CO_2 management is an important part of EU climate and energy policies. EU-level long-term energy and CO_2 infrastructure planning and development is not in line with EU climate objectives.

Given the cross-border nature and EU relevance of such projects, network planning and target setting may be most effective if done at either or both the EU-level and regional level(s). The EU's long-term network development planning, known as the ten-year network development plans, has guided infrastructure projects in gas and electricity since 2010. They are developed by associations of European transmission system operators for electricity and gas, in line with the electricity directive and the gas directive. The plans evolve to capture the integrated nature of the European energy systems but do not yet reflect the future cross-border CO_2 network identified as a priority thematic area in the TEN-E regulation since 2022. The plans play an important role in cross-border collaboration and investment decisions, including those under the Connecting Europe Facility. So far, they have been considered unfit for the EU's net-zero transition **(ambition gap)**; the Advisory Board has put forward recommendations on how to improve it (Advisory Board,).

The Net-Zero Industry Act's goal of achieving 50 million tonnes of CO_2 storage capacity annually by 2030 enhances investor confidence but lacks specific prioritisation of removals. Specific infrastructure targets for removals could be considered. Systematic potential mapping and progress tracking of CO_2 infrastructure development is needed to refine EU policy and ensure effective implementation.

Policy targets can boost infrastructure roll-out; it is positive that the proposed Net-Zero Industry Act recognises CCS as strategic net-zero technologies and sets an EU target to make an annual operational injection capacity of 50 Mt CO_2 by 2030 (EU, 2024e). This legally binding target indicates a strong policy direction regarding the EU's CO_2 storage needs and can increase investor confidence along the CO_2 value chain. It fails, however, to specify that these capacities need to first and foremost help to counterbalance or reduce emissions in activities with no or limited mitigation alternatives **(ambition gap)**. It also does not address the actual use of the target injection capacity and does not distinguish between its use for reduction and removals **(policy gap)**.

Specific targets underpinning CO_2 infrastructure for removals could be considered with a view to clarifying the EU's policy orientation, with a clear delineation between emission removals and emission reduction through CCS and CCU. The CCUS Forum has called for targets to be based on rigorous analysis of viable decarbonisation pathways and likely residual emissions. (CCUS Forum, 2023a).

The storage targets are reinforced by other EU measures: the requirement for Member States to assess CO_2 storage capacity on their territories, set out in Article 4 of the CCS directive; the European Commission plans to compile an EU-wide atlas based on that (EC, 2024z), taking forward the assessment of the CO_2 storage potential in Europe as part of the EU funded projects such as CO_2Stop and CGS Europe (see e.g., Wildenborg et al., 2013). The EU's plan to map CO_2 storage sites and to match them with point sources can help to give investors a better view of the future and reap benefits from economies of scale. In addition, at the national level, many Member States have set indicative CCS and CCUS, BECCS and DACCS targets in their updated NECPs (EC, 2023b). While the targets are generally helpful in terms of policy monitoring, currently there is no systematic tracking of progress in CO_2 infrastructure readiness at the EU level **(policy gap)**. This could be addressed by tracking expected CO_2 infrastructure capacity expansion based on the carbon storage permits notified to the European Commission under the CCS directive, as well as the number and status of CO_2 projects with PCI and PMI status and those funded with EU contributions or through notified State aid. Regular progress monitoring can inform EU policy cycles, enabling corrective action when necessary (Borchardt, 2023).

9.3 Setting regulatory framework facilitating CO_2 infrastructure development and use

9.3.1 Need

The EU needs to develop a predictable regulatory framework ensuring interoperability and third-party access to CO_2 infrastructure, as well as the environmental integrity, climate resilience and safety of the CO_2 physical assets. Permitting needs to balance the speed and sustainability of CO_2 infrastructure projects.

Since part of CO_2 management, notably large pipeline transport networks and storage sites, will become a utility network industry, many CO_2 infrastructure assets will need to be regulated (IEA, 2022a). Asset regulation aims to ensure competition and the cost-effectiveness of natural monopoly operations, which are likely in the case of large CO_2 infrastructure assets (Jones, 2023; Joskow, 2007). The cross-border nature of CO_2 infrastructure and the necessary economies of scale call for harmonisation of technical and environmental standards across the Member States and the EU's partners (Dixon et al., 2015, Heffron et al., 2018). Likewise, the risk of climate and other hazards to critical infrastructure requires a reassessment of infrastructure network governance in complex systems, as suggested by Lindbergh and Radke (2021) and the Advisory Board (Advisory Board,) Likewise, the risk of climate and other hazards toon critical infrastructure requires a reassessment of infrastructure networks governance in complex systems, as suggested by Lindbergh and Radke (2021) and the Advisory Board (Advisory Board,). Future regulation needs also to expedite CO_2 infrastructure buildout and operation without harming the environment and people. It should also ensure strategic project prioritisation based on need, capabilities, conditions on the ground, and creating options for the future. In addition, infrastructure ownership is linked to risk sharing and liabilities along the CO_2 value chain and thus requires regulatory intervention and oversight (Heffron et al., 2018). Robust monitoring and control of the CO_2 infrastructure performance will be key to ensuring its environmental integrity and safety. The environmental integrity and safety of CO_2 networks, relying on long-term management, for instance in closure and post-closure phases, is key to their public perception and market confidence (Nordic Council of Ministers, 2023; Yanagi et al., 2019, Lezaun et al., 2021).

9.3.2 Status and policy gaps

The EU lacks a comprehensive regulatory framework facilitating CO_2 infrastructure development.

Since 2009, geological storage of CO_2 has been regulated by the CCS directive (EU, 2009b), which sets permitting rules to ensure the safety and environmental integrity of CO_2 storage and prescribes transparent and non-discriminatory access to the infrastructure. These rules are far from a comprehensive regulatory framework along the entire CO_2 value chain (Jones, 2023), notably for industrial removals and for certain CO_2 uses and the required cross-border coordination and planning (EC, 2024z). Academic and practitioners' insight into the regulatory needs underpinning scale-up and operation of CO_2 infrastructure highlights the following aspects, which are addressed in more detail in this section:

a. ownership and competition,
b. environmental integrity, resilience, and safety,
c. permitting,
d. monitoring and control,
e. allocation of risk and long-term liability.

Different models of ownership of CO_2 infrastructure assets will develop, requiring various models of regulatory intervention to safeguard competition.

Private ownership may be most common in CO_2 networks within direct lines connecting a single industrial emission centre to the nearest CO_2 backbone. Regulation of asset owners may emerge in backbone CO_2 pipeline networks linking key clusters with major storage sites (Jones, 2023). Backbone (onshore and offshore) CO_2 pipeline networks could be owned by network operators (e.g. storage operator or a separate pipeline operator). Storage is likely to be owned by oil and gas companies except for assets not linked to oil and gas activities such as salt cavern storage (Jones, 2023). Studies from the United Kingdom indicate that, in order to initiate widespread, commercial deployment of CCS, shared, sequential ownership between government and the private sector could be considered. Government could initially own the CCS value chain with ownership being transferred to the private sector late , as CCS evolves and risk is reduced (Heffron et al., 2018).

Third-party access to major transport networks and storage sites is not yet harmonised at the EU level. A common CO_2 quality standard needs to be developed to unlock interoperability of assets and unlock economies of scale.

Ownership of essential facilities in carbon management may need to follow similar regulatory safeguards of competition to those of other network utilities. Over time regulated third-party access and unbundling of capture and transport and storage activities may become necessary. For the time being, the CCS directive (EU, 2009b) warrants third party access to CO_2 transport networks and storage sites, and 11 countries, bound by the directive, have put procedures in place to ensure fair and open access to such assets (EC, 2023m). Nevertheless, there is little experience with such regulation, and, as multi-user CO_2 transport and storage infrastructure becomes a business model with the emergence of new players, third-party access will need to become subject to rules harmonised at the EU level (IEA, 2022a).

Regulators will also play a role in the development and application of harmonised standards and CO_2 network codes which are currently lacking at EU level **(policy gap)**. Harmonised CO_2 quality standards enable interoperability between capture, transport and storage assets; for example, they allow large-scale cross-border transport infrastructure to handle CO_2 streams from different sources (CCUS Forum, 2023b; EC, 2024z; Simonsen et al., 2024). Simonsen et al. (2024) suggest that cost–benefit analyses may help to settle CO_2 quality as a trade-off between the costs of purification and infrastructure material.

The EU legal framework applicable to CCS infrastructure requires efficient resource use, environmental safeguards and public engagement, but does not sufficiently address climate adaptation and the resilience of CO_2 infrastructure, or link industrial pollution reduction with GHG reduction objectives.

The necessity to apply the energy efficiency first principle and run environmental impact assessment is embedded in the existing EU laws, notably the energy efficiency directive (EU, 2023c) and the environmental impact assessment directive (EU, 2012). The environmental impact assessment of CCS infrastructure projects will become relevant for the wider certification audit of removal activities under the CRCF regulation. As a standalone requirement under the environment impact assessment directive, in transboundary contexts, and the Espoo Convention (UNECE, 1991), it is binding on the Member States. The environmental impact assessment is not only a tool that helps to safeguard the environment; by including rules on active participation of the public concerned, it plays a role in building public engagement and trust. Emerging evidence suggests that current environmental impact assessment requirements may fall short of addressing social conflicts (Larsen et al., 2018; Liu et al., 2021) (see also Chapter 10). Assessing energy efficiency solutions when making major investment decisions such as CCS infrastructure is required under Article 3 of the energy efficiency directive (EU, 2023c). This requirement risks being void, however, due to the very high investment decision threshold set out in the energy efficiency directive **(ambition gap)**, as pointed out by the Advisory Board in 2024 (Advisory Board, 2024).

The industrial emissions directive, complements the EU ETS directive and lays down rules to prevent or reduce industrial emissions into air, water and land and to prevent the generation of waste (EU, 2010). The most recent revision of the industrial emissions directive did not sufficiently reinforce the link between industrial pollution and decarbonisation, missing out on an opportunity for better policy coherence (Advisory Board, 2024). Creating better links between depollution and decarbonisation should be an important angle for the next revision of the directive and could take into account the increasing role of CCS in industrial installations including large combustion plants (UK Environment Agency, 2024).

The London protocol binds Member States of the European Economic Area. It entered into force in 2006 with the aim of protecting and preserving the marine environment from all sources of pollution by banning the unregulated dumping of waste. While the protocol is criticised for having the 'unintentional consequence that it effectively prohibits cross-border transfer of CO_2 for the purposes of geological storage offshore' (ZEP, 2023), it provisionally allows for bilateral agreements between parties that signed the 2009 amendment enabling the export of CO_2 streams for sequestration (IMO, 2024). While removing unintended regulatory barriers, the EU has to ensure that harmonised rules safeguard the environmental integrity and safety of offshore CO_2 operations and do not lead to further lowering of protection levels of EU marine protected areas (Aminian-Biquet et al., 2024). The European Commission's ambition is to promote the development of any necessary guidelines on safe transportation of CO_2 by sea through the International Maritime Organization (EC, 2024z). It is a welcome ambition, as it could help address the challenge of regulating a in multilateral context beyond the EU, and need for cross-border cooperation on CO_2 infrastructure (JRC, 2024b). In this field, approaches within the international governance of deep seabed mining could prove informative, especially in terms of project development in international waters (Dingwall, 2020).

The EU is committed to preventing marine pollution from GHG emissions under UNCLOS, with due diligence varying by state capacity. Climate adaptation rules should be extended to CO_2 infrastructure under EU funding and permitting.

In addition, the EU is a signatory of the UN Convention on the Law of the Sea, the UNCLOS (UN, 1982). The convention requires signatory States to exercise their best effort to ensure that the marine environment is adequately protected. In this respect, the obligation to take all necessary measures to prevent, reduce and control marine pollution from anthropogenic GHG emissions is one of due diligence. The standard of due diligence under article 194, paragraph 1 of the UNCLOS, is stringent, given the high risks of serious and irreversible harm to the marine environment of such emissions. However, the implementation of the obligation of due diligence may vary according to States' capabilities and available resources (ITLOS, 2024).

The EU Taxonomy Climate Delegated Act (EC, 2021b) includes technical screening criteria for underground permanent geological storage of CO_2, including 'do no significant harm' criteria for water pollution and biodiversity based on the EU's water framework directive and the environmental impact assessment directive, which may provide guidance for ensuring the environmental integrity of both private and public investments. The EU taxonomy addresses climate adaptation concerns, which fall under the 'do no significant harm' criteria of a CO_2 infrastructure investment. Screening of infrastructure should thus be: "adapted to adverse impact of the current climate and the expected future climate, thereby preventing serious negative *impacts* on the health, safety, security or economic well-being of citizens or the effective functioning of governments in Member States". This echoes the need to avoid maladaptation when building infrastructure (UNDRR, 2023).

Apart from broader risk management, including liability mechanisms, the CCS directive does not explicitly require climate-proofing of CO_2 infrastructure (EU, 2009b) which is an **ambition gap**. The TEN-E regulation (EU, 2022) stresses the importance of adapting to the adverse impacts of climate change, and that climate adaptation objectives need to be adequately reflected in the revised trans-European energy networks framework. It defines 'climate adaptation' as:

> *'a process that ensures that resilience to the potential adverse impacts of climate change of energy infrastructure is achieved through a climate vulnerability and risk assessment, including through relevant adaptation measures.' (Article 2 (19))*

While the wording of the TEN-E definition of climate adaptation only explicitly refers to adaptation in energy infrastructure projects **(ambition gap)**, its interpretation could be extended to CO_2 networks given the overall scope and purpose of the regulation. Notably, climate adaptation measures are required from the project promoters to underpin their permit requests for PCI and PMI eligible for EU funding support and favourable regulatory treatment. Given that CO_2 infrastructure projects are among the project categories eligible for PCI and PMI status, the definition of climate adaptation under the TEN-E regulation should be extended to CO_2 assets, so their permitting encourages the pursuit of 'best and innovative practices with regard to mitigation of environmental impacts, including climate adaptation, during permit granting processes and project implementation' highlighted in Article 21(e)(iv) of the TEN-E regulation. Such an adjustment would be in line with the rules governing EU funding for PCI and PMI, namely the Connecting Europe Facility (see also Chapter 5).

Several EU funds, including the Connecting Europe Facility, InvestEU, the European Regional Development Fund, Cohesion Fund, and the Just Transition Fund lay down climate resilience and adaptation requirements for any infrastructure projects receiving EU support. In 2021 the European Commission issued "Technical guidance on climate proofing of infrastructure" (EC, 2021c). This is in line with the overarching obligation for the EU and national authorities to ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change, as set out in Article 5 of the European Climate Law and Article 7 of the Paris Agreement.

The EU makes efforts to harmonise safety rules and develop international guidelines for CO_2 transport.

Regarding the safety aspect of CO_2 management, policy needs to consider human safety at the development, operation, and decommissioning stages of CO_2 infrastructure projects. CO_2 is a hazardous substance and its physical behaviour at different scales of transport and storage, and the risks related to CO_2 leakages, are not yet fully understood (Alhajaj and Shah, 2020; PHMSA, 2022; Simonsen et al., 2024). This uncertainty seems to be higher for transport than for geological storage formations (Deng et al., 2017). The EU could address these risks through technical standards and emergency response guides based on dispersion modelling and impact assessment in specific contexts, notably urban (e.g., impact of carbon leakage in densely populated areas) and rural (e.g., impact of carbon leakage on crops). Experience from the United States suggests that preventive safety practices such as odourising of CO_2 could be considered to help people detect the leak and initiate the emergency response (CRS, 2023; Kilgallon et al., 2015).

The Net-Zero Industry Act aims to streamline permitting for CO_2 infrastructure projects, recognising that regulatory authorities are developing expertise in this area. Early engagement between project developers and authorities is essential to prevent delays and address public concerns.

Permitting of CO_2 infrastructure projects (e.g. routing permits for CO_2 pipelines and storage permits) is a new competence for national regulatory authorities(EC, 2024z). The Net-Zero Industry Act aims to support CCS and CCU projects with regulatory measures such as accelerated permitting procedures. Judging from experience in development of other major infrastructure projects, often of a cross-border nature, early engagement between permit applicants, local communities and competent authorities during the preparatory phase of a CO_2 infrastructure project will be necessary to avoid time delays. Early engagement with stakeholders and public participation in decision-making can reduce the chance of negative public perception of such projects. The European Commission's ambition is to ensure that CO_2 storage permitting procedures are well defined, transparent and comparable across the EU (EC, 2024z). The permitting is supported by the guidance documents issued in July 2024 by the European Commission under the CCS directive, and could be informed by experience from renewable energy and related infrastructure projects (EC, 2024g).

The material and environmental integrity of the CO_2 infrastructure relies on a robust monitoring and control framework, from the pre-injection to the post-injection phase of a CCS project. Operators are required to establish baselines, identify irregularities and enable independent inspections. The experience from the implementation of the CCS directive has been limited so far.

The existing regulatory framework surrounding CCS requires measurement, monitoring, and verification plans and independent inspections. Regular monitoring is required during all phases of the project from pre-injection to post-injection (Romanak and Dixon, 2022). Monitoring and reporting obligations require establishing baselines and identifying irregularities, and any requirements for independent verification of data (IEA, 2022b). Inspection provisions need to include mechanisms for authorising inspectors, inspector access rights, and operator obligations to allow access and share information (IEA, 2022b; Onyebuchi et al., 2018). Technological development will be key in this respect; for example, state-of-the-art monitoring devices collecting and transferring CO_2 storage data remotely to operations on land can increase the efficiency and safety of offshore surveying activities (IEA, 2022b).

Experience of US CO_2 pipeline operations indicates that CO_2 pipelines may need supranational oversight (CRS, 2023). The CRCF regulation requires operators to take all relevant preventive measures to mitigate reversal risks and duly monitor that carbon continues to be stored over the monitoring period laid down for the relevant activity (Chapter 6). The specific monitoring requirements and the related liability mechanisms will be tailored to the removal methods in question within the certification methodologies (EU, 2024g). The CRCF regulation specifies, however, that in the case of permanent removals through geological storage, provisions of the CCS directive apply, which means the monitoring activity is the duty of the operator reporting to a competent authority at least once a year (Article 13 of the CCS directive). This kind of self-monitoring is complemented by routine and non-routine inspections organised by the competent authorities. Experience with the application of the CCS directive is limited so far but growing with each new CCS project. The guidance documents released by the European Commission in July 2024 provide direction on the allocation of monitoring responsibilities, corrective measures and risk management (EC, 2024o, 2024n), but are limited to surface and injection facilities associated with geological storage. Similarly, CO_2 capture and transport infrastructure requires monitoring and control rules and guidance **(policy gap)**, given the CCS directive's focus on storage infrastructure.

EU guidance and rules can lower uncertainty around operational responsibilities for CO_2 infrastructure assets and ensure long-term stewardship of permanent storage sites.

Allocation of risk between public and private actors is one of the issues to consider in the preparation of CO_2 infrastructure projects before the final investment decision is made. It is related to the ownership model of the assets and has implications for plausible partnership arrangements (Heffron et al., 2018). Operational responsibilities and post-closure stewardship need to be clarified by the regulatory frameworks, notably in cases of permanent large-scale storage of CO_2 that requires centuries -long maintenance and risk management. Operational risks for operators can be lowered through access to specialised insurance products for storage and transport operators that provide for different risk contingencies (DESNZ, 2023; Noussia et al., 2022). Long-term stewardship relates to the operators' financial contribution to the costs of long-term site integrity following closure (IEA, 2022b). The CCS directive requires that responsibility be transferred to the government after the storage site has been closed, and that the operators cover at least the anticipated cost of monitoring for a period of 30 years (Article 20 of the CCS directive). The European Commission has issued guidance on the CO_2 storage life cycle and risk management framework, including rules for the transfer of responsibility to the competent authority on behalf of the Member State and releasing the operator from liability, marking the beginning of the long-term stewardship of the site by the Member State (EC, 2024n).

9.4 Summary of EU policy assessment

Table 20 summarises the policy assessment carried out in this chapter, by providing an overview of the status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024).

Table 20 Summary of the EU policy assessment of Chapter 9

Policy	Status	Gaps and inconsistencies
Net-zero industry act	Supports CCS, CCU and CCUS projects with regulatory measures (e.g., accelerated permitting procedures, net- zero acceleration valleys, investment obligation, and capacity building).	Does not specify that storage capacities need to first and foremost help to counterbalance or reduce emissions where there is no alternative abatement available. → **ambition gap** Does not ensure the actual use of this injection capacity, nor distinguishes between CCS and removals. → **policy gap**

Policy	Status	Gaps and inconsistencies
	Sets an EU target of 50 $MtCO_2$ injection capacity into geological storage per year by 2030, with individual obligations for fossil fuel producers to contribute to the EU-wide target.	
TEN-E regulation	Puts an emphasis on hydrogen infrastructure deployment in 'hard-to-abate sectors' (article. 4).	No prioritisation of CCS infrastructure to activities with no or limited alternative; no explicit focus on removals; climate adaptation definition covering only energy infrastructure. → **ambition gap**
CCS directive and accompanying guidance	Sets permitting rules to ensure the safety and environmental integrity of CO_2 storage and prescribes transparent and non-discriminatory access to the infrastructure.	No CO_2 quality standard or network code. → **policy gap** No explicit climate-proofing requirement. → **ambition and implementation gaps**
Energy efficiency directive	Requires applying the energy efficiency first principle to major infrastructure projects.	Sets a very high investment value threshold for the energy efficiency first principle → **ambition gap**
Other		There is currently no systematic tracking of progress in CO_2 infrastructure readiness at the EU level → **policy gap**

10 Enhancing institutional governance

- **EU governance is not yet suited to handle the scale-up of removals.** Strategic, evidence-based, and innovative removal policies require robust and integrated governance systems across sectors and levels. The EU's institutional framework is not yet designed to manage the GHG budget and to integrate removals into policy frameworks aimed at achieving net-zero emissions by 2050 and net-negative emissions thereafter.

- **The EU's approach to reach net negative has yet to be defined.** Current EU and national policies primarily target net zero and lack a clear commitment and strategy for the net-negative transition. Additionally, inconsistent messaging about removals hinders public understanding of the need for removals and net-negative emissions.

- **Removals should be embedded in plans and strategies.** The EU should embed removals into updated national energy and climate plans (NECPs), long-term strategies and sectoral roadmaps that encourage long-term policy direction and coherence enabling public funding to leverage private finance.

- **Transparency is needed to operationalise the certification.** Delegated acts will play a critical role in operationalising the EU CRCF Regulation that aims to facilitate investments in removals. The EU should develop these acts transparently through participatory processes and make sure they align with EU's climate goals and are up to date.

- **Sustainability is challenged by a lack of policy coordination.** The lack of coordination between energy, biodiversity and LULUCF policies undermines the sustainability of removal methods such as BECCS and biochar. Improving policy integration and addressing implementation gaps are critical to the sustainable scale-up of removals.

- **Public dialogue on EU climate policies is still limited.** Limited stakeholder dialogue and public consultation reduce the transparency, inclusivity and legitimacy of EU climate governance. Member States should establish robust multi-level stakeholder dialogues and ensure meaningful public participation in NECPs and removal policies.

- **EU should facilitate coordination among member states.** National removal planning risks overlooking cross-border interdependencies, leading to fragmented efforts. The EU should enhance its coordination role, by fostering regional collaboration and providing permitting guidance, and use EU funding to leverage private removals investment in line with the polluter pays principle.

- **Enhanced international cooperation is vital** to prevent carbon leakage, ensure fairness in global contributions and harmonise reporting and accounting standards.

10.1 Introduction

Member States' policies and measures to scale up removals need to become a part of the EU climate governance relying on coordination between Member States and between different levels of governance.

Climate action in the EU is currently governed through an integrated and coordinated approach across EU, national and subnational levels, requiring Member States to plan policies towards shared objectives and regularly report on progress made. As presented in Chapters 4 to 0, scaling up removals will involve diverse sectors, technologies, and actors, spanning geographic, administrative, institutional, and policy boundaries (Schenuit et al., 2024a). This new challenge highlights the necessity of further policy integration that enables EU to advance its policy objectives efficiently within the EU climate governance (see, for example, Rietig and Dupont, 2023, IPCC, 2022).

In addition to policy integration within the existing EU climate governance, institutional governance at all levels needs to deliver on the governance functions described so far in this report (Chapters 4-0), namely:

1. Managing the GHG budget to avoid mitigation deterrence and ensure cost efficiency,
2. Maintaining fiscal sustainability and enhancing distributional fairness,
3. Ensuring the quality of removals,
4. Managing land resources and climate risks,
5. Accelerating the innovation cycle and raising public awareness, and
6. Planning and developing the EU's CO_2 infrastructure.

This chapter primarily focuses on the EU institutional capacities to drive domestic action. In addition, Section 10.3.3 highlights key aspects of EU's international cooperation to enable a sustainable scale-up of removals.

10.2 Integrating removals in EU climate governance

10.2.1 Need

Cross-sectoral and cross-border institutional cooperation is key to embedding removals in the EU's climate policy and governance frameworks.

The integration of removals into the EU climate policy framework is critical for achieving long-term climate goals. It requires the adoption and implementation of policy instruments that build on existing rules, procedures and instruments for climate change mitigation (IPCC, 2022f). It will also require enhanced cooperation across governmental services in charge of sectors like agriculture, industry and finance, as well as improved coordination between Member States, for example regarding cross-border infrastructure (Chapter 9) (Schenuit et al., 2024b; WKR, 2024).

10.2.2 Status and policy gaps

While the European Climate Law embeds the long-term goal of net-negative emissions, current EU and national policies primarily target net zero and lack a clear narrative for the post-net-zero transition. Additionally, inconsistent messaging about removals hinder public understanding of the need for removals and net-negative emissions.

The long-term objective of net negative GHG emissions (see Chapters 1 and 4) is embedded in the European Climate Law. Despite the high-level legal framing, the current focus of climate policy at EU and national levels is on reaching net-zero, and there is no or very limited policy narrative and governance to plan for or guide the EU's transition *beyond* net-zero and into net-negative, i.e., when removals exceed GHG emissions **(ambition gap)**.

Moreover, the public generally lacks knowledge which makes them beholden to the agenda of their communicators. EU institutional messaging (see EC, 2024a) is not always clear regarding: the need for removals, and the necessity of reaching net-zero CO_2 emissions before net-zero GHG emissions, the severity of failing to reduce GHG emissions, and the need for net-negative emissions. For instance, the terms "carbon neutral" and "climate neutral" are sometimes synonyms for net-zero CO_2 and sometimes for net-zero GHG emissions (Rogelj et al., 2021). Public bodies at all governance levels are yet to engage in responsible messaging embedded in internally-consistent, context-specific narratives, as suggested by Bellamy et al (2019) and Cox et al. (2024).

NECPs play a critical role in coordinating Member States' contributions to EU climate goals, including removals, by providing a framework for planning, reporting, and monitoring progress.

The EU's climate goals are supported by the governance regulation, which establishes NECPs as key tools for planning, reporting, and monitoring Member States' progress. NECPs and their progress reports help Member States to plan policies and measures while tracking their alignment with EU-wide targets. Developed through an iterative process between the European Commission and Member States, NECPs also require public consultation and stakeholder dialogue to ensure transparency and inclusivity.

Since the EU removal policy is relatively recent, its underlying targets[29] have not been explicit in the common NECP template (EU 2018b). The European Commission guidance (EC, 2022b) on the update of the 2021-2030 NECPs encourages the Member States to reflect on the pathways to reach the EU's removals target of 310 million tonnes of CO_{2e} by 2030 set out in the LULUCF regulation. It further guides the Member States to provide information about relevant CCU and CCS policies and measures, including BECCS and DACCS. It asks to approach BECCS deployment in the updated NECPs "in full consideration of the limits and availability of sustainable biomass" (EC, 2022b, p. 37). Other types of information dedicated to CCS that is expected from the Member States to include in their updated NECPs is presented in Box 7 below.

Box 7 Expected information on carbon capture and storage to be included in updated NECPS

European Commission's guidance on updated NECPs, (EC, 2022b) encourages Member States to provide the following information:

- the annual aggregated projection of inherent process emissions that will have to be abated through CO_2 capture;
- the annual biogenic and direct air CO_2 that will be available for geological storage of CO_2;
- the geological CO_2 storage capacity that can be made operationally available annually;
- annual CO_2 storage capacity that may become available at the end of exploitation of hydrocarbon reservoirs;
- planned CO_2 transport infrastructure;
- public funding support available for investment in CO_2 capture, transport and storage;
- any other measures to support the deployment of long-term geological CO_2 storage opportunities.

Source: European Commission Guidance to Member States for the update of the 2021-2030 national energy and climate plans (2022/C 495/02)

Twenty Member States have included CCU and CCS relevant information in their draft NECPs due in 2023. Thanks to that, it is possible to aggregate national projections and provide EU-level estimates of carbon capture annual capacity in 2030, i.e., up to 34.1 $MtCO_2$ of which 5.1 Mt from biogenic sources. It has also been made known that Member States plan to capture CO_2 emitted in the production of electricity and hydrogen and from process emissions in the cement, steel and fossil gas processing

[29] The targets linked to removals include achieving climate neutrality by 2050 and negative emissions thereafter (ECL), as well as 50 million tonnes of annual operational CO_2 injection capacity by 2030 (art. 20 NZIA); cap of removals contribution to the 2030 net emission reduction target capped to $225MtCO_{2e}$ (art. 4 ECL); and net removals from LULUCF sector of 310 million tonnes of CO_{2e} in 2030 (art. 4 LULUCF regulation). There are also other targets and benchmarks at EU level e.g., the share of EU technologies deployed to reach net-zero (NZIA), that while not specific to removals, support their sustainable scale-up.

sectors. The NECP process also helped to estimate the overall injection capacity planned by the Member States, 39.3 $MtCO_2$ per year in 2030 (EC, 2024z).

NECPs lack critical cross-sectoral integration and long-term planning, limiting their effectiveness in addressing pathways to net-negative emissions and addressing sustainability criteria.

While NECPs provide valuable information for coordinating removals policies at the EU level, significant gaps remain. Cross-sectoral interdependencies, such as the links between energy, biodiversity, and LULUCF policies, are insufficiently addressed in Member States' NECPs **(implementation gap)**. For example, the initial NECPs lacked detailed plans for supplying sustainable biomass, broken down by feedstock, origin and trajectories for forest biomass, and how they are aligned with measures to maintain and increase the carbon sink (EC, 2023d). Updated drafts rarely include references to biomass sustainability criteria or cascading principles (EC, 2023a). Both the sustainability criteria and the cascading principles are key to the sustainability of some removal methods (see Section 7.3). Furthermore, the link between the 10-year NECPs and national long-term strategies covering at least a 30 year perspective is generally insufficient (Advisory Board, 2024), leaving removals goals for 2050 and beyond underdeveloped **(ambition gap)**. This lack of integration hinders the EU's ability to commit to net negative emissions after 2050 at the latest.

The NECP process faces challenges in participatory governance, as insufficient stakeholder dialogue and public consultations weaken transparency and inclusivity.

Implementation and ambition gaps in participatory governance have been a persistent issue in the NECP process. Many Member States fall short in organising the required muti-level stakeholder dialogues to support the design and implementation of their plans (Advisory Board, 2024). Public consultations are often limited or delayed, reducing opportunities for meaningful input from citizens and stakeholders. Strengthening participatory governance is essential to improving the transparency, inclusiveness, and legitimacy of NECPs, and garnering public acceptance.

The expected revision of the governance regulation offers an opportunity to integrate removal policy within the NECP process, strengthen links between NECPs and long-term strategies, and enhance multi-level stakeholder engagement. Sectoral roadmaps prepared at the EU level could support this integration, but their development has been limited.

The Governance Regulation is expected to be revised in 2026 to reflect the latest policy and legislation, and to support the achievement of EU climate and energy targets beyond 2030. The revision is an opportunity to integrate removal policy planning, monitoring, and reporting in the NECP process and further enhance the EU's climate governance in line with the Advisory Board recommendations published in January 2024. This includes a reinforcement of the link between the long-term strategies and NECPs, and a clarification of the existing requirement for multi-level stakeholder dialogue (Advisory Board, 2024).

Sectoral roadmaps, encouraged under Article 10 of the European Climate Law, can guide investments in removals and empower private actors to take proactive steps towards climate goals (Kloo et al., 2024; Sovacool et al., 2023). These roadmaps can highlight supply and demand for removals solutions and encourage best practice across stakeholders like energy and industry. Several transition pathways have been prepared so far at EU level. However, it is unclear how they will support a sustainable and rapid scale-up of removals and their indicative and voluntary nature may limit their impact (**ambition gap**).

10.3 Delivering on the governance functions

10.3.1 Need

Delivering on the governance functions introduced in Chapters 4 to 0 relies on institutional capacities within the EU governance framework (see e.g., Lezaun et al., 2021). The public tasks and related institutional capacities range from securing a long-term political commitment to net negative and ensuring high-quality of removals, to balancing fiscal sustainability and distributional considerations while mobilising investment and innovation. Institutional set-ups will also play a role in collecting and sharing data and knowledge across stakeholder groups and governance levels, as well as safeguarding procedural justice and public trust in EU climate action (Filipović et al., 2022; IPCC, 2022n; McCauley and Heffron, 2018; Voicu-Dorobanțu et al., 2021). While not a comprehensive assessment, Section 10.3.2 outlines a few selected parts of the existing institutional set-up relevant to each of the six governance functions, and identifies areas where institutional reinforcement may be required.

10.3.2 Status and policy gaps

Governance function 1: managing the GHG budget to avoid mitigation deterrence and ensure cost effectiveness

The EU manages GHG emissions through targets set under the European Climate Law and other legal measures with the EU ETS playing a central role in incentivising GHG emissions reduction. Removals are governed through fragmented policies, including targets under the LULUCF regulation. The EU's institutional governance has yet to address the need to integrate removals into its overall GHG budget management.

As explained in Chapter 4, managing the GHG budget to avoid mitigation deterrence and ensure cost effectiveness entails: (i) determining the required volume of removals up to 2050 needed to counterbalance residual emissions and achieve and go beyond net zero, (ii) specifying the respective roles of permanent and temporary removals, and (iii) providing appropriate incentives to deliver the required volume of GHG for the EU to achieve net-zero by 2050 and net-negative GHG emissions after 2050.

Currently the EU’s GHG budget is managed through policies and measures aimed at achieving binding net GHG emission reduction targets embedded in the European Climate Law, which are further defined in the Governance Regulation, Effort Sharing Regulation, EU ETS directive, LULUCF regulation, and sectoral legislation.

Based on the needs for managing the volume and incentives, the most relevant institutional setup for removals can be found under the EU ETS, where the emission cap is defined by the co-legislators and managed the European Commission and EU ETS operations are centralised into a single EU registry operated by the European Commission. The EU ETS does not yet acknowledge removals **(policy gap)** but allows for trade in emission allowances which are unique financial instruments created by EU law. Their primary market takes place under an auctioning process. The integrity and transparency of the European carbon market is monitored by the European Securities and Markets Authority[30], and the European Commission publishes regular reports on the market’s functioning (EC, 2023n).

[30] In 2021, the European Commission asked the European Securities and Markets Authority to assess trading of allowances under the EU ETS (ESMA, 2022), and the 2023 revision of the EU ETS directive introduced a requirement for the European Securities and Markets Authority to monitor the integrity and transparency of the European carbon market and provide the European Parliament and the Council with annual monitoring reports.

In terms of land sector removals, multiple existing institutional actors are active under the LULUCF regulation, the CAP, as well as forestry and nature protection policies. Apart from the European Commission cooperating with the Member States on the implementation of the LULUCF regulation, no other institutional actor at EU level is explicitly mandated to pursue removals through activities in the land sectors, including reversal prevention and management. Moreover, the LULUCF regulation time horizon, i.e., 2030 is too short to sufficiently underpin EU's long-term climate policies **(policy gap)**.

Governance function 2: Maintaining fiscal sustainability and enhancing distributional fairness

Maintaining fiscal sustainability while scaling-up removals requires long-term policy commitment and public funding to encourage private investment in removals. EU institutions have experience with leveraging private finance including for CCS projects but may need to further innovate to strengthen the application of the polluter pays principle.

As explained in Chapter 5, removals need sufficient public and private sources of funding in the context of constrained public finance. To mobilise private sector, public institutions play a role in delivering long-term investment signals, and funding to de-risk investments in removals. While not dedicated to removals and the net-negative transition (see Section 10.2), the EU's climate governance already includes processes and entities tasked with leveraging private investment. For example, the de-risking of CCS projects, including for permanent removals, through the Innovation Fund is currently in the hands of the EIB and CINEA (the European Climate, Infrastructure and Environment Executive Agency). The EIB provides tailored financing solutions, capacity building, and policy entrepreneurship (Liebe and Howarth, 2020; Rayner et al., 2023; Draghi, 2024).

Enhancing distributional fairness requires procedural justice and policy assessments that consider socio-economic impacts in specific contexts. Both aspects could be improved at the EU level.

To ensure distributional fairness, policies need to address the socio-economic impacts of removals policies (see Chapter 5). To understand such impacts, the EU law-making rules require socio-economic assessments of policies before and after their implementation (EC, 2023a). However these are not systematically conducted, and the link between EU climate and social policies remains insufficient (Advisory Board, 2024). Notwithstanding, the Just Transition Mechanism and the social climate fund have been created to address regressive impacts of the EU's climate transition. While the social climate fund predominantly deals with the future impacts of the EU ETS 2, the Just Transition Mechanism has a wider scope, ensuring that the transition towards a climate-neutral economy happens in a fair way, leaving no one behind (EC, 2024). The Just Transition Mechanism does not yet address the transition to net-negative, nor does it directly tackle the scale-up of removals **(ambition gap)**. It functions through the Just Transition Platform and the Just Transition Fund. Knowledge sharing through the platform builds on outputs of several working groups of stakeholders from across Europe covering topics relevant to removals: stakeholder engagement, carbon recycling, and CO_2 infrastructure in the context of a just transition in the cement sector (EC, 2023g).

The Just Transition Fund supports just transition regions in shared management between the Member States and the European Commission (EC, 2024r). The shared management principle means that to implement the fund, the Member States need to establish a broad partnership including regional and local authorities, economic and social partners, civil society and research institutions and universities (EU, 2021a). The involvement of partners under the Just Transition Fund programmes and the territorial just transition plans has not always been in line with this requirement **(implementation gap)** (Advisory Board, 2024).

Governance function 2: ensuring the quality of removals

Ensuring the quality of removals will involve a diversity of actors. Enhanced institutional capacity is essential to ensure effective oversight and coordination across the EU and national levels.

A harmonised EU-wide approach to removal certification is being developed under the CRCF regulation (EU, 2024g), with implementation involving national accreditation bodies and the European Commission. The European Commission is responsible for developing removal certification methodologies and reviewing standardized baselines to align certification with the latest available scientific evidence and encourage ambition. It is to adhere to better-regulation guidelines (EC, 2023a) and ensure meaningful participation by Member States, experts, and the public, alongside climate neutrality checks as required under the European Climate Law (Advisory Board, 2024). For example, in delegated acts likely to have significant impacts and where it has discretion, the European Commission is bound to conduct impact assessments (EC, 2023a). The CRCF methodologies, including baselines that are key to defining removals additionality, are laid out in such delegated acts. In addition, they constitute measures whose consistency with EU climate neutrality objective must be assessed by the European Commission prior to their adoption, as stipulated in art. 6 of the European Climate Law . As mentioned in Chapter 6, the implementation of the above procedural requirements is currently not apparent **(implementation gap)**.

Certification organisations (i.e. 'schemes') recognised by and reporting to the European Commission, will be involved in the MRV process in line with the CRCF rules, and so will independent third-party auditors. In CCS projects, they will coordinate with national competent authorities to whom the CCS directive assigns monitoring responsibilities (EC, 2024o). In the bioenergy field, which is relevant to e.g., BECCS and the removals quality criteria set out in the CRCF regulation, deficiencies in the existing biomass certification schemes include delays, fraud and irregularities under RED I and II (EC, 2024a; ECA, 2016; European Ombudsman, 2022) **(implementation gap)**. These call for the enhancement of capacities of all institutions involved at the EU and national levels including market oversight.

In addition to the institutional governance of CRCF certified removals, enhancing land sink will rely on a set of actors and their networks. Many of them, such as those involved in farm advisory services and sustainable forest management already exist across the EU. The increased needs to foster ecosystem resilience and reconcile competing demands for biomass and land (see Chapter 7), suggest that new and expanded roles for institutional actors at all levels of governance will come into play so that the decline of the land sink can be reversed in time for the EU to meet its 2030 climate target, and the sink can be maintained or expanded to meet net zero by 2050.

At the EU level, the EEA provides information to policy makers based on data collected through land monitoring and reporting, including earth observation via satellites launched and operated by the European Space Agency. Land monitoring data supports the compilation of the EU's GHG inventory through the joint efforts of the Member States, the European Commission, the EEA, and Eurostat. The internal coordination between these actors has been working well so far and is likely to intensify thanks to the increased availability of activity-level-data under the CRCF regulation (see Chapter 6).

The implementation of the environmental impact assessment directives in removals plans and projects depends on robust institutional and stakeholder engagement.

Governance structures safeguarding environmental protection linked to specific projects or strategic documents are guided by the environmental impact assessment directive (EU, 2012), and the strategic environmental assessment directive (EU, 2001). Both acts rely on institutional and stakeholder including local community engagement.

Governance function 4: managing land resources and climate risks

Managing land resources is in the hands of various entities implementing sectoral policies. Within the EU's fragmented land-relevant policies, soil and forest monitoring becomes key to the sustainable scale-up of removals. It currently relies on a network of actors implementing the LULUCF regulation and the CAP in which land managers' role is expected to increase. Adaptation goals are jeopardised by a patchwork approach to managing climate risks.

As explained in Chapter 7, EU policies relevant to land management and removals are relatively dispersed and fragmented, with policies dedicated to biodiversity, bioenergy, the agri-food sector, and climate resilience. The corresponding institutional governance reflecting integrated climate environmental and agricultural policies is still largely insufficient (Lovec et al., 2024; Oberthur and Von Homeyer, 2023). Policy integration could be fostered by ensuring that climate neutrality checks are run on relevant draft measures and initiatives and context specific impact assessment and evaluations of policies are conducted, looking beyond purely economic factors (Advisory Board, 2024). Planning and reporting tools are also central to policy integration and should be leveraged under both the Nature Restoration Law (see Chapter 7) and the governance regulation. In this respect, data collection and use come across as an opportunity for further governance enhancement. Land monitoring under the LULUCF regulation and the CAP relies on a network of actors in which EU-level entities facilitate mutual exchange and policy transfer (Cotella, 2020). Alongside national authorities and stakeholders, the European Commission, EEA, and European Space Agency collect and analyse the data, relying on the Copernicus programme (Jutz and Milagro-Pérez, 2020). Land managers' are expected to increase their contribution to land monitoring through data sharing and exchanges of experience, and help to shape removals at the EU level (Gordeeva et al., 2022; Winkel et al., 2022). For example, land-sector organisations e.g. the Confederation of European Forest Owners and European farmers and agri-cooperatives associations are represented in the expert group developing the CRCF methodologies (EC, 2024u).

In climate adaptation, following the direction set by the European Climate Law, the targets defined by Members States are in most cases voluntary, and climate risk assessments and concrete indicators are rarely embedded from policy inception. This results in an unclear ownership of responsibilities among stakeholders at different governance levels and a patchwork of approaches to risk management and reduction. These governance weaknesses jeopardize progress on goals (Chapter 7), increasing the decline of land sinks, risks of reversals and trade-offs for people (Chapter 3).

Governance function 5: accelerating innovation and raising public awareness

As presented in Chapter 8, accelerating innovation needs public investment and guidance towards diversification of removal portfolios. In addition, broader societal engagement is necessary to build public awareness and acceptance of removals.

Current institutional governance of EU innovation policy does not specifically target removals but addresses them as part of the wider efforts to foster climate action.

Innovation governance remains centred around the European Commission including its Joint Research Centre and executive agencies: the European Research Council Executive Agency, the European Research Executive Agency, and the European Climate, Environment and Infrastructure Executive Agency. It also involves also the European Institute for Innovation and Technology (EU, 2021) with its nine thematic knowledge and innovation communities, and the European Investment Bank (EIB, 2024). These organisations do not specifically target removals but address them as part of the wider innovation efforts to foster climate action. Whereas this is not an issue as such, experience so far has shown that it has resulted in a limited focus by existing entities on scaling up removals **(ambition gap)** (see also Chapter 8).

The EU has laid the basis for measures increasing public awareness of removals involving multiple public and private bodies.

Increasing public awareness of removals will play a role across at least three interconnected dimensions: (i) knowledge development and sharing, (ii) public debate and understanding, and (iii) participative policy making and project development. The examples of the requirements stimulating institutional and stakeholder exchanges on removals are listed in the Box 8 below.

Box 8 Selected requirements for institutional and stakeholder exchanges on removals

Main function, legal basis, and action	Actors involved
The CRCF Regulation	
Cross-disciplinary cooperation	European commission (EC), member states (MS), research institutions, scientists, farmers and SMEs
The net-zero industry act art. 15, 38, 21	
Rights of defence of individuals and local communities	Courts, stakeholders
The Net-zero Europe Platform	EC and MS
Transparent CO_2 storage capacity data	EC and MS
Net-zero acceleration valleys	EC, MS, industry, other stakeholders
CCS directive art. 26, 10, 15	
Public environmental information	MS
Review of draft storage permits	EC, MS
Public inspection reports	MS
LULUCF regulation art. 15, 8	
Public accounting rules and Union registry	EC (Central Administrator)
National forestry accounting plans assessment	EC, MS, stakeholders
Better regulation interinstitutional agreement	
Public, expert and inter-service consultations, impact assessments, evaluations	EC, stakeholders
Innovation Fund regulation art. 21, 27	
Assistance and consultation: fund implementation	MS and EC
Communication, knowledge sharing, publicity	EC, CINEA, project promoters
Horizon Europe regulation annex I, art. 6, 19	
Open research infrastructure and innovation	EC, MS, academia
Multi-stakeholder consultations in strategic plans	EC, MS, EP, stakeholders
Ethics checks	EC, national and local bodies
Governance regulation art. 11, 10, 9	
Multi-level stakeholder dialogue	EC, stakeholders
Public consultation	MS, public
Regional cooperation	MS
NECP iterative process	EC, MS
Trans-European Energy Networks regulation, art. 9, 12, 13	
Transparency and public participation in permitting	MS, public
Public and stakeholder consultation, publication of scenarios and infrastructure gaps	Operators, stakeholders, public, EC, MS, ACER, Advisory Board

Source: Advisory Board

Note: Main functions marked with the colour code as follows: Knowledge development and sharing Public debate and understanding Participative policy making and project or programme development

Governance function 6: Planning and developing the EU's CO_2 infrastructure

Cross-border CO_2 infrastructure is governed under the TEN-E regulation and the CCS directive. In the future it could require EU-level representation and further support to inter-governmental coordination, permitting, and regulatory oversight.

As mentioned in Chapter 9, CO_2 network planning is a part of an integrated energy infrastructure planning undertaken by associations of electricity and gas transmission operators (ENTSO-E and ENTSOG) and the Joint Research Centre of the European Commission. However, the integrated planning is not yet aligned with EU's climate and energy policy objectives (Advisory Board, 2024). At a project level, infrastructure planning, development, and oversight are governed under the TEN-E Regulation and the CCS directive (EU, 2009b), in the latter case involving the European Commission and national authorities. Under the TEN-E Regulation, the permitting process typically takes much longer than what the TEN-E regulation requires (Sikow-Magny, 2024). The Draghi report inspired a call to set up a permanent European Coordinator, for monitoring progress in the permit granting process and facilitating regional cooperation. This aims to ensure support for cross-border infrastructure from all Member States concerned, which is promising (Draghi, 2024; Sikow-Magny, 2024).

Cross-border energy infrastructure projects involve the national, regional and local authorities, and in some cases the European Commission, CINEA (the European Climate and Infrastructure and Environment Executive Agency) and ACER (the EU Agency for Cooperation of Energy Regulators) (Meeus and Keyaerts, 2015; Pototschnig and Rossetto, 2024). Connecting Europe Facility grants for cross-border CO_2 projects advances inter-institutional coordination between EU and national level authorities, enabling practice sharing and capacity building across the governance levels of the involved entities (CINEA, 2023). In addition EU supports inter-governmental coordination through collaborative investment frameworks (EC, 2024j, 2022c) as well as permitting guidance (EC, 2024g; EC, 2024f), but so far with no specific focus on CO_2 infrastructure for removals.

In case the CO_2 infrastructure creates cross-border networks, it may require similar industry representation and regulatory oversight as cross-border energy infrastructure. ACER fosters cooperation among the EU's energy national regulatory authorities and helps ensure that EU's internal energy market functions well, by, among other functions, contributing to the alignment of trans-European energy infrastructure with the EU priorities. No regulatory agency at EU level currently oversees the functioning of emerging cross-border CO_2 infrastructure **(policy gap)**.

10.3.3 International cooperation

While an in-depth assessment of needs, status and policy gaps in the EU's international cooperation fostering removals is beyond the scope of this report, the following three global aspects could guide future policy discussions: carbon leakage prevention, fairness of EU's contribution to global mitigation, and integrity of international trade in removal credits.

CO_2 removals can complement international climate policy by reducing carbon leakage and promoting greater cooperation. However, persisting free-rider incentives related to reduced climate impacts require a comprehensive approach, including climate clubs, technology sharing, and transfer payments, to stabilise cooperation and ensure global ambition.

International climate policy suffers from two fundamental cooperation problems: free-riding (i.e. some countries reap the benefits of reduced GHG emissions without contributing to the costs) and carbon leakage, stemming from unilateral emission reductions (Jakob, 2021; Tavoni and Winkler, 2021). Carbon leakage occurs when domestic mitigation leads to increased GHG emissions elsewhere, reducing the benefits of unilateral climate policy. This effect is well studied in the context of emissions reduction (see e.g., Grubb et al., 2022) but less so when removals deployment effects are considered. Edenhofer et al. (2024b) argue that removals do not directly affect fossil fuel prices, and that thereby they minimise leakage effects and enhance the effectiveness of unilateral climate efforts by individual countries. By reducing leakage, removals could emerge as a mechanism to strengthen international cooperation and increase the likelihood of broader participation in ambitious climate agreements (Franks et al., 2023). Without supply-side leakage in mitigation (see Box 9) or in high-cost scenarios, the potential of removals in enhancing international cooperation diminishes (Edenhofer et al., 2024b). Accurate estimates of carbon leakage are therefore fundamental for informing the international climate policy debate (Misch and Wingender, 2024), especially for net fossil fuel importers aiming to balance domestic benefits with global climate objectives. However, even if removals emerge as mechanism to enhance climate cooperation, they do not resolve all challenges in international climate policy. Incentives to free-ride on other countries' efforts persist, as avoiding climate impacts constitutes a public good. The literature outlines general proposals to address this issue. Coalitions, or "climate clubs", could be formed. These are broad groups of countries, implementing similar carbon pricing mechanisms and climate tariffs on free-riders and sharing technology among the club members (Edenhofer and Kalkuhl, 2024; Pihl, 2020). Launching coalitions helps reduce competitive disadvantages and leakage by creating a level playing field internationally (Ernst et al., 2023). International cooperation could be further stabilised through transfer payments via dedicated funds (Kornek and Edenhofer, 2020).

Box 9 Carbon leakage risks in the context of scaling up removals

Based on Franks et al. (2023), in the context of missing global uniform carbon price, two primary forms of carbon leakage can occur:

- Free-rider leakage: when a region unilaterally reduces its GHG emissions, it contributes to global climate benefits, such as reduced climate damages. Other regions, not bearing the costs of these mitigation efforts, may perceive a diminished urgency to reduce their own emissions, potentially leading to an increase in their emissions.
- Supply-side leakage: a unilateral reduction in fossil fuel demand by one region can lead to a decrease in international fossil fuel prices. This price drop makes fossil fuels more affordable elsewhere, potentially increasing their consumption in other regions.

Removals policies primarily address atmospheric carbon and do not directly influence fossil fuel markets. Consequently, removals subsidies are less likely to induce supply-side leakage than carbon taxes, which directly affect fossil fuel demand and prices. They do not eliminate free-rider leakage, however, or the implications for terms of trade between net fossil fuels importers and exporters. Carbon leakage could also occur also if removals-driven policy in one jurisdiction shifts land uses, increases unsustainable practices beyond its borders, for instance through biomass value chains, or both (see e.g., Chiti et al., 2024).

Source: Franks et al. (2023)

The EU needs to ensure fairness in its contribution to global mitigation through actions both within the EU and beyond its borders.

A fair contribution by the EU to global mitigation means that EU actions support the international balance of GHG emissions and help manage temperature overshoots (Advisory Board, 2023), as also explained in Chapters 1 and 5. This implies that the EU's incentives to removals are part of a broader set of measures that ensure an overall fair contribution by the EU and its Member States to the collective goals and commitments of the Paris Agreement (Advisory Board, 2023). These measures include EU finance, technical assistance, and capacity building outside the EU, on top of the EU's measures to achieve net-zero GHG balance within its own jurisdiction (Article 2 of the European Climate Law).

Partnerships and cooperative initiatives, such as those encouraged under the Article 6 (8) of the Paris Agreement, can advance the deployment of removals globally, promoting shared responsibility and equitable contributions to climate goals. By taking these actions and effectively communicating their purpose on the international stage, the EU can foster solidarity and shared responsibility in addressing climate change. In this respect, the EU could build on the existing cooperation frameworks for example environmental sustainability and climate change mitigation is one of the priority areas of the EU's partnership with the member states of the Organisation of African, Caribbean, and Pacific States (EU and OACPS, 2023). The EU's increasing its strategic capacity through coordinated domestic and international actions could reinvigorate the bloc's climate leadership in global diplomacy (Oberthür and Dupont, 2021).

The reporting and accounting of removals need to be harmonised at the international level; trade in removals credits under the Paris Agreement needs to maximise its positive spillovers while avoiding climate injustice.

Harmonisation of reporting is expected to come with the update to the UNFCCC framework through the upcoming IPCC methodologies for reporting removals in the national GHG inventories (IPCC, 2024). As for the GHG accounting, operationalising the Paris Agreement Crediting Mechanism (Article 6(4) of the Paris Agreement, see also Section 6.7) will play an important role given the mechanism is considered a reference point for harmonised, high-integrity international carbon markets (see e.g., G7 Carbon Market Platform; 2024). The resulting international trade in removals credits needs to maximise knowledge and technology spillovers and contribute to achieving other sustainable development goals (IPCC, 2022e) while avoiding climate injustice attributed to equivalence between GHG emissions and removals across different locations, that is across geographies with different biophysical and socio-political characteristics (Carton et al., 2021).

10.4 Summary of EU policy assessment

Table 21 below summarises the policy assessment carried out in this chapter, by providing an overview of the status and gaps. For the latter, it uses the same typology of gaps as used in its 2024 report 'Towards EU climate neutrality: progress, policy gaps and opportunities' (Advisory Board, 2024).

Table 22 Summary of the EU policy assessment of Chapter 10

Policy	Status	Gaps and inconsistencies
Governance Regulation	Sets out rules for the NECP process, which covers the planning, monitoring, and reporting of climate policies and measures. The process involves Member States and the European Commission, public consultations and stakeholder dialogues. Requires NECPS and Long-Term Strategies to be consistent with each other and developed through transparent and participatory processes.	Cross-sectoral interdependencies, such as the links between energy, biodiversity, and LULUCF policies are not yet sufficiently reflected in NECPs. → **implementation gap** The link between NECPs and long-term strategy is insufficient. → **ambition gap** Insufficient multi-level stakeholder dialogue. → **implementation gap**

Policy	Status	Gaps and inconsistencies
European Climate Law	Sets out EU climate objectives, including the EU's commitment to aim to achieve net negative emissions after 2050. Requires the European Commission to engage with sectors that choose to develop net-zero roadmaps.	No or very limited policy narrative and governance to plan for or guide the EU's transition beyond net-zero. → **ambition gap** To date several roadmaps have been developed, but their impact is uncertain as their development is voluntary and they are only indicative. → **ambition gap**
EU ETS directive	Sets out the governance of the EU's GHG emission cap and trade	Does not cover of removals. → **policy gap**
LULUCF regulation	Rules and governance enabling LULUCF sector contribution of EU GHG emission reduction targets until 2030	Does not provide any clarity for the period after 2030. → **policy gap**
CRCF regulation	European Commission develops removal certification methodologies through delegated acts. Methodologies are under development by the expert group	Unclear if public consultation and the climate neutrality check will be applied to the methodologies in the delegated acts. → **implementation gap**
RED II/III	Sustainability and GHG saving criteria for biomass use in energy supply with certification scheme.	Implementation deficiencies in certification (e.g. delays, fraud). → **implementation gap**
TEN-E, electricity and gas directives	Establish market rules and govern long-term planning and development of energy and CO_2 infrastructure. Establish mandates for electricity and gas transmission system operators' legal representation.	No mandate or legal representation of CO_2 transmission system operators, no regulatory oversight of CO_2 infrastructure development at EU level. → **policy gap**
Just Transition Mechanism and Fund	Support to just transition regions in shared management between the Member States and the European Commission, requiring broad partnership with local partners and stakeholders. Working groups insight support the overall mechanism.	Does not yet address the transition to net-negative, nor does it directly tackle the scale up of removals. → **ambition gap** Insufficient partnerships in some cases. → **implementation gap**

Policy	Status	Gaps and inconsistencies
Other	Several EU level entities dedicated to climate innovation in general, without a specific focus in removals.	EU entities supporting climate innovation have so far had a limited focus on accelerating innovation of removals . → **ambition gap**

Part C – Policy instruments: a dynamic approach to integrating removals into the EU's climate policy framework

The policy gaps identified in Part B of this report are summarised in Table 23 below, for each of the seven governance functions. Part C identifies, assesses and compares options to address some of these gaps, focusing on incentive instruments for net-zero emissions, net-negative emissions and temporary removals, while considering the need to fulfil all governance functions to manage opportunities and risks.

Table 23 Policies assessed for gaps and inconsistencies across governance function chapters

Policy	Policy gap	Ambition gap	Implementation gap	Policy inconsistencies
Managing the GHG budget				
European Climate Law	■			
EU ETS directive	■			
Effort sharing regulation	■			
LULUCF regulation	■		■	■
Net-Zero Industry Act	■			
Maintaining fiscal sustainability and distributional fairness				
Recovery and Resilience Facility	■			
Multiannual financial framework		■		
Other	■		■	
Ensuring the quality of removals				
EU ETS directive		■		
Governance regulation/LULUCF regulation		■		
CRCF regulation	■	■		■
Better regulation			■	
Managing land resources and climate risks				
LULUCF regulation			■	
RED II/III		■		
CRCF regulation		■		
Industrial emissions directive	■			
Governance regulation			■	
Common agricultural policy	■	■	■	
Soil Monitoring and Resilience Law	■			
Forest Monitoring Law	■			
Birds and habitats directives			■	
Other	■			■
Accelerating innovation and raising public awareness				
Horizon Europe		■		
EU ETS Innovation Fund		■		
Other			■	
Planning and developing the EU's CO_2 infrastructure				
Net-zero industry act	■	■		
TEN-E regulation		■		

CCS directive	■	■	■	
Energy efficiency directive		■		
Other	■			
Enhancing institutional governance				
Governance regulation		■	■	
European Climate Law		■		
EU ETS directive	■			
LULUCF regulation	■			
CRCF regulation			■	
RED II/III			■	
TEN-E, electricity and gas directives	■			
Just Transition Mechanism and Fund		■	■	
Other		■		

Note: This table groups specific policies with their associated directives and delegated acts. The definitions of gaps' categories can be found in the introduction of Part B of this report.

11 Options to incentivise removals towards climate neutrality

- **Removals can be incentivised in multiple ways.** The scientific literature highlights several possible instruments to incentivise removals. These include the integration of removals into pricing systems, the use of separate mandates or takeback obligations, and the provision of subsidies and public procurement. These instruments could be implemented in parallel or at different times.
- **Three main models exist for integrating removals into the EU ETS.** In the literature, these proposals generally follow three broad models:
  - direct, unconstrained integration, whereby entities can use removal credits as an alternative to emission allowances without any restrictions;
  - integration with supply and demand controls, whereby the use of removal credits under the EU ETS would be subject to quantitative, qualitative or other types of restrictions; and
  - integration via an intermediary institution, whereby that institution purchases credits from removal projects, and then manages the supply of these credits to the EU ETS.
- **Providing or funding removals can be enforced with direct obligations.** Removal mandates and takeback obligations would require entities to remove or contribute to removing a certain share of the greenhouse gases they emitted. This requirement could be imposed either on the emitting entity or upstream in the value chain (i.e. on fossil fuel producers or importers). Such mandates could start at a low rate but progressively increase over time.
- **Removals can be subsidised or purchased through public funds.** Subsidies, fiscal incentives and public procurement could be used to channel public funds towards the development and deployment of removals. Such instruments are specifically considered in the context of early commercialisation, but their continued use for large-scale deployment of removals is also possible.

11.1 Typology of instruments

Various policy instruments have been outlined in the scientific literature for managing and incentivising removals to reach net-zero emissions.

Various proposals and typologies of instruments to create incentives for removals can be found in the literature. While there are different ways to categorise these (Honegger, 2023; Hickey et al., 2023; Sultani et al., 2024) for other examples of typologies, instruments for removals can be broadly categorised in several groups:

- **GHG pricing instruments:** introducing removals into pricing instruments, using the GHG price signal as the main mechanism to create demand and incentives for removals. These can be price-based, such as a Pigouvian carbon tax and subsidies; or quantity-based, with the integration of removals into a cap-and-trade system such as the EU ETS.
- **Mandates and takeback obligations:** quantity-based instruments that create a mandatory obligation for actors to physically remove greenhouse gases, or to contribute financially to removals. If the mandates and takeback obligations are placed on fossil CO_2 producers or

emitters, these are generally calculated in proportion to the emissions they or their products generate.

- **Subsidies and public procurement:** separate funding or financial incentives provided by governments to bodies that deploy removals, through public procurement or partial market deployment subsidies and fiscal incentives aimed at reducing costs. These can also be used in both price- and quantity-based settings.
- **Information instruments:** creating indirect incentives to provide removals, generally in the voluntary markets through improved information, labelling and quality assurance. Robust information instruments such as certification systems are also minimum preconditions for the implementation of other price- and quantity-based instruments. As these instruments are primarily covered in Chapter 6, they are not evaluated further in this chapter.
- **Other indirect incentives and instruments**: other instruments can create or facilitate indirect incentives for removals, such as through investment in enabling infrastructure and innovation policies. These are not elaborated further in this chapter but are instead elaborated in their Chapters 8 and 9.

Table 24 provides a summary of the three main categories of instruments to create direct incentives for removals. Within these three categories of instruments, there are many additional variants, examples and specific proposals found in the literature, as indicated in Table 24 below. It should be noted that these instruments are not always mutually exclusive: some can be combined and layered simultaneously, and, while others may have conflicting or diluting effects, they may still be part of a dynamic policy mix (see Section 14.3).

As explained in Section 4.2.1, the EU currently lacks clarity on how to balance the overall contribution of emission reductions and removals towards climate neutrality. There are two broad ways that policymakers can shape this balance within the overall climate policy framework: a 'target-led' approach, where policymakers determine the balance between emission reductions and removals directly by setting separate targets; or a 'price-led' approach, where policymakers create price signals for reductions and removals, allowing market mechanisms to determine their exact balance towards the overall climate neutrality objective. The analysis concluded that a combination of these approaches – with minimum targets for removals, maximum limits on their contribution towards net emission reduction targets, and price signals to determine the balance between these boundaries – could have advantages in terms of cost-effectiveness, while helping to avoid mitigation deterrence. These instruments described in Table 24 are also generally compatible with both target-led and price-led approaches, as described in their respective sections.

Furthermore, it should be noted that the literature often discusses these instruments in the context of a net-zero objective. As presented in Chapter 4, challenges associated with achieving net-negative emissions and with temporary removals require special consideration in how these instruments are designed and used. There are different ways that these instruments could be used and extended to achieve net-negative emissions to varying degrees of effectiveness, with variants of these instruments to achieve net negative are laid out in Chapter 12. For temporary removals, challenges in establishing equivalence, the need to manage and price reversal, and particular challenges for MRV in the LULUCF sector all require additional mechanisms to address these challenges. Mechanisms to account for these risks while incentivising temporary removals are elaborated in Chapter 13.

Table 24 Typology of instruments to incentivise removals

Category	Instrument *(type)*	Description	Variants and proposals
GHG pricing instruments	**Integration into a carbon tax system** *(price-based)*	Governments cover emissions and removals by setting a uniform carbon price, taxing emissions and rewarding removals at the same price.	
	Integration into cap-and-trade systems *(quantity-based)*	Governments set an overall net emissions target with a cap-and-trade scheme, with removals becoming an option (in some form) to achieve the market cap.	*EU ETS integration options:* • *Direct, unconstrained integration* • *Integration with supply and demand controls* • *Integration via an intermediary institution*
Mandates and takeback obligations *(quantity-based)*		Governments impose a mandate for emitters or fossil fuel producers to remove, or contribute to removing the equivalent of a certain share of their emissions.	• *Carbon takeback obligation upstream on fossil fuel producers* • *Downstream mandate on emitters*
Subsidies and public procurement	**Capital support and research, development and demonstration grants** *(price-based)*	Governments provide capital grants or loans for research, development or demonstration projects.	• *Research and development grants* • *Capital demonstration grants*
	Subsidies and fiscal incentives to support and complement market deployment *(price-based)*	Governments provide partial or full subsidies and fiscal incentives at fixed prices per tCO_2 removed.	• *Carbon contracts for difference* • *Feed-in tariffs* • *Tax and fiscal incentives*
	Public procurement *(quantity-based)*	Governments procure removals, meaning that they provide financial payments to actors that deploy removals.	• *Reverse auctions*

Source: Advisory Board, based on proposals and descriptions provided in Chapter 11

Sections 11.2 to 11.4 describe these instruments in greater detail, while the role and recommendations for information instruments and voluntary markets are described in Chapters 4 and 5.

11.2 Integration into the EU emission trading system

Price- and quantity-based GHG pricing instruments create a price signal that internalises the cost of emissions. Extending this price signal to removals could create new incentives for their deployment.

GHG pricing instruments play an important role in climate policies. By placing an explicit price on emissions, GHG pricing instruments force producers and consumers to internalise the social costs of their emissions, with well-functioning market mechanisms then enabling actors to identify and exploit the most cost-effective ways to reduce emissions in line with a given climate objective. For this price signal to function optimally, these instruments need to be combined as part of a policy mix, to address other market failures, technology support, social and distributional impacts, and carbon leakage (Advisory Board, 2024).

Just as GHG pricing instruments create a price signal to internalise the cost of an emission, the possibility of extending the same price signal to incentivise removals (in some form) has featured heavily in the literature (Burke and Gambhir, 2022). The mechanisms for doing this can differ depending on whether the instrument is based on price or quantity (Edenhofer et al., 2024a):

- With a price-based instrument (i.e. a carbon tax), the government levies a fixed price per emission and allows quantities to fluctuate based on supply and demand. Extending the same approach to removals, governments could extend this price signal to reward removals at an equivalent rate as the tax, using carbon tax revenue to provide subsidies for removals[31].
- With a quantity-based instrument (i.e. a cap-and-trade scheme), the government fixes the 'cap' or overall quantity of net emissions allowed in the economy, allowing prices instead to fluctuate based on the supply of and demand for tradeable emission allowances. Here, removals could generate a new type of credit that can be used to counterbalance residual emissions under the overall market cap.

With the EU ETS as the only explicit EU-wide GHG pricing instrument in operation, several proposals have explored the possible integration of removals into this system as an incentive, and as a way to maintain the viability of the system as the cap approaches zero.

In the European context, various proposals have focused on leveraging the EU ETS to create new incentives for removals, albeit under different models and governance structures (Sultani et al., 2024; Edenhofer et al., 2024a; Rickels et al., 2021, 2022; Fridahl et al., 2023). This focus reflects practical considerations, not least because the EU ETS is currently the only explicit EU-wide GHG pricing instrument in operation. As noted in Chapter 5, it also reflects the tendency of the EU to favour quantity-based environmental policy instruments; largely due to the limited size of the EU budget and the requirements for unanimity among Member States to implement taxation measures. In particular, this dynamic also affected the original decision to establish the EU ETS, after previous unsuccessful attempts to establish an EU-wide carbon tax (Delbeke, 2024). Similarly, the EU's climate architecture is largely governed on the basis of quantity-based targets, for which quantity-based instruments such as the EU ETS can more effectively guarantee target compliance (Goulder and Schein, 2013). Given this, the analysis in this section focuses on different models for EU ETS integration, and the option of introducing a price-based carbon tax is not explored any further.

Integration of removals in the EU ETS has also been highlighted as a way to secure the long-term viability and stability of the EU ETS as the system's cap approaches zero. Under current legislation, the emissions cap for stationary installations under the EU ETS is projected to reach zero by 2039, and the cap for aviation activities would reach zero by 2045, marking the system's end-game phase. However, as described in Chapter 1, some residual GHG emissions are likely to persist until at least 2050 in sectors that are – or are expected to be – covered by the system. The combination of persistent residual

[31] Another possibility noted by Hickey et al. (2023) is to allow companies to offset their tax liabilities through purchasing approved removal projects, such is the case in Colombia's carbon tax system.

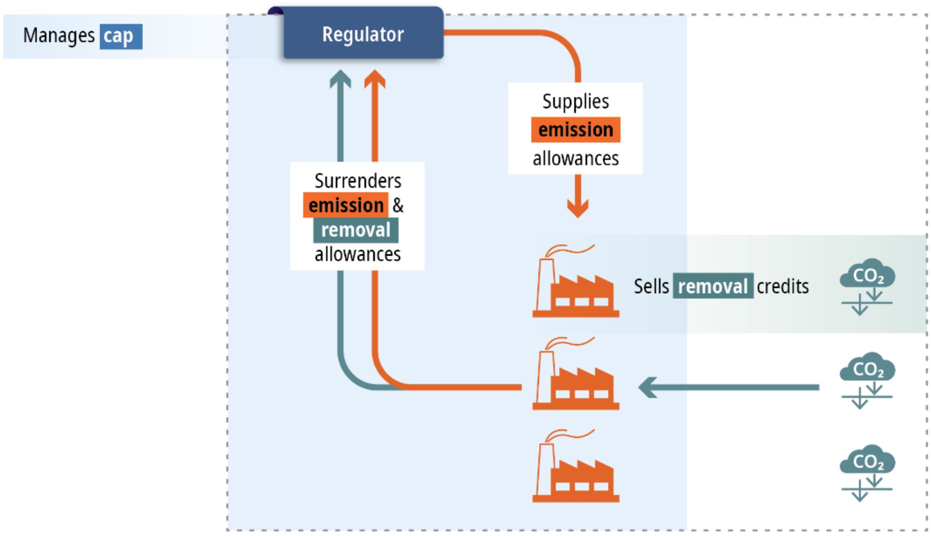
emissions and a cap that is quickly approaching zero (and could even become negative thereafter) presents significant uncertainties for future market stability. Pahle et al. (2023) highlight the risk that this combination creates a highly volatile market, with substantial price spikes that has the potential to jeopardise political acceptance of the EU ETS to achieve EU climate objectives. The Advisory Board has also called for an urgent discussion on the future of the EU ETS to address these uncertainties and the future viability of the EU ETS, among the options could be the inclusion of removals as a way to compensate for any remaining emissions as the cap approaches zero (Advisory Board, 2024). The latest revision of the EU ETS directive requires the European Commission to report in 2026 on the potential inclusion of removals (EU, 2003).

Options for integrating removals into an ETS like the EU ETS generally fall under one of three conceptual governance models, based on a framework developed by La Hoz Theuer et al. (2021): direct, unconstrained integration (described in Section 11.2.1), integration with supply and demand controls (described in Section 11.2.2) and integration via an intermediary body or institution (described in Section 11.2.3).

11.2.1 Direct, unconstrained integration

Direct, unconstrained integration of removals would allow emitters to purchase and use removals to counterbalance their emissions within the overall EU ETS cap, without limits or restrictions. Assuming the existence of a certification scheme for removals, this conceptual model of direct and unconstrained integration of removals would allow firms under the EU ETS to freely purchase and surrender removal credits as an alternative to surrendering an emission allowance, with no restrictions on the types of removals, volumes or sectors (see Figure 28). While all options are evaluated in more detail in Chapter 14, it should be emphasised at this stage that this is generally not considered a viable proposal due to its risks of mitigation deterrence, environmental externalities and unmanaged reversals of temporary removals, as presented in Chapters 4 and 14.

Figure 28 Model 1: direct, unconstrained integration of removals into an ETS



Source: Advisory Board, adapted from models described in La Hoz Theuer et al. (2021)

11.2.2 Integration with supply and demand controls

Integration with supply and demand controls could enable EU ETS entities to purchase and use removals to counterbalance residual emissions directly, but subject to specific restrictions imposed by regulators.

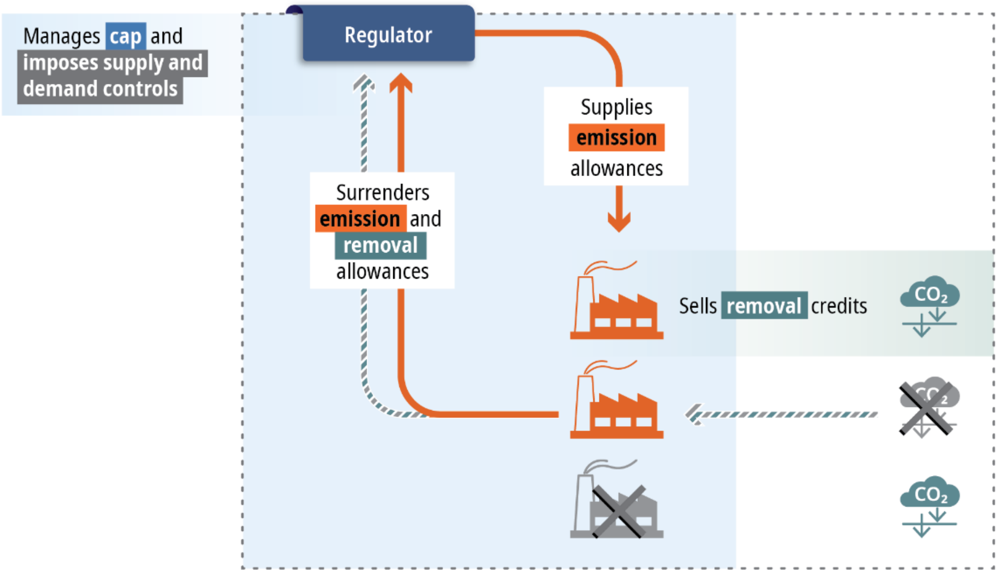
This model incorporates additional restrictions and controls that generally aim to reduce mitigation deterrence and other environmental risks by limiting excessive deployment of removals, their use in specific sectors or applications, or imposing sustainability limits on specific methods. Common options for supply and demand controls highlighted in the literature include the following:

- **Temporary removal limits or exclusions**. Due to the risks associated with temporary removals (see Chapters 3 and 4), many proposals recommend the exclusion of temporary removals from emissions trading schemes such as the EU ETS, and that only permanent removal methods be used to counterbalance residual fossil CO_2 emissions in carbon markets (Schuett, 2024; McLaren et al., 2019; Burke and Schenuit, 2023). Others argue that the integration of temporary removals may be possible, but conditional on strict and robust mechanisms to address MRV challenges and manage reversal (Sultani et al., 2024). Others argue that the integration of temporary removals may be possible, but conditional on strict and robust mechanisms to address MRV challenges and manage reversal risks (Sultani et al., 2024). Options for temporary removals and mechanisms to manage reversal are considered in Chapter 13.

- **Quantity limits**. To reduce mitigation deterrence and manage market expectations regarding the contribution of removals towards meeting the net emissions cap, limits could be implemented as a supply-side cap on the overall quantity of removals allowed in the ETS. Limits could also be imposed on the demand side by setting a maximum share of a firm's emissions that can be counterbalanced by removals (UK Government, 2024). Some authors suggest, further, that demand-side limits could be tailored to specific sectors or activities with high levels of residual emissions (i.e. focused on those deemed to have no or limited mitigation alternatives), rather than relying on the carbon price signal alone to do so (Ecologic and Oeko-Institut, 2023a; Rickels et al., 2021).

- **Sustainability limits and conditions**. Specific limits or conditions could apply to any removal methods whose large-scale deployment is likely to create negative environmental spillovers, particularly BECCS (see Figure 29).). This can take the form of quantity caps (as above), or more targeted measures. For instance, several authors have suggested the possibility of prioritising or restricting BECCS to existing installations or those that operate on residual biomass waste sources (Rosa et al., 2021a; Sultani et al., 2024; Ecologic and Oeko-Institut, 2023a). Others have highlighted broader reform of bioenergy and biomass policies in the EU as a necessary preconditions for any expansion of bioenergy applications, including BECCS (Faaij, 2022) (CONCITO, 2023). These issues and options relating to biomass are described in greater depth in Chapter 7).
- **Adjustments to emissions caps**. Rules on managing the emissions cap, such as withdrawing a certain number of emission allowances for every removal credit supplied to the market. This would limit the use of removals to facilitate a higher level of gross emissions (Burke and Gambhir, 2022).

Figure 29 Model 2: direct integration of removals into an ETS with supply and demand controls



Source: Advisory Board, adapted from models described in La Hoz Theuer et al. (2021)

Notes: Figure is intended to illustrate possible ways that a regulator could manage supply and demand. However, the specific quantitative and qualitative restrictions can differ between proposals.

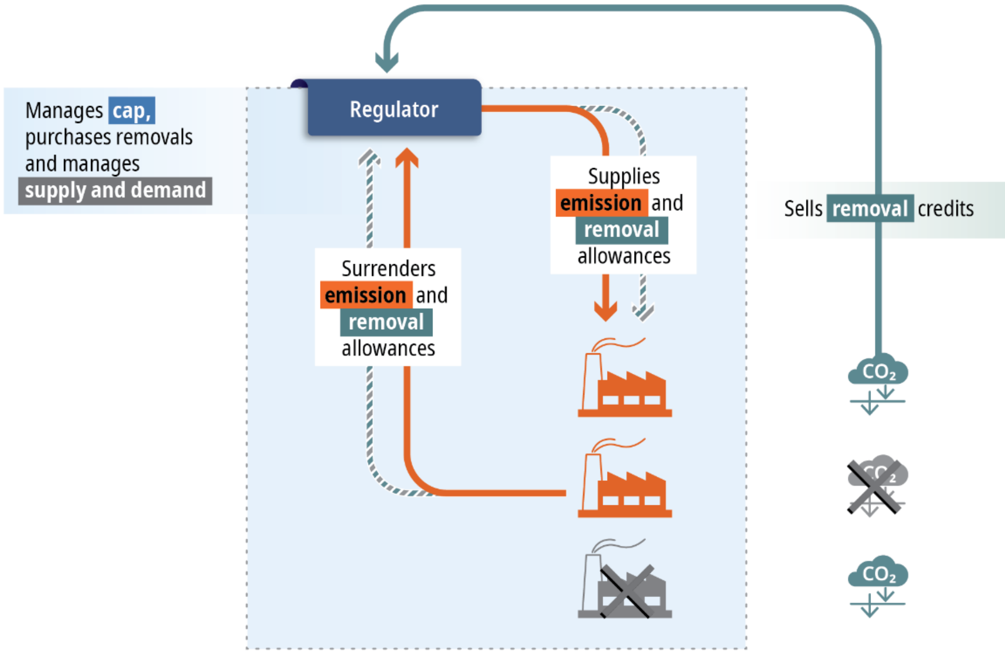
11.2.3 Indirect integration via an intermediary

Removals could also be integrated into the EU ETS indirectly, through an intermediary institution acting as a bridge between the removal and emission trading markets.

Instead of allowing removal companies and emitting companies to trade directly, an institution or institutions could be established or designated to act as an intermediary[32] between removal and emissions trading markets (see Figure 30). This intermediary would organise the purchase of removals, translate these into removal credits in accordance with established equivalence and fungibility rules, and then supply these credits into the market as a (generally limited) option to counterbalance residual emissions by activities covered under the overall market cap (La Hoz Theuer et al., 2021). While their role in managing the supply and demand of removal credits would allow the intermediary to impose any similar supply and demand controls to those described above in Section 11.2.2, it also implies a more dynamic and discretionary approach to managing these restrictions, with greater flexibility to adapt over time compared to one where these restrictions are implemented through static or rule-based demand and supply controls (Rickels et al., 2022; Sultani et al., 2024).

[32] This section refers to the broad role of an intermediary institution, although the specific institutional setup differs between proposals. In proposals for the European context, this role is often described as being fulfilled by the European Commission or similar agency as an extension to their role of managing the EU ETS; or alternatively by a newly-established '(European) Carbon Central Bank' (Edenhofer et al., 2024a; Fridahl et al., 2023; Meyer-Ohlendorf, 2023; Rickels et al., 2022). Specific institutional questions are addressed in Chapter 10.

Figure 30 Model 3: indirect ETS integration via an intermediary



Source: Advisory Board, adapted from models described in La Hoz Theuer et al. (2021)

Notes: Figure is intended to illustrate possible ways that a regulator could manage supply and demand. However, the specific quantitative and qualitative restrictions can differ between proposals.

One key difference from other models is that by having the intermediary (rather than individual firms) responsible for purchasing removals, demand and funding for removals is not strictly dependent on the prevailing carbon price. Several proposals under this model envisage the intermediary body taking an active role in developing development of an initially-separate removals market, by launching advance purchase programmes for high-cost emerging removal methods. Additionally, this gives the possibility of tailoring these supports to prioritise specific policy objectives (e.g. develop a diverse portfolio, reduce sustainability risks, ensure regional balance) (Edenhofer et al., 2024a; Rickels et al., 2021, 2022). The intermediary would then decide on the timing and volume of integration of removals into the ETS market. This leaves the possibility of supplying removals immediately into the market, gradually over time, or holding them in reserve until specific conditions are met. For instance, Sultani et al. (2024) propose that an intermediary would gradually integrate removal credits into the EU ETS by setting specific entry conditions for specific removal methods (i.e. DACCS, BECCS), depending on their unique governance, sustainability challenges, etc.[33] Expanding on this concept of advance purchase programmes, Rickels et al. (2022) also propose that rather than supplying any purchased removal credits to the EU ETS market immediately, an intermediary could instead build up a reserve of credits. They outline how this could replace the existing market stability reserve[34] as the main mechanism to promote price stability in the EU ETS, meaning that removal credits would only be released onto the market

[33] This proposal is discussed in greater detail in Chapter 14, in relation to the literature on sequencing.

[34] The Market Stability Reserve is a quantity-based mechanism that is used to adjust the total number of emission allowances in circulation (TNAC). In general terms, when the TNAC is above a defined threshold in a year, a share of the auction volume for the next year is transferred to the Market Stability Reserve, and vice versa if the TNAC falls below a defined threshold (Rickels et al., 2023).

conditionally if ETS prices became especially volatile or exceeded pre-defined price pathways (Rickels et al., 2022).

An intermediary institution could also play a role in managing and enforcing long-term liabilities associated with removals. Edenhofer et al. (2024a) highlights the need for institutions to manage long-term liabilities created by temporary removals (i.e. to continually replace removals that have been reversed), and argues for management and enforcement of these liabilities to be enforced by an intermediary institution. Given the limited liability of firms (i.e. the possibility of going bankrupt and avoiding these liabilities), Lessman et al. (2024) elaborate the potential for a similar institution to introduce 'clean-up certificates' as a way to enforce an intertemporal carbon debt, in the context of allowing net-negative emissions within an ETS. Specific options and instruments for net negative are addressed in Chapter 12, while options and instruments for temporary removals are presented in Chapter 13.

11.3 Mandates and takeback obligations

Separate mandates to provide or purchase removals could be applied to individual fossil fuel producers and importers, or as additional obligations on emitters.

Models for integrating removals into GHG trading systems rely on the price signal to influence the volumes of CO_2 that are abated or compensated for with a removal (before net zero). Governments could also manage this balance directly by imposing mandates or quotas on individual firms. Proposals for removal quotas generally draw on the principles of extended producer responsibility commonly found in other sectors (e.g. electronics), whereby producers or retailers are given a legal responsibility to contribute to the collection and treatment of the waste they generate. Similarly, producers or users of fossil carbon could be legally required to clean up the CO_2 'packaging' that accompanies the energy they sell, with mandates to provide or purchase removals equivalent to a certain percentage of the emissions from the products that they sell (Jenkins et al., 2021).

One way to impose these mandates is upstream on fossil fuel producers and/or importers of fossil carbon products[35]. Jenkins et al. (2021, 2023) propose a carbon takeback obligation that would require these producers to simultaneously provide or purchase removals corresponding to an increasing share of the emissions generated from their products. They note the low administrative burden by imposing obligations on primary extractors of oil, gas, limestone etc., but also highlight the possibility of applying this obligation as a carbon border adjustment aimed at addressing carbon leakage from imported products. The EU's Net-Zero Industry Act already imposes a similar obligation for oil and gas producers to contribute to developing CO_2 injection capacity on a proportional basis according to their 2020-2023 production levels, although not specifically for removals, and without the requirement to actually use this capacity (EC, 2024s).

Alternatively, mandates could be imposed downstream on emitters. For example, the proposed Californian Carbon Removal Development Act would require entities already covered by its cap-and-trade system to purchase negative emissions credits as an increasing share of their emissions each year (Meyer-Ohlendorf, 2023). In this case, these are proposed as *additional* and *separate* obligations to the need to surrender emission allowances to cover their residual emissions under the cap-and-trade system (Lebling and Riedl, 2023). However, if applied as a separate obligation on companies already covered by the EU ETS, this could constitute a form of double regulation.

[35] In Jenkins et al.'s (2021, 2023) proposal they note that the takeback obligation could also apply to primary extractors of limestone for cement products etc.

In both proposals, the percentage of emissions that must be met with a removal would increase over time. For instance, entities in the California proposal would be required to purchase removals equivalent to 1% of their emissions in 2030, 8% in 2035, 35% in 2040 and 100% in 2045 (Meyer-Ohlendorf, 2023), with a similar trajectory modelled for the carbon takeback obligation (Jenkins et al., 2021, 2023). To provide an initial flexibility option, the California proposal also would allow emitting entities to meet their obligations in two phases: firstly by purchasing a temporary removal credit, with a binding commitment to later purchase a permanent removal credit following the expiration of the guarantee period (Meyer-Ohlendorf, 2023).

11.4 Subsidies and public procurement

Governments could subsidise or purchase removals, either as a complementary measure to support integration into carbon markets, or as the primary driver of demand.

This group includes a range of instruments that governments could use to subsidise or purchase removals, including capital grants, reverse auctions, and feed-in tariffs and tax incentives, as shown in Table 25 below. While the advantages and disadvantages of these instruments will be considered in greater depth in Chapter 14, these instruments have been highlighted and used in several contexts, including to support the deployment of removals in voluntary markets, to complement their integration into wider carbon markets, or to finance large-scale deployment of removals.

Table 25 Examples of market deployment subsidies and public procurement instruments

Subsidy type	Description	Example or proposal
Reverse auctions *(quantity-based)*	Removal projects submit competitive bids to receive public subsidies per tCO_2 removed under long-term government contracts. The lowest-priced bid (EUR per tCO_2) is successful, and receives a fixed subsidy at this winning rate (Lundberg and Fridahl, 2022).	Sweden's proposed reverse auction system for BECCS, approved by the European Commission in July 2024, will offer a total of EUR 3 billion in state funding via a series of reverse auctions to be held in 2024-2028. Successful BECCS projects will receive subsidies per tonne of CO_2 removed under 15-year contracts (EC, 2024d).
Carbon contracts for difference *(price-based)*	Like reverse auctions, projects bid for long-term government contracts. However, the winning rate ('strike price') is a price guarantee rather than a fixed subsidy: the government pays top-up subsidies if project revenues (e.g. from carbon markets) fall below this strike price, but any surpluses above this price are paid back to the government (Clean Air Task Force, 2024a).	Several Carbon contracts for difference schemes have been established in European countries, including the Danish CCUS Fund, the UK's Industrial Carbon Capture contract, and the Dutch sustainable energy production and climate transition incentive scheme. These provide support for a wide range of carbon management and CCS technologies, with criteria that balance performance, cost-effectiveness and other criteria (Clean Air Task Force, 2024a).
Tax credits *(price-based)*	Removal companies reduce their tax liabilities by a fixed rate per tonne of CO_2 removed (Hickey et al., 2023).	The 45Q tax credit in the USA offers a credit of USD 180 per tonne of carbon captured and geologically stored from DACCS. Recipients must repay any amounts received in the event of reversal (Hickey et al., 2023).

Source: Advisory Board

In addition to funding for early-stage research, development and demonstration (see Chapter 8), many of these instruments have been highlighted as having a distinct role in supporting the early-stage scale-up of emerging technologies, where promising (but commercially not yet viable technologies) struggle to attract investments in commercial settings, often referred to as the 'valley of death', (Nemet et al., 2018a; Anadón et al., 2022). Many proposals for removals would use subsidy and procurement instruments in a similar context, aimed at promoting early deployment and accelerating cost reductions through experience-based learning. In some proposals, this stage is explicitly intended to facilitate or complement their integration into wider carbon markets. Several authors have drawn parallels with the experiences of the European power sector, where governments successfully used instruments such as feed-in tariffs, contracts for difference, reverse auctions etc. to bring down the costs of renewable energy technologies through learning and scale effects, and gradually make their integration into EU energy markets more viable (Lundberg and Fridahl, 2022; Burke and Gambhir, 2022; Honegger et al., 2021b). For example, Lundberg and Fridahl (2022) similarly propose the use of state-led reverse auctions as an 'interim' measure aimed at supporting the development of emerging removal methods, and potentially their future integration into carbon markets. When used in this context, many of these proposals assume that subsidies and public procurement would be gradually phased out as technologies become more mature and commercially viable (Dolphin et al., 2023).

However, other authors have argued for the continued long-term use of these instruments at a larger scale, focused on directly procuring removals as a public good rather than just supporting their integration into carbon markets. These arguments often accompany proposals to manage the volumes of removals using separate targets (see Chapter 4). For instance, Grubert and Talati (2024) argue for a publicly funded and publicly accountable removals sector, where governments would procure removals based on government-established separate removal targets. Similarly, Nawaz et al. (2024a) propose the establishment of 'national removal administrations', with a long-term mandate to develop removals capacity in line with government climate, social and environmental objectives.

12 Options to incentivise removals for net negative

- **Transitioning from net zero to net negative presents challenges for conventional incentive instruments to manage the GHG budget.** However, subject to specific design features aimed at overcoming long-term commitment and enforcement challenges, many of these instruments described in Chapter 11 could also be used to incentivise net-negative emissions.
- **Current emitters could contribute to removing their CO_2 in the future.** Recent literature has identified a range of options for instruments to introduce and enforce an extended emitter responsibility, which when used, would assign a responsibility to current emitters to provide or pay for removals at a future time.
  - These options could be implemented as an extension to the EU ETS (through clean-up certificates), or as a broader form of intertemporal mandate or takeback obligation (through removal obligations or atmospheric CO_2 removal deposits).
  - The main challenge of such approaches is to ensure that entities covered comply with their future removal obligation. To address this, all options include enforcement mechanisms sharing some common features, although differences in their design and governance architecture require careful consideration.
  - A common characteristic of these different options is that, the earlier they are introduced, the greater is their ability to generate net-negative emissions under the remaining GHG budget. While careful deliberation is necessary, timeliness will also influence the effectiveness of these instruments.
- **Net-negative emissions may require public funding.** In addition, subsidies, fiscal incentives and public procurement could be used to deliver net-negative emissions. To finance these instruments, the EU could begin to set aside public funds today, or rely on future public income, with different implications for fiscal sustainability and intergenerational fairness.
- **Different instruments can co-exist.** These different instruments are not mutually exclusive and could be implemented in parallel. An assessment of their respective strengths and weaknesses is included in Chapter 14.

12.1 The challenge of transitioning from net zero to net negative

As many proposals for instruments to incentivise removals have been mainly designed to achieve a net-zero objective, the transition to net negative creates additional challenges in generating and sustaining sufficient incentives.

Chapter 11 described the main groups of policy instruments that could be put in place to incentivise the deployment of removals, with a focus mainly on how they would be used to counterbalance residual emissions to achieve and maintain net-zero emissions. As typically described in the literature, those instruments – particularly integration into an ETS, and mandates and takeback obligations – generally rely on simultaneous links between emissions and incentives for removals: that is, at a certain time, the level of emissions generates sufficient incentives or funding to provide an equivalent level of removals needed to counterbalance these emissions at the same time. Once net-zero emissions are achieved, extending these instruments directly to achieve a net-negative objective is possible in principle without significant changes, but in practice, could become increasingly challenging to implement and sustain as time goes on. Examples follow:

- **Integration into the EU ETS.** Regulators could design a net-negative cap under the EU ETS, which would require firms that still have residual emissions after the date of net zero to deliver or finance *more* removals than strictly necessary to counterbalance their residual emissions (Rickels et al., 2021). This would be through the use of multipliers, i.e. for each tonne CO_2e of residual emission after this date, covered entities could be required to submit 2 tonnes CO_2e of removals at the same date (or at any similar ratio depending on the size of the net-negative cap).
- **Mandates and takeback obligations.** As a similar concept outside of an ETS, regulators could impose a net-negative mandate or takeback obligation on firms who still have emissions after the date of net-zero (or producers of fossil carbon), requiring these to remove more than strictly necessary to balance their residual emissions (or the emissions associated with the products they sell) after 2050. This would involve setting a removal fraction of greater than 100% (see Section 11.3).
- **Subsidies and public procurement.** Governments could procure additional removals on top of those required to counterbalance residual emissions. These removals could be financed by imposing additional levies or carbon taxes levies on any remaining residual emitters, or from general government budget.

However, the first two approaches (in particular) would place the entire effort of achieving net-negative emissions on a small number of residual emitters who continue to have no or limited mitigation alternatives. As the volume of residual emissions and number of firms and activities with residual emissions is gradually expected to fall in line with the EU's overall climate neutrality objective, this could make it increasingly difficult to sustain a large net-negative cap using these types of mechanism. Alternatively, trying to assign and enforce such obligations or taxes retrospectively (i.e. by identifying the historic emissions of specific firms) becomes increasingly challenging and unfeasible as time goes on, with firms' limited liability and general market turnover meaning that many firms and historic emitters will just cease to exist over the intervening period (Lemoine, 2020).

12.2 Incentives through extended emitter responsibility

New instruments based on the concept of an extended emitter responsibility may be needed to ensure that a broader group of emitters contributes to the financing of net-negative emissions.

To prevent the burden of delivering and maintaining net-negative emissions from being entirely pushed onto a small group of future residual emitters, and otherwise to society at large, recent literature has explored options to operationalise the concept of *extended emitter responsibility* (see Section 4.5.1), which has also been referred to by other authors as 'carbon debt' (Bednar et al., 2021; Lessmann et al., 2024) or a 'CO_2 emitters liability' (Lyngfelt et al., 2024). There are various contexts in which this concept can be applied, and the literature describes several options for instruments to assign and enforce this, such that those responsible for producing CO_2 have some direct responsibility for removing it from the atmosphere. In most cases, these have proposed as variants or extensions to instruments described in Chapter 11, but with specific mechanisms aimed at addressing enforcement and commitment problems. For instance, these instruments could be introduced as a new type of emissions allowance within EU ETS (e.g. Carbon clean-up certificates), or as an enforceable intertemporal mandates and takeback obligations (e.g. removal obligations or atmospheric CO_2 removal deposits). Box 10 below provide examples of proposals in the literature to operationalise an extended emitter responsibility.

Box 10 Examples of potential instruments to operationalise extended emitter responsibility for net negative

Atmospheric CO_2 removal deposits (Lyngfelt et al., 2024)

Atmospheric CO_2 removal deposits are a general concept for an instrument to operationalise extended emitter responsibility for net-negative emissions, and one that could be applied in different contexts (e.g. within or outside an ETS, as targeted obligations for certain sectors). This is described in the context of an early depletion of the global or regional GHG budget, where after that date, anyone that emits fossil CO_2 to the atmosphere would be obliged to remove at least an equivalent volume of CO_2 in the future. To guarantee this obligation, emitters would have to pay a financial deposit with a public institution, getting a deposit receipt in return. The public institution would hold these deposits, with the underlying value of the deposit receipt only refunded to the holder once they can prove a physical removal has taken place. The original emitters could also trade their deposit receipts on secondary markets, allowing other firms to claim the value of the deposit when the removal occurred. The authors describe how this could create a competitive market for removals, with removal firms vying to deliver cost-effective removals in order to claim the value of the deposits.

Carbon clean-up certificates (Lessmann et al., 2024)

Clean-up certificates follow a similar broad concept to atmospheric CO_2 removal deposits, but have been proposed as a new type of allowance that could be introduced and offered to emitters within an ETS. As above, these allowances would allow a covered entity to emit 1 tonne of CO_2, but would come with a carbon debt, to remove one or more tonnes of CO_2 in future (with the required amount of removals per tCO_2e emissions to be decided by the regulator). Emitters would be given the option to use clean-up certificates as an alternative to regular ETS allowances, which they might choose to use if they expected future removal costs to become lower than the price of regular ETS allowances at the time of the emission.

The potential impact of such certificates on the overall GHG budget under the ETS is determined by the regulator, who decides on the supply of clean-up certificates and to what extent this supply is combined with a withdrawal of regular emission allowances from the market. As clean-up certificates could be used as an alternative for regular ETS allowances and thus reduce demand for them, the regulator could decide to reduce the overall supply of regular emission allowances (through lower auctioning volumes) accordingly to prevent a temporary increase in overall GHG emissions under the ETS. When the emitter removed one or more tonnes of CO_2 in the future, the overall, cumulative volume of GHG emissions under the ETS would decrease.

Similarly to the approach above, firms would deposit a collateral with the regulator, which would only be returned to the holder of the certificate when the physical removal took place. In the event of default, the regulator would claim the collateral, acting as a 'lender of last resort'. Firms would also be allowed to trade clean-up certificates on secondary markets, helping to increase liquidity and to play a role in revealing market expectations regarding future removal costs.

Carbon Removal obligations (Bednar et al., 2023a)

Removal obligations are described as a compulsory instrument in the event that a given GHG budget is depleted, meaning that every emission beyond this point would come with a carbon debt that must be repaid with a physical future removal. This carbon debt would enter the emitter's balance sheet as a form of financial debt, issued by commercial banks. Emitters would be charged a 'base premium' on the debt, either as a one-off fee or as a series of regular interest payments, with the value determined by (monetary) central banks. The issuing commercial bank would also be able to charge additional commercial risk premiums (i.e. to reflect the relative risk of different 'borrowers'). This carbon debt would only be written off when the removal occurred. The responsibility for enforcing the debt and ensuring that removals are provided in the event of default would fall to commercial and central banks.

While these options differ in their specific design elements, they all rely on strong mechanisms and institutions to overcome liability and enforcement challenges.

While each of these approaches would work differently, they all face a similar challenge in enforcement, and ensuring that covered entities comply with their extended emitter responsibility. To overcome this challenge, the three options all share a broadly similar architecture based on four key elements:

- **A new type of allowance with extended emitter responsibility attached.** Compared to regular emission allowances or GHG budget concepts, this allowance would allow entities to emit one tonne of CO_2e but would come with a time-bound obligation to remove an equal or predetermined volume of CO_2 in the future. This would only be formally 'repaid' once a physical removal took place. As outlined in Section 4.5.1, and by Lessman et al. (Lessmann et al., 2024) with the example of 'clean-up certificates' in an ETS, the overall effect on the cumulative GHG budget depends on government and regulator decisions on the supply of regular emission allowances. If the regulator introduced clean-up certificates without changing the supply of regular emission allowances, the cumulative budget and ambition level would remain the same, but it would allow a higher level of gross emissions in the short-term to be balanced by a higher level of removals in the future. However, if the regulator simultaneously withdraws regular emission allowances, for the same level of gross emissions in the short-term, a greater level of removals in the future could be achieved, and therefore a lower cumulative budget. As further argued in Section 4.5.1, these decisions should primarily be with the aim of increasing ambition, which corresponds best to the second approach.
- **Financial instruments to underpin the emitter responsibility.** To address the risk that emitters will default on their obligation to provide or procure a removal in future, most options would require those emitters to make upfront payments to the issuing institution in the form of a 'collateral', 'deposit' or 'base premium' (Lessmann et al., 2024; Lyngfelt et al., 2024; Bednar et al., 2023b) .In most cases, this collateral would be refunded to the holder only once the physical removal took place. If the emitter defaulted on this liability (e.g. because of bankruptcy) the issuing institution would step in and claim the collateral to pay for the removals directly, effectively acting as a lender of last resort'to maintain the integrity of the system (Lessmann et al., 2024).
- **Institutional governance.** In all proposals, institutions are required to issue or assign the instrument, to determine and collect collaterals, and to enforce the responsibility over time. If introduced as part of an ETS, this would also include overall management of the cap (Lessmann et al., 2024). Given the potentially long time horizons of this liability, as well as mitigation deterrence and moral hazard risks (i.e. that emitters might willingly assume such liabilities, expecting that they might no longer be in operation when obligations are due), most proposals also see a strong role for public institutions in carrying out these functions, including possibly as a lender of last resort should the original holder default (Lessmann et al., 2024; Lyngfelt et al., 2024; Coffman and Lockley, 2017). In the proposal for a removal obligation, commercial banks would be tasked with issuance and enforcement, but under the supervision of financial central banks.
- **Secondary markets to allow trading of the instrument.** If backed by a financial deposit or collateral, these instruments could become an attractive asset for any firms that believe they are able to deliver removals at a lower cost than the value of the initial deposit. The development of secondary trading markets is a key aspect of some proposals to increase liquidity and reduce the effective costs paid by firms i.e. those that can immediately sell the collateral or deposit instrument, while also encouraging a competitive market among providers of removals trying to claim the value of deposits (Lessmann et al., 2024; Lyngfelt et al., 2024). Secondary market mechanisms could also have advantages in overcoming information asymmetries, by effectively forcing market actors and project developers to reveal their expectations of the future costs and potentials of removals. However, as with any financial asset, secondary markets present risks of bubbles or speculative

behaviour among market actors e.g. if the announcement of a speculative new technology leads to a significant shift in market expectations. Given the particularly uncertain trajectories of future removal costs, Coffman and Lockley (2017) highlight that any significant failure to accurately predict future removal costs in such markets could have systemic climate and economic impacts, with insufficient funds or removal capacity to deliver on the promised removals and widespread default on the extended emitter responsibility.

The ability and scale of these instruments to deliver net-negative emissions probably depends on their swift introduction: the earlier they are introduced, the greater the extent that emitters will contribute to future net-negative needs. However, specific proposals still raise open questions that require further consideration.

While these proposals provide a starting point to consider options for net-negative emissions, this field of scientific literature is developing rapidly, with several avenues for further research and analysis. As shown above Box 10, the different options identified so far differ in many aspects, including the circumstances in which an extended emitter responsibility should be considered, the way the costs are calculated, and the design of enforcement mechanisms and institutions. This highlights several open questions, and the need for further research and evaluation.

All of the options described would apply to remaining emitters, only after such an instrument or liability is reduced. However, the more progress the EU makes towards its climate objectives, the smaller the volume of remaining emissions is under the EU's GHG budget. Given the practical, legal and political challenges to imposing such requirements retroactively (i.e. long after an emission has taken place), their capacity to generate net-negative emissions through extended emitter responsibility therefore depends on the timing of the introduction of these instruments. The longer governments wait to introduce such instruments, the less able they are to deliver net-negative emissions (Lyngfelt et al., 2024).

12.3 Incentives through subsidies and public procurement

Even with the swift introduction of these instruments, public procurement of removals for net-negative emissions will probably be needed to some extent, raising important questions and challenges for long-term fiscal sustainability and intergenerational fairness.

Sultani et al. (2024) highlight that even if instruments to operationalise extended emitter responsibility are put into place, delivering sufficient removals to contribute to managing future global temperature overshoot will probably require additional funding sources. They point to the likely role of governments as the primary buyer of removals in a net-negative economy (Sultani et al., 2024) Funding future net negative removals through subsidies and direct state procurement is therefore likely to some extent, and current governments should start planning for.

To that end, the Netherlands Scientific Climate Council suggests that in addition to the specific instruments described above, the concept of a 'current emitter' for extended emitter responsibility should be understood in a broader sense, meaning that governments should begin to earmark some current tax revenues to create long-term investment funds for removals, similar to pension and national reserve funds (WKR, 2024). This possibility has also been noted in conceptual terms by other authors in the net-negative literature, but not explored in depth (Bednar et al., 2023b; Lyngfelt et al., 2024). Finally, public subsidies and procurement can also be financed by future public funds. Both approaches could require substantial volumes of public finance, and raise important ethical questions regarding historic responsibilities, intergenerational fairness and long-term fiscal sustainability. These issues are covered in greater detail in Chapter 14**.**

13 Options to incentivise temporary removals and manage reversal

- **Multiple options for temporary removals or storage are available.** Incentives for temporary removals (or storage) could be introduced through a range of possible instruments. So far, the EU has implemented a mix of targets, regulatory approaches and subsidies to reduce emissions and enhance removals in the LULUCF sector, but with limited effect. The Advisory Board has previously recommended that the EU consider instruments to price emissions and removals in the LULUCF sector.

- **These pricing models can be based on carbon fluxes or storage.** There are three conceptual models for pricing emissions and removals (or storage) from temporary sources, which have been largely considered in the context of the LULUCF sector:
    - 'upstream' pricing - rewarding removals without explicitly pricing emissions or subsequent reversal, instead of which rewards are discounted based on assumed storage duration, reversal risks and discount factors;
    - 'downstream' pricing - rewarding removals, but also requiring land managers to pay for any emissions or reversals at the same carbon price;
    - 'stock storage' subsidies - providing rewards based on the size of a carbon stock stored at a given point in time.

- **All pricing models face challenges in implementation.** Regardless of the approach taken, designing a GHG pricing instrument to cover emissions and temporary removals in the LULUCF sector would need to address and overcome several design and implementation challenges, primarily:
    - the need for robust MRV systems, including additional support and investments to help land managers adjust to new requirements;
    - the question of additionality; and the role of the instrument in incentivising additional removals, compared with protecting and enhancing existing sinks or carbon stocks;
    - the need for mechanisms to manage reversal risks in a way that promotes due diligence and accounts for the effects of future climate impacts.

- **The models can be integrated into the existing architecture.** There are also different options for how a new pricing mechanism could be integrated into the EU's climate policy architecture, particularly alongside other existing GHG pricing instruments. These could include:
    - integration of pricing systems – credits from temporary removals can be used in other GHG pricing instruments, such as the EU ETS or a potential future pricing mechanism covering the agriculture or agrifood sector;
    - revenue recycling - revenues from other GHG pricing instruments could be recycled into subsidising removal activities in the LULUCF sector; and
    - stand-alone policies – pricing instruments for the LULUCF sector are standalone, with no link to other existing or potential pricing instruments in other sectors.

13.1 Typology of instruments

Current EU policies to manage emissions and removals in the LULUCF sector have focused on regulatory approaches, targets and subsidies, but with limited effect. The Advisory Board has therefore previously recommended extending GHG pricing to the LULUCF and other sectors to incentivise emission reductions and to reward removals.

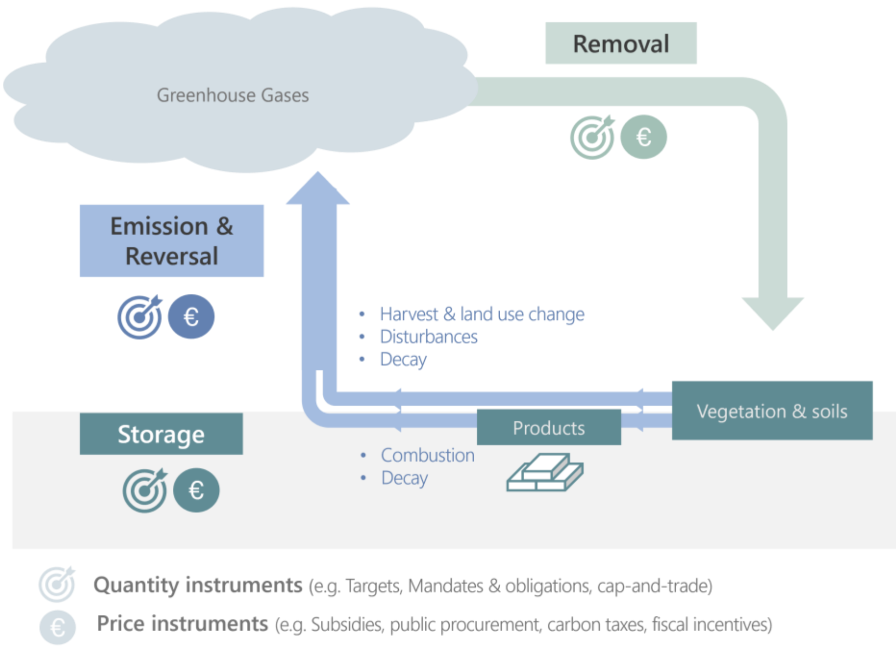
As described in Section 4.4.2, there is an urgent need for stronger policy incentives to halt and reverse the decline of the EU's LULUCF sink. To achieve this, a range of policy instruments could be put in place, which can be categorised along the same typology as used in Section 11.1:

- **GHG pricing instruments**. The EU could introduce new price- or quantity-based instruments in the LULUCF sector to price emissions/removals or carbon stocks. There is currently no EU-wide pricing of LULUCF emissions or removals, although there are several ways that this could be done, as described further below.
- **Mandates, regulatory approaches and targets.** The EU could put restrictions and mandates on land use (e.g. currently already done by EU biodiversity and nature policies, including the Timber Regulation and Nature Restoration Law), or set targets on the required volume of net removals (as done under the current LULUCF regulation, which sets such targets on Member States).
- **Subsidies and public procurement.** The EU could provide subsidies for temporary removals, which could be either action- or result-based. Current example of this approach are the eco-schemes and good agricultural and environmental conditions under the CAP, or forestry subsidy schemes as implemented in different member states. Alternatively, the EU could provide public financing through public procurement (e.g. via reverse auctions) of temporary removals.

Existing EU policies – which to date have mainly adopted regulatory approaches, targets and subsidies, as previously described in Chapters 4 and 7 - have not yet been sufficient to reverse the declining trend in the LULUCF sink, although Chapter 7 highlights opportunities and recommendations to protect and enhance existing sinks, and to manage pressures on biomass resources. Within this context, the Advisory Board has also recommended that the EU should expand its GHG pricing regime to cover all major sectors, including LULUCF, which should reward removals in some form. Pricing of emissions and removals in the LULUCF sector can contribute to a coherent policy framework for the land sector by balancing incentives in how land and biomass resources are used (Advisory Board, 2024).

There are several options for the design such pricing instruments, which as indicated in Figure 31 below, these can be based on CO_2 fluxes (emission and removal flows), or based on storage. These options are described in section 13.2. Section 13.3 will identify major design challenges and choices to address in any pricing system for temporary removals. In particular, as outlined in Sections 4.3.1 and 6.3, any use of temporary removals to counterbalance emissions requires careful management of equivalence, and a pricing system that incentivises temporary removals in these contexts also needs robust quantification, clear additionality and to account for the costs of reversal. However, these design elements can result in trade-offs that need to be carefully considered in the context of broader LULUCF policy objectives. Specifically, pricing mechanisms may need to strike a balance between prioritising activities that provide additional temporary removals on one hand, compared to those that protect existing sinks and carbon stocks on the other; two objectives which may not be fully satisfied by all options. Section 13.4 then describes different ways and options in which pricing mechanisms in the LULUCF sector could interact with other GHG pricing mechanisms at the EU level.

Figure 31 Policy interventions for temporary removals and managing reversal



Source: Advisory Board

Notes: Figure intended to be illustrative, and only activities directly related to removals are shown.

13.2 Pricing options for temporary removals

Pricing emissions and removals in the LULUCF sector can follow three conceptual approaches, described in the literature as 'upstream pricing' (discounted rewards for removals), 'downstream pricing' (pricing emissions and rewarding removals), or 'stock storage subsidies' (rewarding the carbon stock).

Pricing options to incentivise temporary removals or storage have been identified primarily in the context of forestry and forest management, although the mechanisms and principles can apply broadly to other temporary removal methods. One of the major challenges in pricing temporary removals or storage is accounting for the costs of reversal, where a lower typical storage duration of temporary removal methods means that removed carbon is likely to return to the atmosphere at some point (see Section 4.3). Accounting for these costs means that the price or reward received for a temporary removal should be generally less than that of a permanent removal or an emission reduction (Franks et al., 2022; Groom and Venmans, 2024; Balmford et al., 2023), although there are different ways to operationalise this principle in a pricing system.

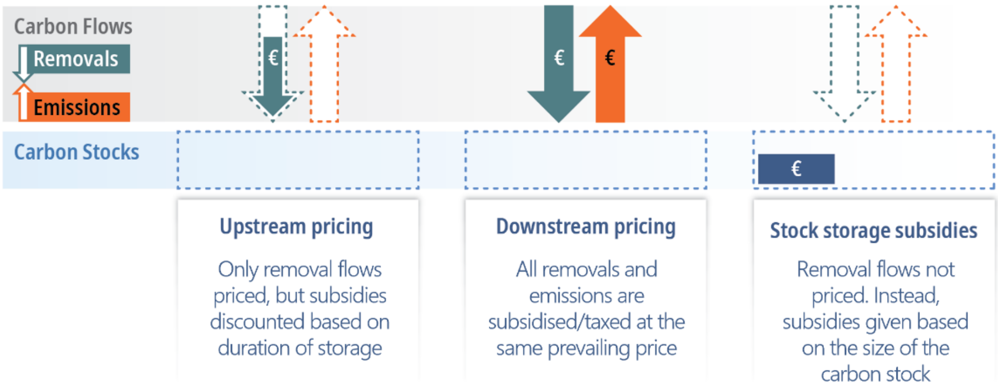
Broadly speaking, pricing systems for temporary removals or storage can be based on carbon fluxes, or on carbon stocks (Assmuth et al., 2024; Enríquez-de-Salamanca, 2022). Based on an overview and terminology provided by Franks et al. (2022), pricing options for temporary removals can be further described under three distinct models, which are described below and in Figure 32.

– **Upstream pricing** rewards specific practices, actions or land use changes that provide removals, such as afforestation or peatland rewetting. The costs of reversal are not directly priced, but rewards received are discounted compared with the carbon price of an emission, according to assumptions regarding the storage duration, reversal risks and discount rates[36]. These are the most common in practice, and as such, there are various additional ways to structure an upstream pricing system that are not elaborated in greater depth in this report[37].

– **Downstream pricing** both rewards temporary removals at the prevailing carbon price, but also requires entities to pay the same price for any subsequent emissions or reversal. That is, changes in the carbon stock are subsidised or taxed at an equal rate. This can also be referred to as a 'subsidy-taxation' approach (Assmuth et al., 2024).
– **Stock storage subsidies** does not directly price removal and emission flows, but rather provides a subsidy based on the size of the carbon stock at a given point in time. Reversal or emissions would not be priced directly as under downstream pricing but would result in a lower reward as the size of the carbon stock decreases. This is sometimes also referred to as a 'carbon rental' approach, whereby governments pay a rent for as long as carbon remained stored (Assmuth et al., 2024).

The respective strengths and weaknesses of these options are assessed in more detail in Section 14.2.

Figure 32 Pricing mechanisms for temporary removals



Source: Advisory Board (2025), adapted from Franks et al. (2022)

13.3 Key design and implementation challenges for pricing instruments for temporary removals

While the three models provide an overview of how temporary removals can be consistently priced within a GHG pricing mechanism, they are largely conceptual. If implemented in the LULUCF sector, temporary removals face several key challenges compared to permanent removals and emissions (see also Section 4.3): they are less straightforward to quantify accurately; it is more challenging to establish their additionality, with potential trade-offs between objectives to increase removals and to preserve existing sinks; and they require mechanisms to reflect their lower storage duration and to manage reversal risks. Even if the magnitude of these challenges varies depending on the eventual pricing approach (see Section 14.2), they would be relevant and need to be addressed under any of the three approaches. The remainder of this section therefore highlights potential options in addressing these

[36] For examples of estimates of the optimal discount factor depending on storage duration and discount rate assumptions, see for example Franks et al., 2023; Groom and Venmans, 2024.

[37] For example, upstream subsidies could be either action-based (e.g. approximated based on the size of the afforested area), or result-based (based on the observed increase in carbon stock in the afforested area). Furthermore, rewards could be provided on a one-off (at the time the removal action is taken) or staggered basis (spread over time to reflect the increase of the carbon stock).

different challenges, which might be applied under either of the pricing approaches described in Section 13.2.

13.3.1 Accurate quantification

Introducing pricing instruments in the LULUCF sector will require improved monitoring systems to quantify removals and reversal, with potentially substantial transaction costs. Whereas new technologies could help, small-scale land managers might require further public support.

Section 6.2 has highlighted the importance of accurate and consistent quantification of removals to ensure their quality and create market trust. Robust quantification of carbon flows or stocks in the LULUCF sector would be a necessary but challenging feature to implement such pricing instruments, especially for those that require accurate and timely information (see Section 14.2.4 for a comparison). Implementing all three approaches could therefore require sophisticated MRV systems to accurate quantification. This is particularly important if temporary removals were used in any context to counterbalance emissions, where establishing equivalence would require that a removal removes at least as much CO_2 as the emissions it aims to counterbalance (Advisory Board, 2023); see Section 4.3.

As outlined in Section 3.4.1, MRV challenges differ across removal methods. For some methods in the land sector (particularly from peatland and wetland restoration and soil carbon sequestration), as well as emerging removal methods, methods to accurately quantify emission and removal fluxes remain underdeveloped, and rely to a greater extent on direct field measurements and sampling to ensure accurate quantification (Smith et al., 2024, Chapter 10). The costs of such robust MRV systems can be substantial for land managers, with some reviews from voluntary markets showing a range of MRV and transaction costs of up to 80-90% of the value of issued credits. For smaller land managers, these costs can be especially challenging (Grafton et al., 2021; Henderson et al., 2022).

Combining satellite, remote sensing, or artificial intelligence tools with conventional MRV systems at a larger scale could both improve the accuracy of MRV systems for temporary removals, while reducing transaction and compliance costs for land managers (Andries et al., 2021). For smaller land managers who might lack the infrastructure or expertise to take advantage of these data, developing standard MRV methods, emission factors and open access tools – often supported through public investment – is key to create a supporting enabling environment and improving the feasibility of implementing robust pricing systems for temporary removals or storage (Fassnacht et al., 2024). However, given the variance across methods (including for some methods where there can also be significant variance between locations and sites), developing standardised and robust systems to quantify CO_2 fluxes and storage at scale may represent an ongoing challenge (Smith et al., 2024, Chapter 10).

13.3.2 Additionality

Restricting incentives to additional removals using well-designed baselines or additionality tests is necessary to establish equivalence and to avoid over-crediting in any context where temporary removals are used to counterbalance emissions.

The scope of any pricing system for removals depends on how additionality is defined. As explained in Section 6.3, baselines are often used in the context of certification and incentive schemes to identify the level of removals or carbon stocks that are additional to background or passive effects, and therefore, the level that can be certified or incentivised. The CRCF regulation will use baselines to establish the additional climate effects of a removal or carbon farming activity, along with other tests for other forms of additionality (e.g. financial additionality, regulatory additionality). When crediting carbon fluxes or stocks in the pricing mechanisms described above, it would also be possible to apply similar baselines to price only those above a given level.

The rationale for applying baselines or additionality criteria depends on the objective of a pricing instrument. Clear additionality is an essential component when considering equivalence between temporary removals, permanent removals and emission reductions, and therefore needs to be taken into account wherever temporary removals are used to directly counterbalance emissions from other activities or sectors (see Section 4.3). This is especially relevant if credits from temporary removals are integrated into voluntary or compliance carbon markets, where firms might make use of these credits to support their emission reduction claims or to meet legal obligations. The literature has highlighted numerous instances of inadequate baseline-setting in these settings, resulting in over-crediting from interventions that do not actually provide additional removals or net climate benefits (Probst et al., 2024; Badgley et al., 2022b; Nolan et al., 2024).

The use of these credits to support questionable emission reduction or removal claims therefore risks undermining the environmental integrity of these markets, and facilitating mitigation deterrence. For instance in the California ETS, where emitters are allowed to use forestry credits to counterbalance a share of their emissions, recent assessments have suggested flaws in the baseline method used to demonstrate additionality, resulting in systemic over-crediting of passive carbon sequestration that was not backed by underlying changes in management practices (Randazzo et al., 2023; Badgley et al., 2022b). In such contexts, strong additionality criteria for temporary removals are a necessary precondition to ensure environmental integrity and prevent mitigation deterrence.

In addition to these factors, additionality criteria and baselines may serve other policy objectives. Subsidising removals or carbon stocks without additionality requirements has the potential to become prohibitively expensive for public budgets, and could thus present significant challenges for fiscal sustainability and public acceptability. Baselines (combined with other instruments to conserve existing stocks or prevent land use change) can reduce this impact, and make it more feasible to sustain such schemes in the long run (Tahvonen and Rautiainen, 2017; Assmuth et al., 2024). Baselines can also be important to ensure that the introduction of new policies do not inadvertently introduce perverse incentives, for example, that land managers cannot simply reduce stocks with the intention of earning rewards for building them up again once the policy has been introduced (Franks et al., 2022; Edenhofer et al., 2024a). This can occur both during the transition period, such as a spike in deforestation seen just before the integration of forestry into the New Zealand ETS (Carver et al., 2022), but can also occur in some upstream pricing models.

On the other hand, strict additionality criteria and baselines may result in some practices to conserve existing carbon stocks or sinks being overlooked. These trade-offs require careful considerations in the context of the EU's LULUCF objectives.

However, pricing instruments that only reward removals under strict additionality criteria could fail to recognise and incentivise certain removal methods with greater MRV challenges, as well practices primarily aimed at maintaining existing carbon sinks or stocks (Assmuth et al., 2024; Nolan et al., 2024; Enríquez-de-Salamanca, 2022). This potential trade-off has also been highlighted previously in Section 6.3.2 in the context of the CRCF, where the exact scope of activities recognised is still uncertain, and can depend on the methodologies is an established for baselines and additionality tests. If the main objective is to address the decline in the EU's LULUCF carbon sinks, it is important to ensure sufficient incentives for maintenance and conservation activities, even for existing sinks or methods where additionality is challenging to measure. However, if the pricing instrument allows temporary LULUCF removals to counterbalance emissions from other sectors, strict additionality criteria become essential. Balancing these objectives within a single instrument may not always be feasible, highlighting the need to consider how such instruments will integrate into the broader policy framework over time (see section 13.4 and section 14.3). Ultimately, LULUCF pricing instruments will be part of a comprehensive policy framework for managing land and biomass resources in the EU, and will likely need to exist within a mix of instruments, policies, and funding sources to support the maintenance and enhancement of the EU's LULUCF sinks and ecosystems (see Chapter 7).

13.3.3 Management of storage duration and reversal risks

Pricing for removals needs to account for their storage duration and risk of reversal. While the pricing models above can account for the lower storage duration of temporary removals, additional mechanisms may be needed to manage the risk of reversal, and to promote ongoing diligence and maintenance.

Mechanisms for temporary removals need to fulfil several key functions: to account for a lower typical storage duration than permanent removals; to promote due diligence by encouraging good management and maintenance of temporary sinks; and to ensure that any reversals that occur are compensated by a new removal or reduction. 'Compensation' in this context refers to ensuring that (the required funds to finance) an equivalent volume of removals is available to maintain the climate benefit over time, even if reversals of the original removal occur (Schuett, 2024). This depends on the policy objective, but is especially important in any context or market where temporary removals are allowed to counterbalance or substitute for emission reductions. In such cases, it is important to ensure that the costs related to monitoring and compensating reversals are reflected in the pricing mechanism, to avoid mitigation deterrence (see also Box 2 in Chapter 4) (Burke and Gambhir, 2022; Prado and Mac Dowell, 2023).

Some of these functions may be captured by the design of the pricing models above, although some gaps remain in mechanisms to maintain long-term storage. In particular, commitment problems in upstream pricing models, i.e. that project operators do not face direct financial penalties if future reversal occurs, mean that additional mechanisms are required to incentivise ongoing due diligence, and to compensate for future reversal risks. For downstream pricing and stock storage subsidies, such commitment problems are less obvious than for upstream pricing, as operators are directly penalised whenever reversal occurs. However, limited liability can, in some cases, require additional mechanisms to ensure that firms cannot avoid the costs of reversal events (Franks et al., 2022). Beyond commitment, mechanisms to manage reversal risks can provide additional safeguards (e.g. to compensate for large-scale reversal events due to climate change) (Badgley et al., 2022a), or to reflect uncertainties or margins of error in the quantification.

To address the challenges associated with maintaining long-term storage, a range of possible mechanisms for managing reversals can be found in the literature and in carbon markets (see Table 26 and also Burke & Schenuit (2023) and Oeko Institut (Öko Institut, 2022) for more detailed overviews).

Table 26 Instruments to manage reversals

Mechanism	Description
Equivalence ratios and discounting	At the time of issuance, the number of credits issued from a removal project is discounted according to assumptions of the storage duration and/or reversal risks, similar to the upstream pricing model above, for example require two units of (temporary) removals to generate one removal credit. This would require estimates of the typical storage duration and reversal rates/risks, which at least for known/assumed reversals or storage durations, can ensure that future reversals are compensated upfront. However, it does not provide ongoing incentives to avoid reversal, and may not be sufficient to account for reversal risks.

Mechanism	Description
Temporary credits	Temporary credits can be facilitated by attaching expiry dates to removal credits, requiring buyers or sellers to 'renew' these credits after a set time period with new removals. In some cases, these are structured as 'two-stage' credits, meaning that the buyer is required to purchase a permanent removal when renewing. Alternatively, they could allow for renewal with further temporary credits indefinitely. As with equivalence ratios, temporary credits can account for known/assumed storage durations, but could struggle to enforce the renewal in cases of bankruptcy. Additional mechanisms may also be needed to manage risks from premature reversals.
Credit cancellation or surrender	Where reversal occurs, any resulting credits that have been issued or sold are cancelled. If already sold to a buyer, such as an emitter within a carbon market, the buyer is required to purchase a new emission allowance or removal credit. If credits have already been used within a compliance mechanism such as a cap-and-trade scheme, the regulator could also withdraw an equivalent number of emission allowances from the future GHG budget (e.g. from future auctions). Enforcement (e.g. due to bankruptcy) may be the biggest challenge, although the ability to cancel or withdraw other credits may ensure that the net climate effect is maintained.
Contractual or statutory liabilities	Contracts, legal restrictions, or other regulatory measures can be used to directly hold project owners accountable for addressing and compensating reversals (e.g. requiring forest owners to replant after felling). To address firm limited liability, these can apply to the land.
Buffer accounts	As removal projects generate credits, they are required to set aside a certain share of the removal credits into a buffer account. The number of credits set aside can differ across projects depending on project-specific risks, and the resulting buffer accounts can be 'non-pooled', with separate buffer accounts for each project; or 'pooled' buffer accounts, with one common reserve covering the whole system. Credits in the buffer account are not sold, but held in reserve, and cancelled from the buffer account to compensate for any reversals that occur in or after the monitoring period. Project owners may be required to contribute to replenishing the buffer account after reversals.
Insurance	Project owners purchase private insurance for their project, which in the event of reversal, can compensate the reversal by enabling the project owner or programme to procure certified removals.

Source: Adapted from descriptions provided in Burke and Schenuit (2023) and (Institut 2022)

While these mechanisms have advantages and disadvantages when considered on their own, combining and layering mechanisms to address reversal risks can be complementary.

Burke and Schenuit (2023) highlight that these mechanisms should generally not be considered mutually exclusive, and argue that they are likely to be most effective when combined and tailored to the specific needs of the policy framework. For example, some mechanisms require operators to provide removals upfront to account for a lower storage duration or possible reversal risks (e.g. through buffer pools or equivalence ratios), while others only do this ex-post (e.g. through surrender of emission allowances when reversal events occur). Upfront compensation can ensure that removals are available to compensate for known or assumed reversal, even if the original operator goes bankrupt or is unable to provide this compensation. However, it would not necessarily incentivise ongoing due diligence and might not fully compensate future reversals if based on optimistic assumptions of future risks. Layering additional ex post mechanisms could fully compensate future reversals and promote good management to avoid triggering these liabilities (Burke and Schenuit, 2023; Schuett, 2024).

Similarly, some mechanisms may also be better suited to specific removal methods or contexts. For example, for temporary removal methods where there are measurement challenges or a lack of traceability (e.g. for products), it could be difficult to identify reversal events for the purposes of enforcing liabilities or compensation. Mechanisms such as equivalence ratios and temporary credits may be a more feasible way of accounting for a lower storage duration and higher reversal risks in these cases.

The long-term viability of these mechanisms could be undermined by climate change, which increases the risks of unexpected and large-scale reversal events. They might therefore need to be combined with compensation or insurance mechanisms, to be made contingent on implementing best-practice adaptation strategies.

While it is important to price reversal in some form to discourage deliberate reversal events (e.g. through land use change, poor management practices, timber harvest etc.), climate change has already and will further increase the risks of reversal events in the LULUCF sector caused by disturbances such as wildfires, droughts, diseases and pests. In some EU countries, the LULUCF sector has become a net source of CO_2 during such exceptional events, and it is likely that large-scale reversal events will become more common in future (EEA, 2024b). This will threaten the effectiveness of instruments such as buffer pools to compensate for large-scale reversal events, requiring adequate capitalisation to account for the range of potential risks over the necessary storage duration (Schuett, 2024). For example in the California ETS, it has been estimated that most of the share of the buffer pool earmarked to compensate for wildfires had already been depleted in the first ten years of the programme (despite a 100-year liability), and that another major disease or pest outbreak had the potential to exhaust the buffer pool entirely (Badgley et al., 2022a).

While climate risks can be reduced to some extent through good management and adaptive practices (see Section 7.5), the systemic impacts of climate change across ecosystems and regions will mean that even when land managers have followed best practices, reversal risks and costs may be outside of their control in many cases. The introduction of pricing instruments in the LULUCF sector, without mechanisms to compensate for the costs of unavoidable climate-induced reversals, could therefore exacerbate and add to the ongoing economic burdens from climate change faced by land managers in vulnerable parts of Europe. This is particularly true for forestry, as carbon pricing encourages lengthened rotations that also increases exposure to natural hazards over time (Ekholm, 2020). While this report does not examine this in detail, the forestry literature offers a reasonable starting point to consider options for compensation against natural and climate hazard impacts, highlighting the role of both private insurance and public assistance schemes (Brunette and Couture, 2023) (see Section 7.5). However, offering unconditional public compensation for natural hazards is known to induce (or at least, fail to discourage) risk-taking behaviour by land managers and forest owners (referred to as 'charity hazard') (Raschky and Weckhannemann, 2007). It is therefore important that any insurance or compensation schemes are also conditional on carrying out adaptive management practices (Brunette et al., 2017).

13.4 Links to other pricing instruments and policies

Pricing mechanisms for temporary removals and storage could be implemented as standalone instruments within the LULUCF sector, or linked (in several ways) to emissions pricing mechanisms for other sectors.

The different pricing models have largely been proposed in conceptual terms, and do not necessarily address how they should be integrated into the EU's climate policy architecture. This includes how rewards or subsidies for temporary removals should be financed, or how these pricing mechanisms should be linked to GHG pricing systems for other sectors (e.g. the EU ETS system). Each of the pricing models described previously could be applied in many settings, and in the form of both price- and quantity-based instruments (i.e. as a way to generate monetary flows, or credits). In relation to the EU's existing policies, there are also three general ways in which the three pricing approaches could be linked to other EU GHG pricing mechanisms:

- **Standalone policies.** Under this approach, pricing or subsidy mechanisms for temporary removals or storage would operate as a standalone pricing instrument within the LULUCF sector, with no direct link to other ETS' or pricing systems. This would require new public funding sources to finance rewards for temporary removals or storage.
- **Links to other GHG pricing instruments.** Alternatively, pricing instruments could be linked to other EU GHG pricing instruments as a way to finance rewards for temporary removals or storage in the LULUCF sector. This could either be in the form of:
    - **Revenue recycling.** Under this approach, temporary removal credits could not be used to directly counterbalance reductions in another GHG pricing system. Instead, revenues from any other GHG pricing instrument could be used to finance temporary removals through subsidies or public procurement.
    - **Integration.** Under this approach, credits from temporary removal projects could be used to meet compliance obligations under other GHG pricing instruments (e.g. within the existing EU ETS, within a future ETS or GHG pricing system for the agriculture or agrifood sectors). As with the options described in Chapter 11, there are further options for structuring this integration, and the use of such credits could be either unconstrained, subject to supply and demand limits, or be managed by an intermediary (see Section 11.3). While upstream and downstream pricing models could be compatible with an ETS, it is not clear whether it would be possible to integrate a stock-based pricing instrument with a (flow-based) ETS in the same system.

There are also further options with which these links could be made, including with the existing EU ETS and EU ETS2, or with a potential future pricing instrument in the agrifood sector. As shown in Box 11, several examples exist of jurisdictions within or outside the EU where these different approaches have been implemented.

Box 11 Examples of links between LULUCF pricing policies and other GHG pricing instruments

Incentive schemes for temporary removals in the LULUCF sector in several countries highlight a range of options to create direct or indirect links to wider GHG pricing instruments, including:

- **New Zealand's** ETS has included forestry as a full ETS sector, meaning that afforestation projects can generate new emission allowances that can be traded and used by other sectors to meet their own emissions obligations. As forest owners are also fully covered, they too must surrender allowances in cases of reversal through deforestation or land use change (Carver et al., 2022).

- **California's** statewide cap-and-trade system allows emitters to purchase verified offsets from (mostly) forestry to meet their compliance obligations, up to a maximum limit of 4-8% of their emissions, depending on the compliance period. There are also provisions aimed at ensuring common quality standards for offset credits, including the use of standard certification protocols and baselines, as well as a buffer pool system aimed at insuring against the risk of reversal over a 100-year horizon (Meyer-Ohlendorf, 2023). However, as noted previously, the literature has highlighted some weaknesses in this approach, including over-crediting and an undercapitalisation of the buffer pool to deal with future climate risks (Badgley et al., 2022a).
- The **United Kingdom** has also explored the integration of forestry credits as an option for sectors to counterbalance their emissions under its ETS. This would use the existing Woodland Carbon Code as the standard for certifying removals, which includes both legal provisions to prevent deforestation or land use changes, alongside buffer pools to manage and compensate for reversal risks.
- While there are many examples of temporary removal projects being funded through revenue recycling from carbon pricing schemes, the recent agreement to establish an agricultural emissions tax in **Denmark** provides a more explicit example of this in operation. Under the scheme, a share of the revenue from the pricing of livestock and peatland emissions will be invested into a 'Green Land Fund', which will fund actions aimed at increasing on-farm carbon sequestration, such as afforestation and peatland rewetting.

Any forms of integration of temporary removals into other GHG pricing systems creates more stringent requirements for quantification, additionality, and managing reversal.

Introducing incentives for temporary removals through any form of integration into another GHG pricing instrument (i.e. where temporary removals substitute for reductions) could only be considered subject to strict conditions and the implementation of stringent MRV systems. This reflects the discussions in the previous sections and in Chapter 4, where the need to ensure equivalence between different mitigation options and to avoid mitigation deterrence creates more stringent requirements with regards to quantification, additionality and maintaining long-term storage. However, these requirements are likely to be difficult to meet under current policies and MRV systems (Sultani et al., 2024; Burke and Gambhir, 2022). As noted previously, for standalone pricing instruments aimed solely at addressing policy objectives within the LULUCF sector, or those that are funded only through recycling revenue from other pricing systems, these conditions may not be required to the same extent.

However, even if operating as a separate or standalone system, policymakers would still need to consider potential synergies and distortions between different parts of the EU's policy framework. The use of separate pricing systems for the LULUCF sector, the existing ETS sectors, and potentially, a future pricing instrument in the agrifood sector could lead to price differentials between the systems. While extending GHG pricing in some form to the LULUCF sector would likely reduce some of the existing distortions (particularly those from the incomplete carbon pricing of biomass use in the EU), potential distortions may still arise when actions cut across different systems. Distortions and synergies may also arise from other policies or funding instruments within the LULUCF sector, although this funding will likely be necessary to encourage activities or practices that may not be directly incentivised by a LULUCF pricing instrument, for instance nature restoration and adaptive practices (see Chapter 7 for a more detailed overview).

14 Assessment and comparison of incentive instruments

- **Gradually and conditionally integrate permanent removals into the EU ETS.** Assessing the instruments contained in Chapter 11, the Advisory Board concluded that the gradual integration of permanent removals into the EU ETS could incentivise their development and deployment to meet the EU's net zero (and net negative thereafter) objectives, with advantages in terms of long-term cost effectiveness and fiscal sustainability compared with other options. At the same time, it could also provide a mechanism to maintain the viability of the EU ETS if there are still residual emissions when the cap reaches zero and thereafter.
- **The integration of removal credits should be managed by an intermediary.** This integration would require care, as direct and unconstrained integration of removals into the EU ETS is not a viable option. To avoid mitigation deterrence and other environmental risks, an intermediary institution should manage supply and demand of removal credits, including the conditions, volumes and timing by which different removal methods are integrated.
- **A dynamic policy mix is needed.** A dynamic policy mix can effectively combine instruments to reflect their strengths and weaknesses at different points in time. Other complementary policies and instruments would be needed to reinforce the policy framework where the EU ETS would be insufficiently effective on its own. In particular, subsidies or public procurement (e.g. reverse auctions) are needed to support early deployment of high-cost, emerging removal methods, and as a complementary source of finance to deliver net-negative emissions after 2050.
- **Pricing LULUCF emissions and removals.** Integrating temporary removals into the existing EU ETS would create significant risks and governance challenges that cannot be managed in the short- to medium term. Given the urgent need to reverse the declining trend in the LULUCF sector, the EU should therefore consider separate pricing instruments to incentivise efforts to protect existing sinks and reward temporary removals. Future integration of temporary removals or links to the wider EU ETS system should only be considered only once these governance challenges have been adequately addressed.
- **Implementing LULUCF pricing instruments depends on the quality of the MRV system**. There are different options for pricing instruments in the LULUCF sector. An upstream pricing approach to reward temporary removals may be more feasible initially, combined with strong regulatory measures and complementary mechanisms to address reversal and environmental risks. However, this may not be sufficient to incentivise efforts that protect existing sinks, and wider investments and policies in the land sector would be needed (see Chapter 7). Over time, when MRV systems have improved, more comprehensive models to price fluxes or stocks in the LULUCF sector could be considered based on a downstream or stock storage subsidy approach.
- **Institutional capacities need to improve.** This transition implies several new governance functions to be carried out by public institutions, and a need to enhance institutional capacities and coordination. In particular, this presents a role for an intermediary institution to manage the process of integrating removals into GHG pricing in a way that balances commitment to long-term climate goals with flexibility to respond to new information. This role could be assigned existing institutions, or a new institution with a strong legal mandate.
- **Achieving and financing net negative.** Instruments to operationalise an extended emitter responsibility could contribute to achieving and financing future net-negative emissions. While options still require careful consideration, planning and implementing such instruments can contribute to reducing the financial burden for future generations.

14.1 Incentive instruments towards net zero and net negative

14.1.1 Overview of comparison and assessment criteria

Chapters 11 and 12 describe three broad categories of instruments found in the literature to incentivise removals, namely:

1. integration into the EU ETS, with three distinct models identified within this category:
    - direct, unconstrained integration,
    - integration with supply and demand controls,
    - indirect integration via an intermediary;
2. mandates and takeback obligations; and
3. subsidies and public procurement.

Based on the proposals and literature described in Chapters 11 and 12, the main features of these instruments were compared and assessed qualitatively against the criteria displayed in Table 27. Instruments were compared in terms of their key features, and whether proposals found in the literature contain mechanisms to address the governance functions and needs described in Part B.

Table 27 Comparison and assessment criteria

Mechanisms to:	Description
Incentive removals	Mechanism by which the instrument incentivises removals, either by: a) providing **rewards** or creating new sources of demand for providers of removals, b) creating **obligations** for actors to provide removals.
Achieve and sustain net zero	Mechanisms to incentivise the delivery of sufficient removals to achieve and sustain net-zero emissions.
Achieve net negative	Mechanisms to incentivise the delivery of sufficient removals to achieve net-negative emissions.
Avoid mitigation deterrence	Mechanisms to avoid mitigation deterrence.
Promote static and dynamic cost-effectiveness	Mechanisms to promote cost-effective outcomes. As outlined in Chapter 4, this depends on several factors, including mechanisms to: a) identify and prioritise the most **cost-effective balance** of removals and abatement; b) **incentivise early deployment of a diverse removal portfolio**, necessary for dynamic cost-effectiveness by bringing down costs through experience-based learning; and c) **account for and manage negative externalities**, to avoid and control potential adverse environmental or social impacts.
Maintain fiscal sustainability	Mechanisms to minimise the fiscal impacts of removals on public budgets taking into account, including: o **for net zero and** o **for net negative.**

Beyond these key features, the performance of these instruments to incentivise removals depend on the wider policy architecture for removals, and must be considered as part of a coherent policy mix. For instance, implementing any incentives for removals – whether it be through GHG pricing, mandates or subsidies for removals - would require robust certification and MRV system to be in place as a necessary precondition to ensure that high quality and sustainable removals are incentivised. Complementary instruments and policies are also needed to manage land and biomass resources (see Chapter 7), accelerate innovation (see Chapter 8), provide infrastructure (see Chapter 9), and address potential distributional impacts (see Chapter 5). Furthermore, the role of dynamic policy mixes is considered in Section 14.3, while the role of institutions and capacities is considered in Section 14.4.

14.1.2 Incentive mechanisms for removals

The instruments differ in the mechanisms by which they create incentives for removals, either by rewarding actors that provide removals or by creating obligations on actors to provide removals.

Broadly speaking, these instruments would create new incentives to scale up removals in two ways. The first is by rewarding actors that provide removals, either directly through subsidies and public procurement, or indirectly by creating new sources of demand for removals (Table 28). Options to integrate removals into the EU ETS would generally fall into this latter category, creating new demand for removals to the extent as firms are allowed to use removals to meet their obligations under the cap. However, incentives for removals under these models depend on the relative cost of reduction and removals. Some authors have highlighted that carbon prices may be too low to incentivise the deployment of removals during the early stages of integration, particularly for high-cost, permanent removal methods (Burke and Gambhir, 2022). However, as with subsidies and public procurement, a key feature of integrating removals via an intermediary institution is that it can create additional incentives for deployment during these stages where carbon prices are likely to be sufficient, for example through advance purchases, reverse auctions and complementary subsidies. This distinction also has further implications for dynamic cost-effectiveness (see Section 14.1.6).

Secondly, the scale up of removals can be incentivised with mandatory obligations on firms to develop removals capacity directly. This is most clear in proposals for carbon takeback obligations on producers and importers of fossil fuels and fossil carbon products, which would be obliged to provide removals equivalent to a defined fraction of the emissions they produced (Jenkins et al., 2021). While subsidies or most ETS options would generally not create mandatory obligations on providers of removals, there may be some exceptions. For example, if instruments such as clean-up certificates were introduced as a new type of emissions allowance within an ETS, in exchange for the allowance to emit one tonne of CO_2, it would require emitters to also provide (or purchase) a certain volume of removals in the future, with mechanisms to secure and enforce this obligation over time (Lessmann et al., 2024) (see Section 14.1.4).

Table 28 Mechanisms to incentivise removals

Instrument contains mechanisms to:	*EU ETS Integration*			Mandates and takeback obligations	Subsidies and public procurement
	Direct, unconstrained	Supply and demand controls	Via intermediary		
Incentivise removals					
by rewarding providers of removals					
by requiring actors to provide removals					

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.1.3 Achieving and sustaining net zero

In principle, EU ETS options, mandates and takeback obligations, and public procurement could all be applied at a scale to achieve net-zero emissions, although sustaining this commitment may be more challenging in some options depending on their treatment of temporary removals.

Integrating removals into the EU ETS has also been highlighted as a way to secure the long-term viability and stability of the EU ETS as the system's cap approaches zero, by providing an option to counterbalance any residual emissions within the system that have not yet been fully eliminated by this date. Assuming the availability of removal capacity, the legal obligation for emitters to remain within a net-zero EU ETS cap would require them to either fully reduce emissions, or to provide or purchase removals to counterbalance any residual emissions that remain, and to sustain this balance for as long as they are covered by the cap (Rickels et al., 2022, 2021; Edenhofer et al., 2024a).

Similarly, separate removal mandates or takeback obligations could in principle achieve and sustain net-zero emissions from the point that emitters are required to counterbalance 100% of their residual emissions with a removal, such as proposed in the end stage of a Carbon Takeback Obligation (Jenkins et al., 2021, 2023). Achieving and sustaining net-zero emissions is also possible in principle with public procurement if governments commit to financing sufficient volumes of removals necessary to counterbalance all residual emissions in the economy, although maintaining such a commitment in practice in the long-run could become difficult due to cost-effectiveness and fiscal sustainability challenges (see Sections 14.1.5 and 14.1.7).

Beyond the choice of specific instrument, their ability to *sustain* net-zero emissions depends on decisions regarding temporary removals, in light of the discussions in Chapters 4, 6 and 13. Under models of direct and unconstrained integration of removals into the EU ETS, the implied integration of temporary removals would make it challenging to sustain net-zero emissions in the long term, due to the likelihood of insufficiently-managed reversal risks, the difficulties in enforcing long-term obligations to perpetually remove carbon released from storage, and widespread mitigation deterrence. The seemingly low cost of temporary removals could also crowd out investment in temporary removals methods; investment that is crucial to contribute effectively to long-term climate objectives (Schuett, 2024; Burke and Gambhir, 2022). Other EU ETS models generally contain different mechanisms to address these risks, either through supply and demand controls that restrict entry to permanent or high quality removals only, or with an intermediary institution to impose similar controls, and to manage and enforce long-term liabilities associated with reversal (Edenhofer et al., 2024a).

Similarly for mandates and takeback obligations, sustaining net zero depends on the treatment of temporary removals and how they address related governance challenges. This differs across proposals. The proposal for a carbon takeback obligation would create an obligation for firms to provide *permanent* removals, which Jenkins et al. (2021) outline is necessary to sustain net-zero emissions in the long-run due to challenges in managing reversals. However, for proposals where mandates and takeback obligations also apply to temporary removals, such as indicated in the proposal for a California carbon removal development act (Meyer-Ohlendorf, 2023). This would require additional mechanisms or institutions to enforce a long-term or indefinite obligation to sustain net-zero, particularly in light of firm limited liability (Franks et al., 2022). The significant differences between temporary and permanent removals point to the need to consider implementing instruments for temporary removals separate to those for permanent removals, and these issues are presented in greater detail in Section 4.3.

Table 29 Mechanisms to achieve and sustain net zero

Instrument contains mechanisms to:	*EU ETS Integration* Direct, unconstrained	*EU ETS Integration* Supply and demand controls	*EU ETS Integration* Via intermediary	Mandates and takeback obligations	Subsidies and public procurement
Achieve and sustain net zero					

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.1.4 Achieving net negative

Transitioning to a net-negative objective with conventional instruments presents greater challenges, but proposals for mechanisms to operationalise an extended emitters' responsibility could address this. The potential scale of global efforts to manage a future temperature overshoot may still require additional public funding sources.

As described in Chapter 12, *conventional* cap-and-trade systems or mandates and takeback obligations face greater difficulties in achieving and sustaining net-negative emissions, as they lack a clear basis to generate demand, or mechanisms to enforce long-term obligations to provide net-negative emissions. However, some proposals highlighted in the literature could allow these instruments to achieve net-negative emissions, if combined with mechanisms that operationalise and enforce the concept of an extended emitter responsibility.

For example, instruments such clean-up certificates (see Section 12.2) have been proposed as a new type of emission allowance that could be auctioned in an ETS. While these allowances would allow a covered entity to emit one tonne of CO_2, they would also come with a carbon debt, or an obligation to provide a removal in the future (Lessmann et al., 2024). Of the three EU ETS models, this would only be possible if introduced under the model of integration via an intermediary: Lessman et al. (2024) outline that the limited liability of private entities and moral hazard risks this makes it necessary for public institutions to control the supply of clean-up certificates, set and collect deposits to ensure commitment, and to manage and enforce these long-term liabilities.

Proposals for Removal Obligations (Bednar et al., 2021, 2023a) and Atmospheric CO_2 Removal Deposits (Lyngfelt et al., 2024) are based on a similar concept, but would apply more broadly than in an ETS with a different institutional structure; providing the possibility of achieving net-negative using intertemporal removal mandates and obligations. As with clean-up certificates, both proposals outline specific mechanisms and institutions that would be required to ensure that these obligations are enforced over time.

While this concept of an extended emitter responsibility can ensure that emitters contribute to some extent to future removal needs, as outlined previously, the volume of removals that extended emitter responsibility can directly support is limited to size of the remaining GHG budget. Depending on the scale of net-negative emissions required to manage temperature overshoots, this means that even with additional instruments described above, it is likely that governments will still become the primary buyer of removals for net negative as part of global efforts to manage a future temperature overshoot, with public procurement likely forming a central element of these strategies (Sultani et al., 2024).

Table 30 Mechanisms to achieve net negative

Instrument contains mechanisms to:	EU ETS Integration: Direct, unconstrained	EU ETS Integration: Supply and demand controls	EU ETS Integration: Via intermediary	Mandates and takeback obligations	Subsidies and public procurement
Achieve and sustain net negative	Not a general feature	Not a general feature	Possible feature	Possible feature	Possible feature

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.1.5 Avoiding mitigation deterrence

Of all the EU ETS options, direct and unconstrained integration of removals into the EU ETS would contain few mechanisms to prevent or manage mitigation deterrence, which risks undermining EU climate objectives. The EU ETS options to integrate removals with supply and demand controls, or via an intermediary institution, provide mechanisms to avoid mitigation deterrence risks.

Direct and unconstrained integration of removals into the EU ETS creates significant risks of mitigation deterrence, undermining necessary incentives for emitters to reduce emissions and jeopardising EU climate objectives. Especially where unconstrained integration includes low quality or seemingly-cheap temporary removals that do not fully account for the costs of reversal, or where expectations are not sufficiently managed. This could put downwards pressure on carbon prices, encouraging firms to delay emission reductions in activities with other viable mitigation options (Burke and Gambhir, 2022).

Under other models of EU ETS integration, most proposals contain mechanisms to manage mitigation deterrence risks with supply and demand controls, such as quantitative limits on the overall volumes of removals or qualitative restrictions to specific removal methods. In proposals where removals are integrated via an intermediary institution, authors similarly describe its role in managing supply and demand as a key feature to avoid mitigation deterrence, allowing it to impose similar controls as necessary. Several other mechanisms are available to prevent mitigation deterrence under these models of integration, such as the conditional supply of removal credits based on a carbon price floor (Rickels et al., 2022); the dynamic withdrawal of emission allowances for each removal credit introduced (McLaren, 2020; UK Government, 2024); or the ability to sequentially integrate different types of removals according to their unique risks (Sultani et al., 2024).

Mandates and takeback obligations, or subsidies and procurement would generally not directly affect incentives for emission reductions, also avoiding mitigation deterrence risks.

Other instruments such as mandates and takeback obligations, or subsidies and public procurement are generally described as operating separately to GHG pricing systems, meaning that incentives for removals would not directly affect incentives to reduce emissions. If mandates and takeback obligations are combined or form an additional obligation alongside existing emission pricing schemes, these may even create further incentives to reduce emissions in order for emitters to avoid these costs. For instance, Jenkins et al. (2021) find that imposing upstream carbon takeback obligations in parallel with conventional demand-side policies (i.e. carbon pricing and other emissions reduction policies) could be effective at accelerating short-term emission reductions compared to carbon pricing alone. They also highlight the possibility of applying a carbon takeback obligation as a carbon border adjustment on imported fossil fuels or products, which could help to further limit mitigation deterrence linked to international carbon leakage.

While these instruments generally contain features to avoid mitigation deterrence, their effectiveness will also depend on other elements of the wider climate policy framework, including separate targets (see Chapter 4), and the design of decision-making processes and institutions (see Section 14.4).

Table 31 Mechanisms to avoid mitigation deterrence

Instrument contains mechanisms to:	EU ETS Integration			Mandates and takeback obligations	Subsidies and public procurement
	Direct, unconstrained	Supply and demand controls	Via intermediary		
Avoid mitigation deterrence	Not a general feature of this instrument or proposal	General feature of the instrument	General feature of the instrument	General feature of the instrument	General feature of the instrument

Legend
- ■ General feature of the instrument
- ■ Possible feature of this instrument / feature in certain proposals
- ■ Not a general feature of this instrument or proposal

14.1.6 Promoting static and dynamic cost-effectiveness

In the long-run, a cost-effective level of removals occurs at the point where the marginal cost of removals equals the marginal abatement costs of emission reduction options (Edenhofer et al., 2024a). As outlined previously in Chapter 4.2, instruments based on well-functioning price signals can be an important tool in promoting cost-effectiveness, generating incentives that allow market actors to identify and pursue the most cost-effective balance of reduction and removal efforts towards an overall climate neutrality objective. However, in practice, they may not function effectively if they fail to take into account environmental or other externalities, or under dynamic conditions where further supports are needed to bring down the cost of expensive removal methods. Therefore, comparing instruments in terms of long-run cost-effectiveness must consider several interlinked factors, including whether they contain mechanisms to achieve a cost-effective balance of reductions and removals, to promote early deployment of a diverse removal portfolio, and to manage externalities.

In principle, price and market mechanisms, including EU ETS options, are more suited to identifying and achieving a cost-effective balance of removals and abatement, compared to mechanisms where regulators are required to specify or manage this balance directly.

GHG pricing instruments based on a well-functioning price signal are generally considered to be important tools in climate policies for incentivising cost-effective mitigation decisions, generating incentives for market actors to identify and pursue the most cost-effective outcomes (Auffhammer et al., 2016; Requate, 2005; Edenhofer et al., 2021). If market externalities are accounted for, an integrated market with a uniform carbon price signal for emissions and removals – most associated with the model of direct and unconstrained integration - would be expected to facilitate this process most effectively, helping to find the cost-effective balance of reduction and removal efforts towards climate neutrality (Sultani et al., 2024).

The introduction of restrictions or limitations on the integration of removals would be expected to reduce efficiency to some extent, creating additional economic costs depending on the extent to which the volumes of removals deviate from the cost-effective balance over time. As noted previously, these restrictions may be justified for other reasons, including to manage externalities or mitigation deterrence (Merfort et al., 2024; Edenhofer et al., 2024a). However, even with these limits, the ability for firms to trade and to manage their own contribution of reductions and removals to the overall market cap within an EU ETS could still facilitate more cost-effective outcomes. Integrating removals via an intermediary offers other possible mechanisms to further help to find a cost-effective balance, particularly in allowing for a more dynamic management of supply and demand controls (Rickels et al., 2022), or additional mechanisms to facilitate price discovery such as reverse auctions or clean-up certificates (Lessmann et al., 2024).

Conversely, mechanisms that predefine or manage the required volume of removals are generally less suited to achieving cost-effective outcomes, depending on how much they deviate from this cost-effective balance, particularly before net zero[38] (Edenhofer et al., 2024a; Merfort et al., 2024; Paul et al., 2023a). Mandates and takeback obligations would require regulators to specify the fraction of a firms' emissions that would need to be matched with a removal, which could present challenges in achieving cost-effective outcomes due to imperfect or asymmetrical information. For instance, applying the same fraction across all sectors and firms would likely deviate from cost-effective outcomes as different sectors face different abatement costs; as would trying to identify and tailor the appropriate fraction for specific sectors or firms due to information asymmetries. Some mechanisms highlighted under these proposals could minimise the extent to which these fractions deviate from this cost-effective balance: by setting initially-small and progressively-increasing mandates and takeback obligations, or combining these obligations with conventional carbon pricing policies (Jenkins et al., 2021).

Subsidies and public procurement could pose similar challenges for governments in predicting the prices/quantities necessary for a cost-effective outcome, particularly if governments also manage the balance of emissions and removals directly. Governments may face additional economic and political incentives to deviate from an optimal balance of removals and abatement (e.g. to generate additional fiscal revenues, or to respond to political pressures) (Edenhofer et al., 2024a). However, some specific subsidy instruments, such as cost-minimising reverse auctions, include mechanisms that can facilitate price discovery and help reduce information asymmetries (Lundberg and Fridahl, 2022).

As price signals may not capture all externalities, additional mechanisms can still be justified from a cost-effectiveness perspective to avoid negative environmental and social effects. Except for direct and unconstrained integration of removals into the EU ETS, other instruments generally contain mechanisms that could contribute to managing these risks.

However, as outlined in Chapter 4, instruments that rely solely on price signals may not achieve cost-effective outcomes if the price fails to capture the cost of other externalities. In the absence of comprehensive Pigouvian pricing of environmental and other externalities, introducing new and unconstrained incentives for certain removal methods could lead to much higher-than-optimal level of deployment, particularly for methods that make use of land and biomass resources (Merfort et al., 2024; Sultani et al., 2024). While it is apparent that the direct and unconstrained integration of removals into the EU ETS would provide few controls to manage environmental impacts beyond those contained in certification sustainability criteria, other options and proposals generally contain mechanisms allowing policymakers to restrict quantities or certain types of removals to reduce specific environmental or other spillover effects.

However, environmental impacts will still heavily depend on how these instruments are combined with other policies and instruments, particularly with regards to certification and sustainability criteria (see Chapter 6), and policies for managing land and biomass resources (see Chapter 7). For BECCS and removal methods that rely on biomass feedstocks in particular, it may be necessary to combine these

[38] Once net zero is reached, static cost-effectiveness is likely to be similar between ETS options, and mandates and takeback obligations: under an ETS with a net-zero cap, or a takeback obligation set at 100%, each entity will have to either decide to further reduce or to remove, and is likely to base this decision on marginal abatement and removal costs.

with other mechanisms to manage adverse environmental impacts, such as quantitative limits, limiting incentives to the use of BECCS to specific applications (such as on existing processes or facilities), strict enforcement of biomass sustainability and sourcing criteria, and the extension of emissions pricing to the LULUCF sector[39] (see Chapter 7).

Dynamic cost-effectiveness also requires mechanisms to incentivise the early deployment of a diverse portfolio of removal methods, to accelerate innovation and bring down long-term costs. Instruments that rely on price signals alone would provide few additional incentives to encourage the early deployment of high-cost emerging technologies. Other instruments, such as subsidies, direct state procurement or early-stage mandates and takeback obligations, could contribute to boosting this deployment.

As outlined in Chapters 4 and 8, mechanisms to encourage early deployment of a diverse portfolio of removals are important to consider in dynamic cost-effectiveness, as early deployment is necessary to bring down costs through technological experience-based learning and to achieve more cost-effective outcomes in the long-term (Grubb et al., 2021; Anadón et al., 2022). Chapter 8 also highlights the importance of pursuing a portfolio of removal methods, given the uncertainties and risks of relying heavily on any particular technology to achieve the EU's long-term removal goal. Several authors have argued that the current carbon price signal in the EU ETS is insufficient to incentivise the deployment of currently high-cost removal methods (Nemet et al., 2018a; Honegger et al., 2021b; Edenhofer et al., 2024a; Sultani et al., 2024; Smith et al., 2024). This means that models relying on a price signal only in the short-term (direct and unconstrained ETS integration or ETS integration with supply and demand controls) would therefore provide few additional incentives for early deployment, particularly for high-cost, permanent removal methods.

In this context, subsidy and public procurement instruments are important to supporting emerging and early-stage removal methods, particularly in guiding them through the so-called valley of death, the stage where promising but commercially-not-yet-viable technologies struggle to attract investments (Nemet et al., 2018a; Anadón et al., 2022). Drawing on the innovation literature, many authors highlight the need for increased public investment in RD&D, and also highlight a central role for early subsidy or public procurement instruments aimed at supporting and building a portfolio of viable technologies. In particular, competitive reverse auctions or contracts for difference could allow for demonstration of emerging technologies in a commercial environment, but before the large-scale roll-out of incentives; helping to establish the viability of emerging technologies, facilitate price discovery, and identify risks, costs and opportunities (Lundberg and Fridahl, 2022; Hickey et al., 2023; Burke and Gambhir, 2022; Edenhofer et al., 2024a). These can be implemented as standalone subsidy or public procurement instruments, and has also been highlighted as a key feature of integrating removals into an ETS via an intermediary institution: compared to other ETS models, with such proposals outlining an active role for the intermediary in the early procurement of removal credits and in building an early diverse removals portfolio (Rickels et al., 2022, 2021; Edenhofer et al., 2024a).

Proposals for mandates and takeback obligations also contain mechanisms to encourage a faster deployment of removals than carbon pricing policies alone, through initially-small but progressively-increasing obligations on firms to purchase or provide removals (Jenkins et al., 2021, 2023). However, these proposals do not contain clear mechanisms that would encourage the development of a *diverse* portfolio of removal methods or to avoid firms opting for the lowest-cost technology available to meet

[39] The Advisory Board has also previously made recommendations on EU biomass policies; with these challenges and recommendations presented in greater depth in Chapter 7.

their obligations, although this may be possible in some proposals, for instance if policymakers also set additional technology-specific mandates or targets (Jenkins et al., 2021).

Table 32 Mechanisms to promote static and dynamic cost-effectiveness

Instrument contains mechanisms to:	*EU ETS Integration*			Mandates and takeback obligations	Subsidies and public procurement
	Direct, unconstrained	Supply and demand controls	Via intermediary		
Promote static and dynamic cost-effectiveness					
Achieve cost-effective balance	General feature	Possible feature	Possible feature	Not a general feature	General feature
Avoid environmental externalities & risks	Not a general feature	Possible feature	Possible feature	Possible feature	Possible feature
Incentivise early deployment and diverse portfolio	Not a general feature	Not a general feature	General feature	Possible feature	General feature

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.1.7 Maintaining fiscal sustainability

In the long-run, the EU ETS or mandates and takeback obligations contain mechanisms to provide a stable financing base necessary to reach and sustain net-zero emissions. Subsidies and public procurement present the greatest challenges in maintaining this, with funding at greater risk of diversion for other purposes.

Options for the long-run integration of removals into the EU ETS could provide a reasonably stable source of finance to reach and sustain net zero. As above, the obligation for actors in the system to stay within a net-zero cap, through emission reductions or purchasing/delivering removals, would limit the need for additional fiscal resources from public budgets. However, some proposals for integration via an intermediary institution imply the need for additional funding in the shorter-term if they undertake advantage purchase programmes or provide complementary market supports for high-cost removal methods (Rickels et al., 2022; Edenhofer et al., 2024a). Options for separate mandates or takeback obligations would likely have similar effects in terms of fiscal sustainability at net zero, providing a self-sustaining basis for operating firms to counterbalance their own residual emissions with minimal impact on public budgets (Jenkins et al., 2021, 2023).

If subsidies or public procurement were instead used as the primary mechanism to achieve and sustain net-zero emissions, governments would need to commit to financing sufficient removals to counterbalance any remaining residual emissions in the economy, and to sustain this balance in the long-run. This presents clear challenges for maintaining fiscal sustainability. Even if governments committed to earmarking EU ETS or carbon tax revenue and using this to directly counterbalance residual emissions, political economy considerations could present challenges for long-term fiscal sustainability. Several authors have highlighted a tendency for emissions pricing revenues for revenues to be more frequently diverted when passing through general government budgets, compared to quantity-based instruments where removals are more likely to be earmarked to finance climate or environmental measures (Goulder and Schein, 2013; Carl and Fedor, 2016; Edenhofer et al., 2021). Several authors have highlighted similar risks with committing to financing removals through this type of public procurement, suggesting that governments are likely to divert funds over time as economic and political circumstances change (Lyngfelt et al., 2024; Bednar et al., 2023b).

There are also limits to the feasibility of this approach under the existing design of the EU ETS, where most EU ETS revenues currently return to Member State budgets. Member states are required to use this revenue to finance a range of climate measures, which could include removals. However differences in how member states disburse and track ETS revenues also suggests a similar risk of revenue being diverted[40]. Auctioning volumes – and thus revenues – would also be expected dry up once the EU ETS emissions cap reaches zero and the Market Stability Reserve gets depleted, meaning that new revenue sources would need to be found at the EU level to counterbalance any residual emissions remaining in the economy. Ensuring sufficient funding for removals would require either adjustments to the EU ETS to allow for a positive cap and associated auction revenue; or the introduction of new EU-wide carbon pricing systems, which as outlined previously, would likely be challenging to implement at an EU level under the EU's current decision-making structure (Delbeke, 2024).

The cost of net negative could present even greater challenges for fiscal sustainability, although future financial burdens could be reduced by requiring today's emitters to contribute to some extent to these future costs.

As the fiscal costs of net-negative emissions are likely to be significant, and as future generations will also have to bear the brunt of the costs of climate change, reducing these costs in any way can improve both long-term fiscal sustainability and intergenerational fairness. While the priority should be to firstly minimise the *need* for overshoot management through deep, rapid emission reductions and upscaling of removals, as Chapter 12 highlights, considering instruments to introduce an extended emitter responsibility can smooth long-term costs and improve fiscal sustainability. This refers to any mechanisms for today's emitters to also contribute to the future costs of cleaning up the greenhouse gases they emitted in the atmosphere. Given the different instruments to operationalise an extended emitter responsibility, mechanisms to improve future fiscal sustainability also depends on enforcement, and ensuring that funds generated by the instrument are protected from diversion until they are needed.

Similarly to above, while governments could set money aside in funds to support future subsidy and public procurement instruments, several authors have highlighted the lack of mechanisms to protect funds from being diverted by governments over time (Lyngfelt et al., 2024; Bednar et al., 2021). Mechanisms described in Chapter 12 aim to overcome these commitment and problems. While similarly requiring an upfront deposit or collateral from emitters to cover their liabilities, proposals for clean-up certificates (as an option within an ETS) and atmospheric CO_2 removal deposits (as a type of mandate/takeback obligation) proposals protect these funds in the form of ownable, *refundable* deposits; characteristics that the authors argue make it difficult to divert or redirect compared to centrally-held government investment or reserve funds (Lessmann et al., 2024; Lyngfelt et al., 2024). The proposal for removal obligations as a form of financial debt administered and overseen by the financial system is similarly intended to mitigate fiscal sustainability risks (Bednar et al., 2021, 2023a).

However, as outlined previously, these instruments are expected to contribute to a limited extent to funding net-negative emissions, and their capacity to fund net negative also decreases the longer that

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[40] This argument is often attributed to differences in institutional governance between carbon tax and cap-and-trade schemes: with carbon tax schemes often coming under the oversight of finance ministries/committees who tend to favour an increase in general government revenue; and cap-and-trade under environment ministries/committees who favour increased environmental spending (Goulder and Schein, 2013). While the EU ETS is a cap-and-trade scheme, and members states are required under the EU ETS Directive to allocate their share of ETS revenues towards climate action, the way that member states govern and report this in practice differs significantly. Some member states do not earmark revenue at all, and instead pool and redistribute this through the national budget. More generally, several stakeholder assessments have highlighted wider shortcomings in reporting by member states on the use of EU ETS revenue, leading to questionable or non-transparent claims by member states regarding the use of EU ETS revenues for climate action (EC and Ramboll, 2017; Ecologic, 2022b).

policymakers wait to introduce such instruments (Lyngfelt et al., 2024). This means that in any case, it is likely that net-negative emissions to manage temperature overshoot will depend largely on future public budgets, which depending on the overall needs for and the EU's contribution to future global efforts to manage temperature overshoot, could still pose significant challenges for fiscal sustainability.

Table 33 Mechanisms to maintain fiscal sustainability

Instrument contains mechanisms to:	*EU ETS Integration*			Mandates and takeback obligations	Subsidies and public procurement
	Direct, unconstrained	Supply and demand controls	Via intermediary		
Maintain fiscal sustainability					
For net zero	General feature	General feature	Possible feature	General feature	Not a general feature
For net negative	Not a general feature	Not a general feature	Possible feature	Possible feature	Not a general feature

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.1.8 Summary of comparison and assessment

Table 34 summarises the results of the analysis in Section 14.1, highlighting and comparing the main features of different instruments.

In the long run, the integration of permanent removals into the EU ETS could provide the most cost-effective and fiscally-sustainable way of managing their contribution to the EU's GHG budget compared to other instruments.

As noted previously, the EU ETS' 'end-game' (i.e. the challenges and uncertainties faced as the supply of emission allowances approaches zero) has prompted extensive discussions regarding the future of the EU ETS, and the potential integration of removals as an option to counterbalance residual emissions among sectors covered by the cap. In the long-run, integrating permanent removals into the EU ETS in some form could improve the cost-effectiveness of achieving the EU's climate objectives, while providing a stable source of finance for removals that reduces burdens on government budgets. As the only EU-wide GHG pricing instrument in operation, it represents the most feasible way of managing the volumes of removals at an EU level, given the current institutional architecture and the limitations in the EU's budget to provide and sustain extensive subsidies.

Other instruments considered in this report have disadvantages compared to integration into the EU if considered as the primary driver for the deployment of removals towards climate neutrality. Whereas mandates and takeback obligations could have some benefits that are comparable to the EU ETS, they would require policymakers to directly set the removal fraction for different sectors and different removal methods, which would be less effective at finding a dynamically cost-effective balance between reductions and removals up to 2050. If applied as additional obligations on EU ETS firms, while this could create further incentives to reduce emissions, they would also not directly address the challenges associated with the EU ETS end-game as the cap reaches zero, and any price volatility that may accompany the presence of remaining emissions from sectors with no or limited mitigation alternatives by 2040.

The potential of subsidies and public procurement as the primary driver of large-scale deployment towards climate neutrality also faces some key challenges. Similarly, it also be less effective at finding a cost-effective balance between reductions and removals on their own, and is likely to face constraints in the availability of public funds and maintaining fiscal sustainability over time. On the other hand, subsidies and public procurement could be very effective (and even necessary) in the near-term for driving innovation and early deployment of emerging removal methods, and could be combined with integration of removals into the EU ETS to this end. Furthermore, they will likely become necessary as a key source of finance to scale up net-negative emissions after 2050 (see Section 14.2).

Direct and unconstrained integration of removals into the EU ETS is not a viable option, and this requires mechanisms and strict conditions to prevent mitigation deterrence, ensure environmental integrity, support distributional fairness and promote dynamically cost-effective outcomes. Integrating removals via an intermediary institution that manages the supply and demand for removals could address these objectives.

Whereas an integration of removals into the EU ETS thus constitutes a promising option to drive their large-scale deployment, the literature has highlighted several key challenges of this approach which would need to be addressed. Firstly - following similar assessments in the literature - it is clear from the assessment that a direct, unconstrained integration of removals into the EU ETS is not a viable option. The risks of widespread mitigation deterrence and unmanaged environmental spillovers and externalities could threaten the environmental integrity of the EU ETS, meaning that safeguards are required. Direct and unconstrained integration would also still provide few incentives to deploy high-cost permanent removal methods on its own, and complementary policies are required.

The other two EU ETS models – integration with supply and demand controls, and integration via an intermediary institution – both contain mechanisms to manage these risks. However, integrating removals via an intermediary institution provides a more comprehensive toolbox of mechanisms to balance static and dynamic cost-effectiveness objectives, with the need to avoid mitigation deterrence and maintain environmental integrity. With an intermediary institution managing the supply and demand of removal credits, it allows for safeguards and restrictions to be deployed as necessary to ensure environmental integrity, including the conditions, quantities and timing for the integration of different methods into the EU ETS. However, in doing so, it also allows for a more dynamic approach to managing the contribution of removals to the EU ETS cap, and to adapt these controls as necessary to respond to new information, such as on costs, technology and risks. Furthermore, it allows for more effective support to early deployment and for building a diverse portfolio of removals compared to other options, as the intermediary institution can play a role in generating demand even when carbon prices would be insufficient to do so (e.g. if combined with reverse auctions, public procurement etc.). Finally, this model opens up the possibility of achieving a net-negative ETS through the possible introduction of instruments like clean-up certificates, although options to operationalise an extended emitter responsibility still require further consideration and study.

While permanent removals are well-suited for a gradual and conditional integration into the EU ETS, temporary removals present distinct challenges. To urgently reverse the decline of the land sink, the EU should develop alternative pricing instruments for temporary removals or storage, separately to the current EU ETS.

While the EU ETS could therefore effectively incentivise the scale up of permanent removals under these conditions, temporary removals pose much greater risks. This includes a lower typical storage duration, a greater risks and costs from reversal, and challenges in quantification and establishing additionality. If used as an option to counterbalance residual emissions from other sectors without mechanisms to adequately account for these risks, the integration of temporary removals into the EU ETS could threaten the environmental integrity of the EU ETS, induce mitigation deterrence, and crowd out investment in permanent removal methods. These risks cannot be realistically managed in the short-to-medium term.

While elaborated further in Section 14.2 – given the need for urgent action and the challenges in managing the risks of integrating temporary removals under the EU ETS – the EU needs to consider alternative pricing mechanisms for temporary removals, at least in the near term. Beyond the exclusion of temporary removals, other qualitative and quantitative controls would need to be imposed to manage mitigation deterrence and environmental externalities. These particularly must address the risks associated with BECCS and biomass use, as described in Chapter 7.

Table 34 Comparing instruments for incentivising removals towards net zero & net-negative emissions

Instrument contains mechanisms to:	EU ETS Integration			Mandates and takeback obligations	Subsidies and public procurement
	Direct, unconstrained	Supply and demand controls	Via intermediary		
Incentivise removals					
by rewarding providers of removals	Possible	Possible	General	Possible	General
by requiring actors to provide removals	Not	Not	Possible	General	Not
Achieve and sustain net zero	Not	General	General	Possible	Possible
Achieve net negative	Not	Not	Possible	Possible	Possible
Avoid mitigation deterrence	Not	General	General	General	General
Promote static and dynamic cost-effectiveness					
Achieve cost-effective balance	General	Possible	Possible	Not	Possible
Avoid environmental externalities & risks	Not	Possible	Possible	Possible	Possible
Incentivise early deployment and diverse portfolio	Not	Not	General	Possible	General
Maintain fiscal sustainability					
Net-zero	General	General	Possible	General	Not
Net-negative	Not	Not	Possible	Possible	Not

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

Overcoming the shorter-term barriers to integration – particularly the high costs of permanent removal methods – requires a range of complementary instruments as part of a dynamic policy mix.

While each instrument contains features that may be more suited to addressing specific governance objectives, these objectives and instruments are likely to play distinct roles in the policy framework at different points of time. The relative importance of different governance objectives are likely to change over time, with the need to prioritise environmental integrity and improving technological readiness in the early stages of the policy framework, before considering instruments that can deliver more cost-effective and fiscally-sustainable management once these challenges have been addressed.

In particular, subsidies and public procurement schemes are likely to play a particularly important role in providing early-stage support for emerging removal methods, and improving their viability before integration into the EU ETS (Lundberg and Fridahl, 2022). The order by which individual removal methods could be integrated into the EU ETS is also likely to differ, with some at a greater level of technological readiness and certainty than others (Edenhofer et al., 2024a; Sultani et al., 2024; Burke and Gambhir, 2022; Burke and Schenuit, 2023). The role of sequencing, and the potential to combine policy instruments as part of a dynamic policy mix that reflects policy needs at different points in time is explored in greater depth in Section 14.3.

14.2 Incentive instruments for temporary removals

14.2.1 Overview of comparison and assessment criteria

Section 13.2 describes three approaches for pricing temporary removals or storage from the literature, most often described in the context of the LULUCF sector. These approaches are referred to as:

- upstream pricing
- downstream pricing
- stock storage subsidies

As Section 14.1 describes, the features of these three pricing options for temporary removals and storage were compared and assessed qualitatively against relevant criteria displayed in Table 30 below. These criteria differ to some extent from the ones used previously, reflecting the unique needs and challenges of temporary removals.

Table 35 Comparison and assessment criteria for incentive instruments for temporary removals or storage

Features or mechanisms to:	Description
Incentivise temporary removals or storage	Where they contain mechanisms that incentivise: • Establishing **new sinks** • Maintaining **existing sinks or stocks**
Manage storage duration and reversal	Whether they contain mechanisms to: 1. Account for lower typical storage duration 2. Incentivise due diligence and manage reversal risks
Minimise informational requirements	Whether they contain mechanisms to minimise informational requirements for regulators
Maintain fiscal sustainability	Whether they contain mechanisms to maintain fiscal sustainability
Avoid adverse environmental impacts	Whether they contain mechanisms to avoid unintended, adverse impacts on other environmental dimensions, including biodiversity

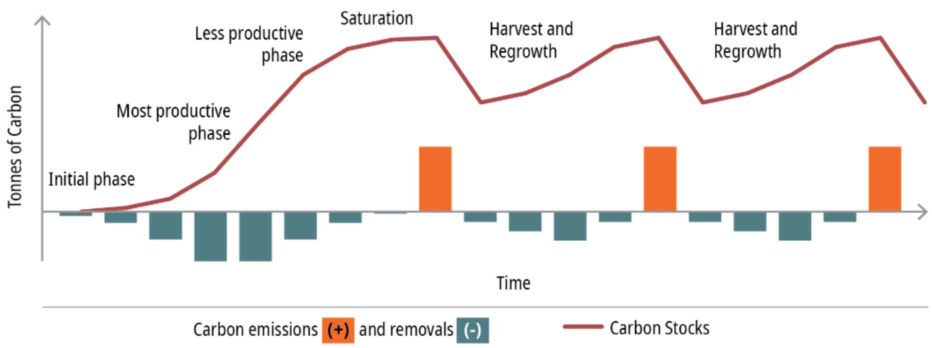
14.2.2 Incentive mechanisms for removals and carbon stocks

Upstream pricing models provide strong incentives for new or fast-growing sink removals, whereas stock storage subsidies provide strongest incentives to conserve existing carbon stocks. Downstream pricing could provide incentives for both increasing sinks and maintaining existing stocks.

Evidence from the literature on forestry generally shows that the introduction of pricing mechanisms for carbon sequestration or storage can incentivise land managers to modify their management practices, assuming that land managers aim to maximise financial returns from timber and carbon income. Although the exact effects can depend on how a pricing system is designed, these changes can include practices in the forestry sector like, such as extending rotation lengths, increased afforestation, adopting continuous cover forestry aimed at maximising returns from both timber and carbon income (Assmuth et al., 2024). In other contexts, incentive schemes and carbon payments are less extensively studied. Some studies have indicated that while carbon payments can provide additional incentives for soil carbon sequestration and peatland restoration, these direct financial incentives can be smaller compared to the value that land managers place on related co-benefits (particularly among farmers), such as increased soil health, productivity or the long-term viability of an enterprise (Buck and Palumbo-Compton, 2022; Canning et al., 2021).

Beyond this, the three pricing instruments and the timing of carbon revenues or costs may further affect land use and management incentives in different ways. As illustrated in Figure 33 below, removal flows and stocks in a typical biomass growth curve are generally maximised at different points in time; with removal flows at their highest in the earlier years of a typical biomass growth curve, and stocks highest in later years as a sink reaches its saturation point (EEA, 2023e). As demonstrated in the literature on forestry, individual land managers are sensitive to the timing of cashflows and have strong preferences for contracts that deliver payments over a shorter time horizon (Lienhoop and Brouwer, 2015). This also suggests that pricing instruments based on carbon fluxes (i.e. upstream and downstream pricing) could be a more attractive option for encouraging land managers to provide removals, while storage stock subsidies may be more effective at encouraging the preservation of existing stocks, which has also been noted by other authors (Assmuth et al., 2024; Enríquez-de-Salamanca, 2022).

Figure 33 Removal stocks and flows in a typical biomass growth, harvest and regrowth curve



Source: Adapted from EEA (2023e), figure 5.3

Notes: Figure also shows harvest and regrowth phases over illustrative rotations

Based on this underlying dynamic, it can be expected that instruments based on upstream pricing would be most effective at incentivising new removals, particularly land use changes or practices that deliver new, fast-growing sinks (e.g. afforestation). However, once established and the payment is claimed, upstream pricing would provide few continued incentives to conserve existing stocks on its own. There is also a risk of perverse incentives during the implementation phase (i.e. of land managers reducing stocks in order to claim subsidies for reestablishing them), which would need to be prevented (Franks et al., 2022).

Downstream pricing would provide strong incentives to both increase or maintain sinks, as well as direct incentives (through avoided costs) to conserve existing carbon stocks. Stock storage subsidies would provide the strongest incentives to conserve existing carbon stocks, with particular advantages for those that are mature or are already near saturation (e.g. peatlands and intact forests). While stock storage subsidies would still create incentives to provide removals or to establish new sinks, this incentive effect may be slow to materialise depending on the rate of biomass growth or carbon sequestration. In practice, land managers who are sensitive to the timing of payments may not perceive additional incentives from some removal methods under a stock storage subsidy system.

A key uncertainty in assessing the effectiveness of any potential pricing mechanisms within the LULUCF sector is how additionality is treated. In particular, incentives created by upstream pricing systems may be affected by baselines designed to price only 'additional' CO_2 removals, or those delivered as the result of a direct and visible intervention. As explained in sections 6.3 and 13.3.2, baselines are generally used in certification systems as a way to identify fluxes that directly result from an intervention, or that are additional to background CO_2 fluxes. Depending on how they are designed, the application of baselines may not recognise (nor incentivise) practices aimed at maintaining existing sinks; even where these incentives might be necessary to maintain the function of existing sinks (Nolan et al., 2024). Even where a practice meets the conditions necessary to be considered 'additional' in terms of its climate mitigation effect, differences in MRV capabilities could result in incentives tending towards visible land use changes or management practices, rather than practices that still increase the sequestration capacity of existing sinks [41] (Assmuth et al., 2024). As the design and treatment of additionality will depend on many factors, particularly the policy objectives and the intended use of credits for temporary removals, it may not be possible to incentivise all necessary actions to maintain and enhance the land sink using the same pricing mechanism. This means that pricing instruments would still need to be accompanied by other public investments and incentives to maintain existing sinks and stocks in the LULUCF sector, as discussed in Chapter 7.

Table 36 Mechanisms to incentivise temporary removals or storage

Instrument contains mechanisms to:	Upstream pricing	Downstream pricing	Stock storage subsidies
Incentivise establishment of new sinks	General feature of the instrument	General feature of the instrument	Possible feature of this instrument / feature in certain proposals
Incentivise maintenance of existing sinks/stocks	Not a general feature of this instrument or proposal	General feature of the instrument	General feature of the instrument

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

41 (Assmuth et al., 2024) give the example of the New Zealand ETS, where there are strong incentives on land use decisions (i.e. towards afforestation, and against deforestation), but little to incentivise practices to increase carbon storage in existing forests.

14.2.3 Managing storage duration and reversal

Downstream pricing and stock storage subsidy systems contain mechanisms to incentivise due diligence and manage liabilities in case reversals occur in the future. Under an upstream pricing approach, additional mechanisms would be needed to achieve this.

In principle, all pricing options can account for the lower typical storage duration of temporary removals and the costs of reversal. Upstream pricing does this by discounting rewards for removals upfront based on the assumed storage duration, while downstream pricing and stock storage subsidies do so by imposing direct financial costs in cases of reversal (Franks et al., 2022).

However, the three pricing options differ in terms of the incentives they provide for ongoing due diligence and mechanisms to manage reversal risks. Under downstream or stock storage subsidy mechanisms, the cost of reversal are managed directly within the payment model: as project owners' payments occur on an ongoing basis, any subsequent reversal translates either results in an immediate tax on emissions from reversal (downstream pricing) or a lower reward (stock storage subsidies). However, Franks et al. (2022) note that incentives for land managers to avoid reversals under a downstream pricing model depends on the continued operation of the manager: in the case of a firm with limited liability, this raises the possibility that the manager may could go bankrupt to avoid this subsequent cost. However, this can be mitigated depending on the design of the scheme: for example in the New Zealand ETS, the liability for forest reversals stays with the land, even when ownership changes (Carver et al., 2022). On the other hand, stock storage subsidies provide fewer opportunities for land managers to avoid these costs these effects. (Franks et al., 2022). Nevertheless, complementary mechanisms may still be needed as additional safeguards, or to manage the risk of potentially large-scale reversal events due to climate change (see Section 13.3.3).

Under upstream pricing models, the performance on this criterion can depends on the design, but under the default approach where rewards are provided upfront, there is no inherent in-built mechanism to promote due diligence. Incentives to avoid reversal could be built into the design of the pricing instrument, e.g. by staggering payments or only rewarding removals as they occur. However, without complementary mechanisms to enforce any subsequent liabilities or costs from reversal, it would otherwise provide few incentives for prevent reversal once payments have been collected (Franks et al., 2022). Therefore, upstream pricing approaches (in particular) would need to be combined with other mechanisms to manage reversal (see Section 13.3.3).

Table 37 Mechanisms to manage storage duration and reversal

Instrument contains mechanisms to:	Upstream pricing	Downstream pricing	Stock storage subsidies
Account for storage duration	General feature of the instrument	General feature of the instrument	General feature of the instrument
Incentivise due diligence and manage reversal risk	Not a general feature of this instrument or proposal	Possible feature of this instrument / feature in certain proposals	General feature of the instrument

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.2.4 Informational and MRV requirements

While some form of upstream pricing system could be implemented with limited informational requirements, these might become substantial as MRV needs become more stringent. Informational and MRV requirements would be most substantial under downstream or stock storage subsidies, posing a substantial challenge for their implementation.

Both downstream and stock storage subsidy approaches would result in substantial informational needs, as they require a regular and detailed monitoring of carbon stocks and fluxes. The corresponding, sophisticated MRV systems to achieve these pose a considerable barrier for the implementation of these comprehensive pricing systems. As outlined in Chapter 3, the viability of such MRV system can vary between removal methods.

In principle, upstream pricing mechanisms could be designed with relatively low informational requirements. To avoid detailed and continuous data requirements on carbon stocks or flows, rewards for carbon sequestration could be estimated based on standard growth factors, and discounted using equivalence ratios based on assumptions of a typical storage duration and reversal risks. However, the need for complementary mechanisms to incentivise due diligence means that informational requirements would grow increasingly stringent to monitor and verify that captured carbon remains stored. Depending on their stringency, this could become comparable to those required under a comprehensive downstream pricing system (Franks et al., 2022; Edenhofer et al., 2024a).

Table 38 Mechanisms to minimise informational requirements

Instrument contains mechanisms to:	Upstream pricing	Downstream pricing	Stock storage subsidies
Minimise informational requirements	Possible feature of this instrument / feature in certain proposals	Not a general feature of this instrument or proposal	Not a general feature of this instrument or proposal

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.2.5 Maintaining fiscal sustainability

The need for public finance would be lowest under downstream pricing instruments and highest under stock storage subsidies. Additionality requirements, baseline setting and links with other GHG pricing instruments could reduce the need for public finance under all approaches.

The impact on fiscal sustainability generally depends on whether and how the different pricing approaches are implemented, and the relationship with other GHG pricing instruments (see Section 13.4). If implemented as standalone instruments without any link, financing necessary to maintain a net LULUCF sink would likely rely on public funds to a large extent. Alternatively, the need for public finance could be reduced by linking temporary removals to other GHG pricing instruments through credits or revenue recycling. However, such links have many other broader implications that need to be considered, and ultimately depend on the objective of the pricing system.

Within the literature, potential fiscal sustainability and public acceptability challenges have been highlighted to a greater extent for stock storage subsidies, where the cost of financing both new removals and the conservation of existing stocks potentially becomes prohibitively expensive. Additionality requirements could reduce the fiscal costs of these pricing policies (i.e. by only subsidising stocks over a given baselines). However, it is unclear the extent to which this would result in trade-offs with other policy objectives, particularly to incentivise efforts to maintain existing sinks or carbon stocks (Tahvonen and Rautiainen, 2017; Assmuth et al., 2024).

Table 39 Mechanisms to maintain fiscal sustainability

Instrument contains mechanisms to:	Upstream pricing	Downstream pricing	Stock storage subsidies
Maintain fiscal sustainability			

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.2.6 Avoiding adverse environmental impacts

The risk of unintended adverse environmental impacts is likely to be higher under upstream pricing than under downstream or stock storage subsidies, therefore requiring stronger wider sustainability safeguards.

As outlined in Chapter 3, the risk of adverse environmental impacts is heavily context-dependent, and depends largely on the types and scale of practices that are incentivised by the pricing system. It also depends on effective mechanisms to certify removals and sustainability criteria to prevent harmful environmental impacts. However, differences in the incentive structure (described above) may also imply some differences in their risk of environmental impacts. In forests for example, carbon payment schemes can incentivise biodiversity-friendly practices in existing forests (e.g. longer rotation periods, reduced disturbances and continuous cover forestry), but if poorly-designed also risk incentivising practices that deliver additional removals, but with negative impacts for local ecosystems (e.g. monoculture plantations) (Assmuth et al., 2024). This may be a greater risk in an upstream pricing system, where stronger incentives for increased removals and lack of penalties for reversals could incentivise such practices. However, environmental impacts will ultimately depend on implementation, making it necessary to tailor the pricing system and sustainability criteria to the specific context, as further explained in Chapter 6 in the context of the do no significant harm requirement laid out in the CRCF regulation (EU, 2024g).

Table 40 Mechanisms to avoid adverse environmental impacts

Instrument contains mechanisms to:	Upstream pricing	Downstream pricing	Stock storage subsidies
Avoid adverse environmental impacts			

Legend
- General feature of the instrument
- Possible feature of this instrument / feature in certain proposals
- Not a general feature of this instrument or proposal

14.2.7 Summary of comparison and assessment

Table 41 below summarises the comparison and assessment of instruments for temporary removals and storage.

To maintain and enhance the EU's land sink, the EU needs new instruments to incentivise temporary removals or storage. While incentives based on upstream pricing models could be more feasible to implement in the short term, the EU should consider introducing developing more comprehensive mechanisms to price emissions and removals (or storage) in the LULUCF sector.

Implementing incentives for temporary removals through upstream pricing models would likely be the most feasible way to do so in the short term, primarily due to fewer informational requirements for regulators and administrative burdens for land managers. However, upstream pricing models would need to be combined with strong MRV systems and mechanisms to reduce and manage the risks of reversal (e.g. buffer accounts and contractual liabilities); as well as strict sustainability criteria to avoid negative environmental impacts. Certification mechanisms being developed under the CRCF regulation could form the basis of managing these risks, although some key uncertainties remain regarding their methodologies and implementation (see Chapter 6). However, incentive instruments based on upstream pricing models could likely be more rapidly implemented in different contexts, including as a way to design incentives to increase carbon sequestration through existing policies (e.g. eco-schemes under the CAP); or as new, standalone GHG pricing instruments.

While incentives based on upstream pricing models create clearer incentives for land managers to provide new removals in the LULUCF sector, it is questionable whether would be sufficient to incentivise practices necessary to maintain and enhance existing sinks or stocks. In line with the Advisory Board's previous recommendation, the EU should consider introducing more comprehensive mechanisms to price emissions and removals (or storage) in the LULUCF sector over time, which could be based on either a downstream pricing or stock storage subsidy model for greatest effect. The implementation of these systems would also require substantial investments in MRV systems to allow for more timely and accurate quantification of carbon fluxes and/or stocks, while still minimising burdens on small-scale land managers and administrations.

Table 41 Comparing price instruments for temporary removals or storage

Instrument contains mechanisms to:	Upstream pricing	Downstream pricing	Stock storage subsidies
Incentivise temporary removals or storage			
- *For new sinks*	General feature	General feature	Possible feature
- *For existing sinks / carbon stocks*	Not a general feature	General feature	General feature
Manage storage duration and reversal			
- *Account for storage duration*	General feature	General feature	General feature
- *Incentivise due diligence and manage reversal risk*	Not a general feature	Possible feature	General feature
Minimise informational requirements	Possible feature	Not a general feature	Not a general feature
Maintain fiscal sustainability	Possible feature	Possible feature	Possible feature
Avoid adverse environmental impacts	Possible feature	Possible feature	Possible feature

Legend
- ■ General feature of the instrument
- ■ Possible feature of this instrument / feature in certain proposals
- ■ Not a general feature of this instrument or proposal

As integrating temporary removals into the existing EU ETS would create significant risks and governance challenges that cannot be effectively managed in the short term, these instruments should therefore be implemented as standalone instruments within a coherent policy framework

for the LULUCF sector. Future links to the wider EU emission pricing system could be considered once challenges have been addressed.

The EU will also need to consider how pricing instruments or temporary removals or storage are funded, and linked to the wider climate policy framework. Regarding possible links with other GHG pricing instruments, previous sections have identified significant challenges in ensuring equivalence between temporary removals, permanent removals and emissions. As highlighted previously in Section 14.1.8, the integration of temporary removals into the EU ETS would create significant risks for mitigation deterrence and environmental integrity, which realistically cannot be expected to be resolved in the short to medium term. Therefore, this section concluded that integration of removals into the EU ETS should be limited to permanent removals at first. Yet, there is still an urgent need for action and incentives to reverse the declining LULUCF sink. This means that the EU should therefore develop incentive instruments for temporary removals separately from the current EU ETS in the short term, where these challenges can more feasibly be addressed without the risks of undermining incentives for emission reductions in other sectors.

While pricing instruments for temporary removals and/or storage should therefore be implemented initially as standalone instruments, future links to the EU's wider emissions pricing system could be considered only once robust mechanisms to establish equivalence and to manage long-term reversal risks have been established. The Advisory Board (2024) has previously noted the possibility of linking incentives for temporary removals in some form to future GHG pricing instruments for the agricultural or agrifood sector, while a study for the European Commission has similarly studied options for doing so (Trinomics, 2023b). The Advisory Board will also examine options to support mitigation and adaptation in the agrifood sectors in a future publication.

Finally, whichever pricing approach is chosen, a LULUCF pricing mechanism should be considered as just one important element of coherent policy framework for managing the EU's land, biomass resources and ecosystems. Addressing land-use conflicts and enhancing policy synergies are essential first steps to rebalancing incentives for land and biomass use. This also needs to be accompanied by other public investments and policies aimed at conserving and restoring the EU's ecosystems, particularly through robust and well-funded implementation of the Nature Restoration Law, better alignment of the common agricultural policy with climate and removal objectives, and development of the EU's land monitoring and MRV systems (see Chapter 7). This also includes complementary measures to incentivise adaptive best practices, which can reduce the risks of reversal events in general, and to compensate for reversal induced by climate change and natural hazards.

14.3 The role of sequencing and a dynamic policy mix

Sections 14.1 and 14.2 highlight that no single policy instrument can meet all needs over time, given the evolving technologies and challenges in removal. This section evaluates the role of sequencing and a dynamic policy mix in balancing these objectives and instruments over time.

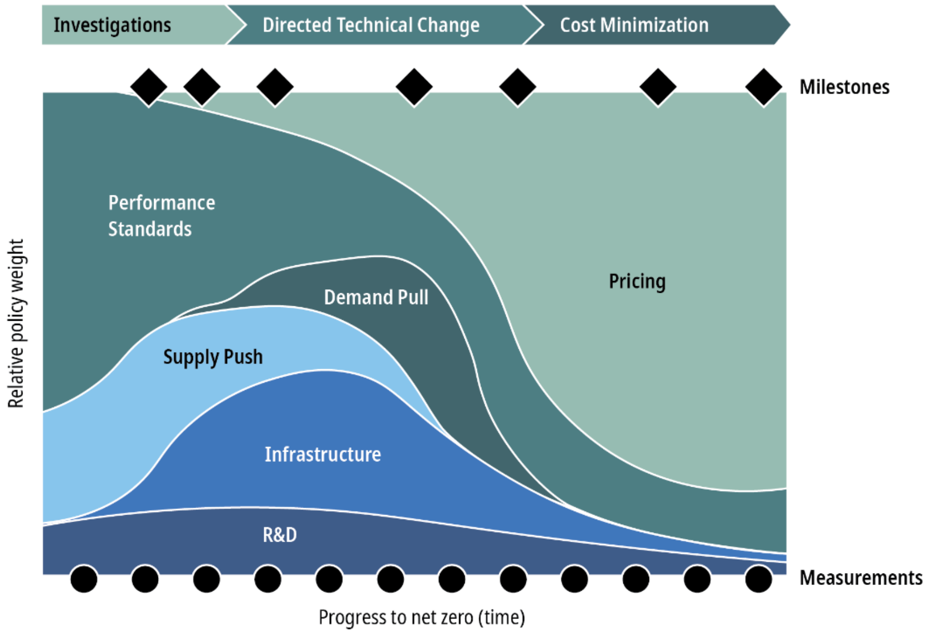
Policy sequencing and a dynamic policy mix can improve the effectiveness, feasibility and credibility of ambitious climate policies.

Several authors (Pahle et al., 2018; Dolphin et al., 2023; Meckling et al., 2017) have highlighted the importance of sequencing in designing effective climate policies, particularly as a way of balancing commitment and flexibility in achieving long-term climate goals. Long-term climate goals, such as the EU's climate targets and climate neutrality objective, are important to signalling commitment and helping to align the expectations of policymakers and economic actors around a common goal.

However, the optimal pathways and instruments to achieve these goals can be uncertain and dynamic, and likely to change when faced with new information, technological evolution and other changing circumstances or priorities over time. Sequencing can ensure that the policy framework is sufficiently adaptive, creating flexibility to respond and adjust the course as necessary at different points in time, while still maintaining and signalling a commitment towards long-term climate objectives (Anadón et al., 2022).

As an illustrative example in Figure 34 below, Dolphin et al. (Dolphin et al., 2023) outline a 'backward induction' approach to designing a sequencing strategy towards long-term climate targets, showing how the policy and instrument mix is likely to change according to several identified objectives. Initially, a diverse range of instruments and policy experimentation is used to overcome barriers to decarbonisation. As these barriers are addressed and optimal pathways become clearer, the focus shifts to cost-effectiveness through the phase-out of less efficient measures and the introduction of more efficient GHG pricing instruments.

Figure 34 Example of dynamically-consistent policy pathway towards net-zero, as illustrated by Dolphin et al. (2022, 2023)



Source: Figure reproduced from Dolphin et al. (2022, 2023)

Notes: The stylised pathway illustrates a dynamically-consistent policy mix towards a net-zero objective, showing how the policy mix and portfolio of instruments is guided by evolving priorities over time. Although pricing instruments are often described as an efficient 'first-best' instrument, costly or uncertain technologies, public and political opposition, institutional weaknesses and other market failures are common barriers to effectiveness and feasibility. In the early stage of the policy framework, where barriers to decarbonisation are high and mitigation pathways are less clear, the policy mix is more diverse, focused on investigating technologies and overcoming these barriers through a wide range of instruments and policy experimentation. As these barriers are addressed and optimal mitigation pathways and technologies become clearer, policy priorities shift to securing greater cost-effectiveness through the phase out of less effective subsidies and performance standards; and the phase in of more efficient GHG pricing instruments.

The literature generally highlights the need to combine instruments over time to firstly address key governance challenges, particularly certification, environmental and social integrity, and support for technological development and deployment. These generally include non-market instruments at first, before the integration of removals into carbon markets can be considered.

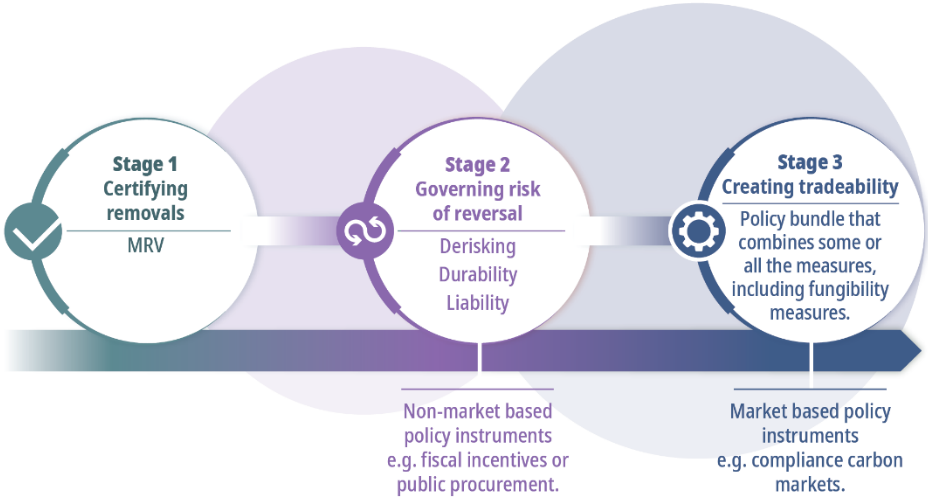
As highlighted in Part B in this report, removals face many similar barriers to scaling up sustainably, from a lack of credible certification and MRV systems for different removal types (Chapter 6), unique pressures on land or biomass resources (Chapter 7), to technological immaturity (Chapter 8). As highlighted previously, many of these instruments also have different effects in terms of mitigation deterrence that need to be balanced over time. Several authors have therefore proposed sequencing strategies for removals in climate policies to overcome these barriers. These strategies generally follow several broad steps, with early stages focused on measures aimed at ensuring environmental and social integrity (e.g. MRV, certification, reversal management and preventing mitigation deterrence) and improving deployment readiness, before a careful phase-in into carbon markets.

Burke and Schenuit (2023) suggest a three-stage conceptual policy mix to integrate removals into EU policies, as illustrated in Figure 35:

1. beginning with certification and MRV as a 'foundational measure',
2. followed by measures to address the risks of reversal,
3. and a final stage 'tradability'.

Robust certification is a minimum precondition for introducing any incentive instruments for removals in their proposal, as well as in sequencing proposals from other authors (Burke and Gambhir, 2022; Sultani et al., 2024; Rickels et al., 2021). During the first two stages of this conceptual sequencing framework, Burke and Schenuit (2023) outline that demand and funding for removals would primarily come from other non-trading-based instruments, and only after robust measures for certification and addressing reversal risks have been put in place would integration into carbon markets be considered.

Figure 35 Example of a sequencing framework for removals, as illustrated by Burke and Schenuit (2023)



Source: Reproduced from Burke and Schenuit (2023), figure ES2

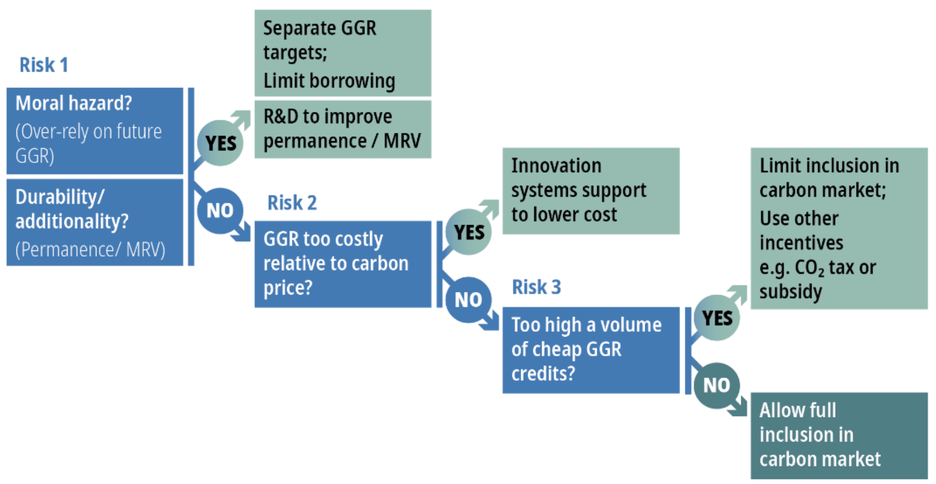
Notes: The figures are added for illustrative purposes. Its inclusion does not imply an endorsement of the approach by the Advisory Board

Proposals for integrating removals into carbon markets generally prioritise the integration of high-quality, permanent removal methods as a first step; and the pursuit of a sequential or conditional integration pathway only once key risks and governance challenges have been addressed.

The third and final stage ('tradability') in Burke and Schenuit's framework (2023) puts in place measures to allow for trade between removals and emissions in compliance markets. These measures (described as 'fungibility' measures) are described as necessary prerequisites for any market integration, although the authors emphasise that this third stage will not necessarily be achieved, or even be the end-goal for all removal policies or methods. Similarly to other authors, they also recommend the need to consider separate markets for temporary and permanent removals, based on similar challenges in establishing equivalence to those described in Chapter 4, and the risk of misplaced substitution between emission reductions and temporary removals.

Burke and Gambhir (2022) highlight similar conditions and steps to integrating removals into carbon markets, although they also suggest a more staged, risk-based decision-making process that could be used to distinguish the suitability of individual removal methods (see Figure 36). These steps consider and address the most significant risks of carbon market integration that they identify in the scientific literature, namely the quality or permanence of different removal methods, and the price of removals relative to emission reductions to ensure that they do not undermine incentives to reduce emissions. As illustrated in Figure 36, they indicate potential strategies or complementary instruments to address each risk in a sequential manner, beginning with separate targets to limit mitigation deterrence, followed by innovation supports and other incentives in separate markets, before allowing the inclusion in carbon markets only once key risks have been addressed.

Figure 36 Example of sequencing framework for integrating removals into carbon markets, as illustrated by Burke and Gambhir (2022)



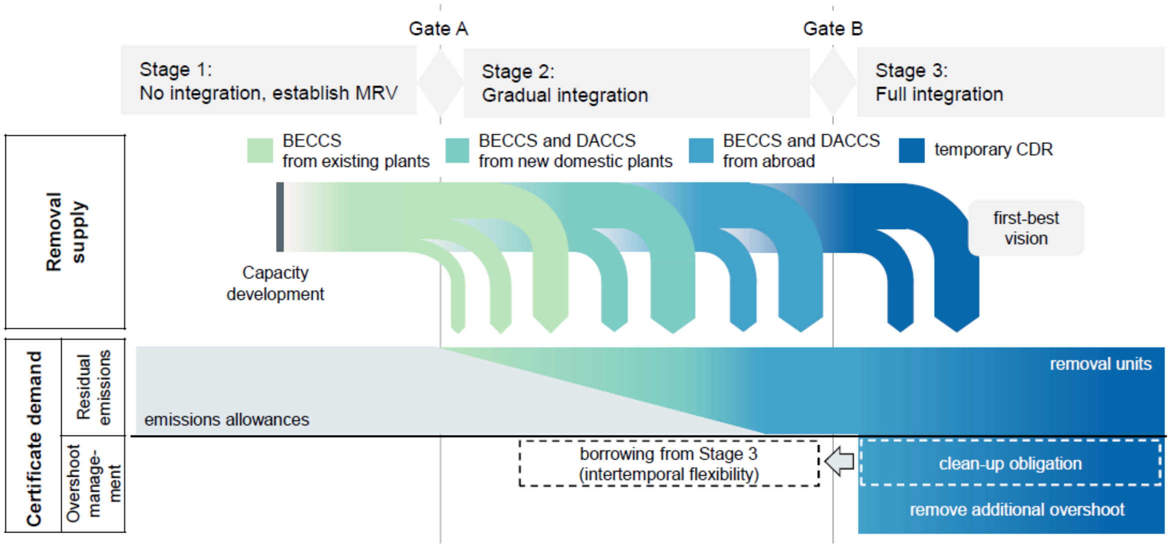
Source: Reproduced from Burke and Schenuit (2022)

Notes: GGR refers to 'Greenhouse Gas Removals'. Figures are added for illustrative purposes, and it does not imply a recommendation of the approach by the Advisory Board

Based on the backward induction approach suggested by Dolphin et al. (Dolphin et al., 2023), Sultani et al. (2024) also suggest a sequential approach to integrating removals into the EU ETS, as shown in Figure 37 below. Assuming that the key risks and barriers associated with integration can be overcome, they describe the necessary conditions to achieve a desirable 'first-best' vision of EU ETS integration, or an ideal cost-effective regulatory framework to govern the scale-up of removals. Achieving this first-best would require comprehensive pricing of externalities and reversal risks, enhanced supply-side efficiency, and the development of a strategy for net-negative and overshoot management. In practice however, they highlight that achieving all of these conditions for all removal methods may not be feasible. On that basis, they outline a proposal for a 'second-best' regulatory framework, and a sequencing strategy for integrating different removal methods based on clear entry condition designed to address key risks.

As part of this sequencing strategy, they propose beginning with removal methods that they assess as having the greatest certainty in terms of permanence, quantifiability and additionality. Assuming the establishment of reliable certification systems, they consider these first phases of integration are likely to prioritise permanent removals with geological storage, namely DACCS and BECCS, although they emphasise the need to first put in place additional conditions or quantitative limits to manage environmental risks from BECCS in particular (Sultani et al., 2024). This early focus on DACCS and BECCS follows similar proposals by other authors (Edenhofer et al., 2024a; Rickels et al., 2021), who expect that methodologies developed under the EU's CRCF regulation (EU, 2024g) could create a basis for more credibly certifying these removal methods, while also noting that the existing CCS directive provides a basis to regulate and manage reversal from geological storage sites (Rickels et al., 2021). However, Sultani et al. (2024) make a further distinction between BECCS applied to existing facilities or processes, and new BECCS facilities; arguing for the former as an option with fewer environmental or sustainability risks and therefore a greater priority for integration in the short-term than new BECCS facilities. For new BECCS facilities, they suggest that these should only be integrated once key environmental conditions have been addressed, particularly the extension of full Pigouvian pricing to biomass (Sultani et al., 2024).

Figure 37 Example of a stage-gate framework for integrating removals into the EU ETS, as illustrated by Sultani et al. (2024)



Source: Sultani et al. (2024)

Notes: The figure is added for illustration purposes. Its inclusion does not imply an endorsement of the approach by the Advisory Board

Complementary instruments and policies for biomass are also discussed previously in Chapter 7. Based on this analysis, these conditions would need to include mechanisms to ensure sustainable biomass sourcing and to reinforce the coherence of EU policies that put pressure on land and biomass resources. While this also highlights the need to extend pricing to emissions and removals in the LULUCF sector, quantitative limits or restrictions on BECCS applications (e.g., restricting its use to specific processes) may also be necessary to prevent excessive biomass use associated with the integration of BECCS.

Sultani et al.'s (2024) proposal highlights the possibility of considering other removal methods for integration to increase 'supply-side efficiency', which in the long term, they suggest could eventually include emerging methods, BECCS and DACCS from abroad[42] and temporary removals. However, they emphasise that these would first have to overcome significantly more challenging governance risks

[42] As noted in section 6.7.2, the European Climate Law requires a balance of domestic emission reductions and removals towards the EU climate neutrality objective. As such, the Advisory Board's advice on a 2040 reduction target emphasised the need to support additional climate mitigation efforts outside of the EU in *addition* to domestic emission reduction efforts, in order to close the gap in the EU's fair share of the global GHG budget (Advisory Board, 2023).

compared to earlier stages, in order to protect both domestic and global environmental integrity and fairness. This echoes previous conclusions in section 14.1 and 14.2 and other assessments, which point to the need to consider alternative pricing instruments for temporary removals at first given these significant challenges.

Similar to other authors (Edenhofer et al., 2024a; Fridahl et al., 2023; Rickels et al., 2022, 2021), they also highlight the potential for an intermediary institution such as a European Central Carbon Bank to manage this integration process, and in particular to ensure a balance between commitment, preventing mitigation deterrence and efficiency. As noted previously, this could also facilitate the introduction of mechanisms to operationalise an extended emitter responsibility within the EU ETS, such as clean-up certificates. The role of institutions is addressed in the next section.

The different assessments summarised above show how a dynamic adjustment of the policy framework could provide a best way forward to address the different governance needs at different points in time. In line with these assessments, the Advisory Board has recommended that a progressive integration of removals into the EU climate policy framework could provide a best way forward to adapt to the evolving needs over time, in order to fulfil the different governance functions described Part B (see Recommendations and Summary).

14.4 The role of institutions and capacities

Some of the approaches above – such as the integration of the removals into the EU ETS via an intermediary – would require specific roles to be assigned to one or more public institutions. Furthermore, as described in Chapter 10, current EU institutions do not yet address many of the key governance functions enabling removals with a view of achieving net-negative emissions. This section briefly outlines two possible ways to enhance institutional capacities: layering of competences on existing actors and creating new institutional entities. It complements them with a set of cross-cutting considerations for the EU's institutional enhancement.

14.4.1 Layering of competences on existing actors

Existing institutions could take on some of the governance roles needed to scale up removals sustainably.

New roles identified for removals could be layered onto existing institutions for the pursuit of wider benefits or broader development concerns (see Chapter 10). Layering is a common approach when climate objectives are embedded alongside other policy considerations, and can contribute to mainstreaming objectives for removals across institutions and governance levels. Prior to the process of layering, sectoral institutions (e.g. in forest and energy sectors) may play an important latent role in shaping net-negative transition, before it becomes of part of their formal mandate. The layering approach is also associated with higher resilience in settings where political support to net negative policy framings is not prominent (IPCC, 2022f).

On the other hand, a layering approach presents several governance risks, such as slow changes to the current set-up. In some contexts, assimilation of climate institutions with the existing bureaucracy may limit their transformative capacity (Hermawan et al., 2023) and strategic action (Dubash, 2021). It may suffer, for instance, from a lack of leadership and unclear responsibilities regarding the success and failure of coordinated initiatives (OECD, 2021), as well as unstable commitment due to shifting political priorities (see, for example, Wonka and Rittberger 2010).

Integration of removal-related mandates into the existing bodies could entail an elaborated multi-level governance structure, including enhanced inter-institutional and inter-service cooperation, which is typical of mission oriented innovation policies (OECD, 2021).

14.4.2 New institutional actors

Assuming a broad political support to net-negative transition, new removals-oriented public entities could emerge, persist and deliver on the long-term vision.

To avoid the governance risks of the layering approach, several academic contributions suggest a need to create at least one new entity that would become central to addressing the new institutional roles. In particular, as highlighted in previous chapters, the option of integrating removals into the EU ETS indirectly via an intermediary implies the need for more active management of the stages and risks of integration. A core task of such an institution is to manage the supply of emission allowances and removal credits, and any associated adjustments to the cap, while responding to any risks or opportunities associated with integration including mitigation deterrence, environmental spillovers, and cost-effectiveness. Any instruments for net negative and temporary removals create additional challenges in enforcing and managing long-term liabilities, which implies additional tasks for public institutions depending on the design of these instruments (see Chapter 12 and 13).

Several proposals to establish a European Central Carbon Bank (Edenhofer et al., 2024a; Jeszke et al., 2024; Rickels et al., 2022), a Carbon Clearing House (Carbon Gap, 2024), or earlier concepts of an Independent Carbon Market Authority (De Perthuis and Trotignon, 2014) foresee a role for such an institution in the 'dynamic management of the supply of allowances', and whose 'main mission would be to ensure the optimal linkage between the different temporal horizons of the climate strategy' (De Perthuis and Trotignon, 2014). The rationale for such institutions is often framed similarly to monetary policy, as an institutional response to balance commitment with flexibility. While fixed rules can reduce risks and ensure commitment to a particular policy path, they can quickly become inflexible or costly, particularly in a context where technologies and information are rapidly evolving. On the other hand, the more discretion or opportunities to revise rules, the greater the potential that short-term political or economic pressures could influence decisions in a way that deviates from a commitment to long-term climate objectives (De Perthuis and Trotignon, 2014). Delegating these functions for removals to a dedicated EU entity could provide direct management of emission allowances and removal credits independently from direct political control, in a similar way the European Central Bank is tasked with managing price stability in the EU (Rickels et al., 2022; Sultani et al., 2024).

Beyond the day-to-day management of the carbon market, many proposals also envisage an intermediary institution with a long-term mandate to support the development of removals capacity from an early stage, helping to shape the overall contribution of removals to EU climate objectives (Edenhofer et al., 2024a; Sultani et al., 2024). Such a purpose-built entity with a strong legal mandate (IPCC, 2022) could offer a strategic long-term focus on the transition towards net zero and net negative, serving as a hub of technical, financial expertise and funding within the EU, while helping to establish links to non-EU partners. As such, it could promote responsible messaging and facilitate knowledge feedback loops (see Chapter 10).

The notion of institutional independence in EU governance is often linked to the regulatory content delegated to the entity, and its complexity requiring expert input from regulatory agencies (Wonka and Rittberger, 2010; Vos, 2016). The type of independence the European Central Bank is bestowed with, is strongly rooted in the EU treaties (EU, 2016) and the ECB is one of the seven EU institutions forming the wider EU's institutional set up. That set-up includes also eight EU bodies, such as the EIB, and over thirty decentralised agencies (EU, 2024h). Regardless of its specific form, a new entity would need to be carefully designed to balance its executive and strategic functions, so as to avoid the risks linked to weak accountability and legitimacy (Edenhofer et al., 2024a).

14.4.3 Cross-cutting considerations

The scientific literature and policy discussions regarding possible institutional set-up to govern future EU carbon markets are only emerging (IPCC, 2022f; Smith et al., 2024). The following five considerations emerge, and should be considered in the EU's decision making:

For institutional capacities to grow, it is essential to ensure sufficient and adequate staffing, financial resources and capacity building of all involved authorities.

Only well-resourced public bodies, including those involved in environmental assessments and permit-granting procedures (see EC, 2024), can foster the new roles needed to scale-up removals sustainably. Resources enable innovative approaches within public administrations that go beyond the minimum compliance needs. Innovation could be stimulated, for example by interactions between regulators, researchers and industry, driven by the common goal of making innovation thrive within the regulatory settings (Clausen et al., 2023).

Ownership of various roles could be considered in terms of the rationale behind its allocation to public or private entities.

While private sector may be suited to deliver technical and financial services within the wider governance functions (e.g. providing tailored insurance products), public institutions will be needed to create policy and regulatory environment to kick-off the demand for removals, develop CO_2 infrastructure, manage long-term commitments and ensure regulatory oversight (IPCC, 2022f; Mac Dowell et al., 2022). In some cases, public-private partnership could emerge as the most efficient enhancement of institutional capacities (Draghi, 2024). Further consideration could be given to the roles of private rating agencies and insurance companies and their link to the public governance of removals scale-up (Burke and Schneuit, 2023).

To preserve the rule of law, institutions tasked with scaling-up removals should avoid reducing normative questions to technical ones.

The separation of executive tasks from political decision-making helps prevent arbitrariness (e.g. picking winners among removal methods) and untransparent consideration of the opportunities and risks of removal options. Important mechanisms for transparency and public deliberation are already embedded in EU law making and implementation, with the European Court of Justice ensuring effective judicial protection supported by the European Court of Auditors and the European Ombudsman in upholding the principles of transparency and rule of law (EC, 2023a). While the executive functions could be delivered by non-legislative bodies, political and strategic functions require a legislative scrutiny, that is, the involvement of the European Parliament and the Council.

Enhanced cross-border and regional cooperation between the Member States will be essential to scale-up removals and consider transboundary costs and benefits of such activities.

In parallel to bilateral memoranda of understanding, regional alliances to foster CCS value chains are emerging, for example the Aalborg Declaration on enabling cross-border CCS and CCU in Europe (2023) has been signed by Denmark, France, Germany, the Netherlands and Sweden. Similar cooperations are contemplated in Central and Eastern Europe (Wise Europa, 2021). The regional, rather than national, approach, to large scale infrastructure planning and development has been successfully driving EU's energy infrastructure roll-out. However, regional cooperation alone may not suffice to realign diverging national objectives (see Ecologic 2015). Similarly, terrestrial and marine ecosystem restoration (e.g.

through the Nature Restoration Law) will often require cross-border and regional cooperation. Encouraging multilateralism in the context of removals could consist of facilitating regional fora or centralizing regulatory oversight at EU level (e.g., building on the role of regional groups in cross-border project selection and planning), and ACER's role in energy markets.

EU's transition to net negative requires strong institutional governance and responsible narratives.

A suitable governance approach involves joining efforts, resources, and knowledge across disciplinary, sectoral and policy silos. It could therefore be inspired by the 'mission-oriented innovation policy' framework developed by the OECD. The framework offers tools and processes that engage stakeholders, align various policy actors and instruments towards the common goal, and increase commitments of public and private resources (OECD, 2021). Such an approach could enable responsible messaging embedded in internally-consistent, context-specific narratives that explain the severity of failed GHG emission reduction and the role of removals in EU's climate policy (Bellamy et al., 2019; Cox et al., 2024). Mission-oriented policies are currently tested in different jurisdictions, including at the EU level under Horizon Europe programme. They offer promising results and useful lessons learnt (EC, 2023f; Mazzucato, 2024; OECD, 2021).

Abbreviations

BECCS	Bioenergy with carbon capture and storage
CAP	Common agricultural policy
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation and storage
CO_2	Carbon dioxide
CRCF	Carbon removals and carbon farming certification
DACCS	Direct air carbon capture and storage
EU	European Union
EU ETS	European Union emission trading system
GDP	Gross domestic product
GHG	Greenhouse gases
IAM	Integrated assessment models
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land use change and forestry
MRV	Monitoring, reporting and verification
NECPs	National energy and climate plans
RD&D	Research, demonstration & development
RED	Renewable energy directive
TRL	Technology readiness level
UNFCCC	United Nations Framework Convention on Climate Change

Glossary

Additionality	The notion of going beyond a counterfactual; in other words, not having occurred in the absence of a particular intervention. It can apply to carbon fluxes (i.e. additional GHG emissions, reductions and removals that can be directly attributed to a particular intervention, that would not have occurred in the absence of that intervention; and to the intervention itself i.e. an action that would not have occurred without dedicated incentives. Various forms of additionality can be specified in different contexts and measured through additionality tests.
Carbon capture and storage (CCS)	A process in which a relatively pure stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. CCS can only result in a removal when the CO_2 that is captured and stored originates from the atmosphere or biomass.
Carbon capture and utilisation (CCU)	A process in which CO_2 is captured and then used to produce a new product. CCU can only result in a removal if the captured CO_2 originates from the atmosphere or biomass, and then stored in a durable product for a climate-relevant time horizon.
Carbon dioxide (CO_2) removals	Anthropogenic removal of CO_2 from the atmosphere and its durable storage in geological, terrestrial or ocean reservoirs, or in long-lasting products.
Cost-effectiveness	For emission reduction pathways, cost-effectiveness (sometimes referred to as cost-efficiency) refers to a portfolio or allocation that achieves a given climate target or GHG budget at the lowest social cost. For any mitigation technologies, including removals, this occurs when the marginal abatement costs are equalised, assuming that costs also take into account wider social costs and externalities. Cost-effectiveness can also be considered in either static terms (i.e. based on assumptions of current costs, technologies and market structures), or as **dynamic cost-effectiveness**, which considers how these factors are likely to change over time.
Carbon market	Trading systems in which carbon credits are bought and sold by individuals, firms or governments, including credits generated from CO_2 removal projects. Where purchases are made on voluntary basis (e.g. for corporate marketing claims), these are referred to as voluntary carbon markets. Where these purchases are required to meet national or international regulatory requirements, they are referred to as compliance markets.
Equivalence	The degree to which different mitigation options (emission reductions, temporary removals or permanent removals) have a similar impact on radiative forcing and the global average

	temperature. This is determined by their quantifiability, additionality and duration.
Extended emitters' responsibility	The responsibility for an emitting entity to remove GHGs it has emitted in the atmosphere.
Fiscal sustainability	Refers to the ability of a public body to sustain its current spending, tax and other-related policies in the long run without threatening its solvency or defaulting on some of its liabilities or promised expenditures. Ensuring public finances are sustainable is important to ensure intergenerational fairness and that governments can issue debt to ensure the smooth functioning of the economy, to respond to unforeseen circumstances. In the EU, sustainability of public finances in the EU is closely linked to principles enshrined in the Treaties, to the Stability and Growth Pact.
Greenhouse gas (GHG) budget	A GHG budget gives an estimate of the maximum remaining cumulative volume of GHGs that can be emitted to keep warming below a given temperature target.
Intertemporal flexibility	The flexibility to shift or reallocate mitigation efforts throughout time. Removals provide an opportunity for intertemporal flexibility as they can be used to reduce the cumulative net GHG emissions over time (by actively removing GHG emitted historically), or to lower the cost of achieving a given GHG budget (provided that the cost of removals decreases substantially in the future) by temporarily allowing emissions which are removed from the atmosphere at later stage.
Mitigation deterrence	The prospect of reduced or delayed emission reductions from the introduction or consideration of CO_2 removals.
Monitoring, reporting and verification (MRV)	Process to measure or estimate the amount of GHG emissions reduced and/or removed, future reversals, and often other sustainability effects of an activity over time, report these findings, and have them independently checked to confirm they reflect reality.
Net-negative emissions	A condition in which the volume of removals exceeds the volume of emissions.
Net-zero emissions	A condition in which anthropogenic GHG emissions are balanced by removals over a specified period of time.
Overshoot	Temperatures temporarily exceeding a specified temperature limit, or emissions exceeding the limit set by a GHG budget.
Permanent removals	Permanent CO_2 removals are generally those that provide the conditions for CO_2 to reliably remain stored for thousands of years (e.g. CO_2 removals with geological). However, different certification schemes and policies may adopt other definitions or timescales to categorise permanent removals.

Polluter pays principle	In a general context, application of the polluter pays principle means that polluters bear the costs of their pollution including the cost of measures taken to prevent, control and remedy pollution and the costs it imposes on society (ECA, 2021). Within the context of the different incentive instruments explored in Part C of this report, application of the polluter pays principle implies that the instrument requires GHG emitters to pay for their emissions (to compensate for the costs these emissions impose on society); or to deploy or finance the deployment of removals to counterbalance their emissions (to prevent or remedy the pollution).
Residual emissions	Within climate neutrality scenarios and targets, residual emissions refer to any emissions that have not yet been abated, and which need to be counterbalanced by removals in order to achieve climate neutrality. Residual emissions are generally assumed to come from **activities with currently no or limited mitigation alternatives**, for which technological or economic reasons could make it prohibitively expensive to achieve climate neutrality through emission reductions alone. Beyond techno-economic considerations, residual emissions are an inherently normative category. The exact level and nature of residual emissions remains uncertain, depending on future technological progress and the full range of supply- and demand-side mitigation policies considered. Therefore, the dynamics surrounding residual emissions require sufficient flexibility to accommodate future transitional challenges.
Reversal	The release of removed GHGs into the atmosphere. Reversal (or reversal events) can occur due to both direct human actions, such as harvests, land use change, or poor maintenance of storage sites; as well as indirect human or natural causes, such as natural hazards and climate change impacts.
Temporary removals	CO_2 removals where CO_2 is stored for decades to centuries (for example via plants).

Bibliography

Abegg, M., et al., 2024, 'Expert insights into future trajectories: assessing cost reductions and scalability of carbon dioxide removal technologies', *Frontiers in Climate* 6, p. 1331901 (DOI: 10.3389/fclim.2024.1331901).

ADEME, 2021, *Transitions 2050: Choisir maintenance agir pour le climat*, Agence de la transition écologique (https://librairie.ademe.fr/cadic/6531/transitions2050-rapport-compresse2.pdf) accessed 31 January 2024.

Adun, H., et al., 2024, 'Sustainability implications of different carbon dioxide removal technologies in the context of Europe's climate neutrality goal', *Sustainable Production and Consumption*, p. S2352550924001003 (DOI: 10.1016/j.spc.2024.04.003).

Advisory Board, 2023, *Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050*, European Scientific Advisory Board on Climate Change, Copenhagen, Denmark.

Advisory Board, 2024, *Towards EU climate neutrality: progress, policy gaps and opportunities*, European Scientific Advisory Board on Climate Change, Copenhagen (https://climate-advisory-board.europa.eu/reports-and-publications/towards-eu-climate-neutrality-progress-policy-gaps-and-opportunities) accessed 29 January 2024.

Agora Agriculture, 2024, *Agriculture, forestry and food in a climate neutral EU*, Agora Agriculture, Berlin (https://www.agora-agriculture.org/fileadmin/Projects/2024/2024-09_EU_Agriculture_forestry_and_food_in_a_climate_neutral_EU/AGR_336_Land-use-study_WEB.pdf).

Agyarko-Mintah, E., et al., 2017, 'Biochar increases nitrogen retention and lowers greenhouse gas emissions when added to composting poultry litter', *Waste Management* 61, pp. 138-149 (DOI: 10.1016/j.wasman.2016.11.027).

Ahonen, H.-M., et al., 2022, 'Governance of Fragmented Compliance and Voluntary Carbon Markets Under the Paris Agreement', (DOI: 10.5167/UZH-229905).

Alcalde, J., et al., 2018, 'Estimating geological CO2 storage security to deliver on climate mitigation', *Nature Communications* 9(1), p. 2201 (DOI: 10.1038/s41467-018-04423-1).

Alhajaj, A. and Shah, N., 2020, 'Multiscale design and analysis of CO2 networks', *International Journal of Greenhouse Gas Control* 94, p. 102925 (DOI: 10.1016/j.ijggc.2019.102925).

Allen, M. R., et al., 2024, 'Geological Net Zero and the need for disaggregated accounting for carbon sinks', *Nature* (DOI: 10.1038/s41586-024-08326-8).

Aminian-Biquet, J., et al., 2024, 'Over 80% of the European Union's marine protected area only marginally regulates human activities', *One Earth*, p. S2590332224003646 (DOI: 10.1016/j.oneear.2024.07.010).

Anadón, L. D., et al., 2017, 'Integrating uncertainty into public energy research and development decisions', *Nature Energy* 2(5), p. 17071 (DOI: 10.1038/nenergy.2017.71).

Anadón, L. D., et al., 2022, *Ten principles for policy making in the energy transition*, Cambridge, UK (https://eeist.co.uk/eeist-reports/ten-principles-for-policy-making-in-the-energy-transition/).

Andersen, A. D. and Gulbrandsen, M., 2020, 'The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway', *Energy Research & Social Science* 64, p. 101447 (DOI: 10.1016/j.erss.2020.101447).

Andreoni, P., et al., 2024, 'Emissions and carbon prices under a 1.5 °C scenario with and without...', *Nature Climate Change* (14), pp. 20-21 (DOI: https://doi.org/10.1038/s41558-023-01871-6).

Andries, A., et al., 2021, 'Can Current Earth Observation Technologies Provide Useful Information on Soil Organic Carbon Stocks for Environmental Land Management Policy?', *Sustainability* 13(21), p. 12074 (DOI: 10.3390/su132112074).

Arias-Navarro, C., et al., eds., 2024, *The state of soils in Europe: fully evidenced, spatially organised assessment of the pressures driving soil degradation*, Publications Office, Luxembourg.

Assmuth, A., et al., 2024, 'Forest carbon payments: A multidisciplinary review of policy options for promoting carbon storage in EU member states', *Land Use Policy* 147, p. 107341 (DOI: 10.1016/j.landusepol.2024.107341).

Astrup, P., 2018, *Sea-level change in Mesolithic southern Scandinavia. Long- and short-term effects on society and the environment*, Sea-level change in Mesolithic southern Scandinavia. Long- and short-term effects on society and the environment.

Auffhammer, M., et al., 2016, 'Chapter 4. Economic Considerations: Cost-Effective and Efficient Climate Policies', *Collabra* 2(1), p. 18 (DOI: 10.1525/collabra.63).

Aumont, O. and Bopp, L., 2006, 'Globalizing results from ocean in situ iron fertilization studies', *Global Biogeochemical Cycles* 20(2), p. 2005GB002591 (DOI: 10.1029/2005GB002591).

Babin, A., et al., 2021, 'Potential and challenges of bioenergy with carbon capture and storage as a carbon-negative energy source: A review', *Biomass and Bioenergy* 146, p. 105968 (DOI: 10.1016/j.biombioe.2021.105968).

Baccour, S., et al., 2021, 'Cost-Effective Mitigation of Greenhouse Gas Emissions in the Agriculture of Aragon, Spain', *International Journal of Environmental Research and Public Health* 18(3), p. 1084 (DOI: 10.3390/ijerph18031084).

Bach, L. T., et al., 2019, 'CO2 Removal With Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems', *Frontiers in Climate* 1 (DOI: 10.3389/fclim.2019.00007).

Bach, L. T., 2024, 'The additionality problem of ocean alkalinity enhancement', *Biogeosciences* 21(1), pp. 261-277 (DOI: 10.5194/bg-21-261-2024).

Bacon, K. L., et al., 2017, 'Questioning ten common assumptions about peatlands', *Mires and Peat* (19), pp. 1-23 (DOI: 10.19189/MaP.2016.OMB.253).

Badgley, G., et al., 2022a, 'California's forest carbon offsets buffer pool is severely undercapitalized', *Frontiers in Forests and Global Change* 5, p. 930426 (DOI: 10.3389/ffgc.2022.930426).

Badgley, G., et al., 2022b, 'Systematic over-crediting in California's forest carbon offsets program', *Global Change Biology* 28(4), pp. 1433-1445 (DOI: 10.1111/gcb.15943).

Baek, S. H., et al., 2023, 'Impact of Climate on the Global Capacity for Enhanced Rock Weathering on Croplands', *Earth's Future* 11(8), p. e2023EF003698 (DOI: 10.1029/2023EF003698).

Bais-Moleman, A. L., et al., 2018, 'Assessing wood use efficiency and greenhouse gas emissions of wood product cascading in the European Union', *Journal of Cleaner Production* 172, pp. 3942-3954.

Balmford, A., et al., 2023, 'Realizing the social value of impermanent carbon credits', *Nature Climate Change* 13(11), pp. 1172-1178 (DOI: 10.1038/s41558-023-01815-0).

Bamber, N., et al., 2020, 'Comparing sources and analysis of uncertainty in consequential and attributional life cycle assessment: review of current practice and recommendations', *The International Journal of Life Cycle Assessment* 25(1), pp. 168-180 (DOI: 10.1007/s11367-019-01663-1).

Bamière, L., et al., 2023, 'A marginal abatement cost curve for climate change mitigation by additional carbon storage in French agricultural land', *Journal of Cleaner Production* 383, p. 135423 (DOI: 10.1016/j.jclepro.2022.135423).

Bárány, A., et al., 2022, *Decarbonisation of the Slovak economy by 2030: formulation of marginal abatement cost curve*, Value for Money Department, Ministry of Finance of the Slovak Republic (https://www.minzp.sk/files/iep/decarbonization_of_the_slovak_economy_by_2030_study_062022.pdf).

Bardazzi, R. and Pazienza, M. G., 2024, 'Decarbonising transport: can we rely on fuel taxes?', (DOI: 10.1016/j.trd.2024.104391).

Bastos, A., et al., 2016, 'European land CO2 sink influenced by NAO and East-Atlantic Pattern coupling', *Nature Communications* 7(1), p. 10315 (DOI: 10.1038/ncomms10315).

Bastos, A., et al., 2022, 'On the use of Earth Observation to support estimates of national greenhouse gas emissions and sinks for the Global stocktake process: lessons learned from ESA-CCI RECCAP2', *Carbon Balance and Management* 17(1), p. 15 (DOI: 10.1186/s13021-022-00214-w).

Bataille, C., et al., 2021, 'Industry in a net-zero emissions world: New mitigation pathways, new supply chains, modelling needs and policy implications', *Energy and Climate Change* 2, p. 100059 (DOI: 10.1016/j.egycc.2021.100059).

Becattini, V., et al., 2022, 'Carbon dioxide capture, transport and storage supply chains: Optimal economic and environmental performance of infrastructure rollout', *International Journal of Greenhouse Gas Control* 117, p. 103635 (DOI: 10.1016/j.ijggc.2022.103635).

Bednar, J., et al., 2021, 'Operationalizing the net-negative carbon economy', *Nature* 596(7872), pp. 377-383 (DOI: 10.1038/s41586-021-03723-9).

Bednar, J., et al., 2023a, 'Beyond emissions trading to a negative carbon economy: a proposed carbon removal obligation and its implementation', *Climate Policy*, pp. 1-14 (DOI: 10.1080/14693062.2023.2276858).

Bednar, J., et al., 2023b, *The role of carbon dioxide removal in contributing to the long-term goal of the Paris Agreement*, No ISBN: 978-91-7883-556-0, IVL Swedish Environmental Research Institute.

Beerling, D. J., et al., 2020, 'Potential for large-scale CO2 removal via enhanced rock weathering with croplands', *Nature* 583(7815), pp. 242-248 (DOI: 10.1038/s41586-020-2448-9).

BEIS, 2021, *Greenhouse gas removal methods and their potential UK deployment*, UK Department for Business, Energy and Industrial Strategy (https://assets.publishing.service.gov.uk/media/616ff80ce90e07197b571c95/ggr-methods-potential-deployment.pdf) accessed 1 August 2025.

Beland Lindahl, K., et al., 2023, ‘Clash or concert in European forests? Integration and coherence of forest ecosystem service–related national policies’, *Land Use Policy* 129, p. 106617 (DOI: 10.1016/j.landusepol.2023.106617).

Bellamy, R., et al., 2019, ‘Perceptions of bioenergy with carbon capture and storage in different policy scenarios’, *Nature Communications* 10(1), p. 743 (DOI: 10.1038/s41467-019-08592-5).

Bellamy, R. and Raimi, K. T., 2023, ‘Communicating carbon removal’, *Frontiers in Climate* 5, p. 1205388 (DOI: 10.3389/fclim.2023.1205388).

Bellassen, V., et al., 2022, ‘Soil carbon is the blind spot of European national GHG inventories’, *Nature Climate Change* 12(4), pp. 324-331 (DOI: 10.1038/s41558-022-01321-9).

Béres, R., et al., 2024, ‘Assessing the feasibility of CO2 removal strategies in achieving climate-neutral power systems: Insights from biomass, CO2 capture, and direct air capture in Europe’, *Advances in Applied Energy* 14, p. 100166 (DOI: 10.1016/j.adapen.2024.100166).

Beresford, A. E., et al., 2016, ‘The Contributions of the EU Nature Directives to the CBD and Other Multilateral Environmental Agreements’, *Conservation Letters* 9(6), pp. 479-488 (DOI: 10.1111/conl.12259).

Berger, S., et al., 2022, ‘Willingness-to-pay for carbon dioxide offsets: Field evidence on revealed preferences in the aviation industry’, *Global Environmental Change* 73, p. 102470 (DOI: 10.1016/j.gloenvcha.2022.102470).

Bertram, C., et al., 2024, ‘Feasibility of peak temperature targets in light of institutional constraints’, *Nature Climate Change* 14(9), pp. 954-960 (DOI: 10.1038/s41558-024-02073-4).

Beunen, R., et al., 2013, ‘Performing failure in conservation policy: The implementation of European Union directives in the Netherlands’, *Land Use Policy* 31, pp. 280-288 (DOI: 10.1016/j.landusepol.2012.07.009).

Bhaduri, A., et al., eds., 2018, ‘Bioenergy, food security and poverty reduction: trade-offs and synergies along the water–energy–food security nexus’, in: *Sustainability in the water-energy-food nexus*, Routledge, Place of publication not identified.

Biber, P., et al., 2020, ‘Forest Biodiversity, Carbon Sequestration, and Wood Production: Modeling Synergies and Trade-Offs for Ten Forest Landscapes Across Europe’, *Frontiers in Ecology and Evolution* 8, p. 547696 (DOI: 10.3389/fevo.2020.547696).

biofuelwatch, et al., 2023, *Sustainable Biomass Program: Certifying paperwork without looking at the forest* (https://www.biofuelwatch.org.uk/wp-content/uploads/SBP-and-SDE-briefing-1.pdf).

Bolsen, T., et al., 2022, ‘Effects of Conspiracy Rhetoric on Views About the Consequences of Climate Change and Support for Direct Carbon Capture’, *Environmental Communication* 16(2), pp. 209-224 (DOI: 10.1080/17524032.2021.1991967).

Bonsu, N. O., et al., 2019, ‘Conservation conflict: Managing forestry versus hen harrier species under Europe’s Birds Directive’, *Journal of Environmental Management* 252, p. 109676 (DOI: 10.1016/j.jenvman.2019.109676).

Borchardt, K.-D., 2023, *Carbon Capture Usage and Storage the new driver of the EU Decarbonization Plan?*, OIES Energy Comment, The Oxford Institute for Energy Studies (https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/10/Carbon-Capture-Usage-and-Storage-the-new-driver-of-the-EU-Decarbonization-Plan.pdf).

Böttcher, H., et al., 2019, *EU LULUCF Regulation explained — Summary of core provisions and expected effects*, Öko-Institut (https://www.oeko.de/fileadmin/oekodoc/Analysis-of-LULUCF-Regulation.pdf).

Böttcher, H., et al., 2022, *Analysis of the European Commission proposal for revising the EU LULUCF Regulation*, Öko-Institut e.V., Berlin (https://www.oeko.de/fileadmin/oekodoc/Assumptions_LULUCF_Proposal.pdf).

Brack, D. and King, R., 2021, 'Managing Land-based CDR: BECCS, Forests and Carbon Sequestration', *Global Policy* 12(S1), pp. 45-56 (DOI: 10.1111/1758-5899.12827).

Brad, A. and Schneider, E., 2023, 'Carbon dioxide removal and mitigation deterrence in EU climate policy: Towards a research approach', *Environmental Science & Policy* 150, p. 103591 (DOI: 10.1016/j.envsci.2023.103591).

Brander, M., et al., 2021, 'Carbon accounting for negative emissions technologies', *Climate Policy* 21(5), pp. 699-717 (DOI: 10.1080/14693062.2021.1878009).

Brander, M., 2022, 'The most important GHG accounting concept you may not have heard of: the attributional-consequential distinction', *Carbon Management* 13(1), pp. 337-339 (DOI: 10.1080/17583004.2022.2088402).

Broad, O., et al., 2021, 'The role of bioenergy with carbon capture and storage (BECCS) in the UK's net-zero pathway',.

Brunette, M., et al., 2017, 'Is forest insurance a relevant vector to induce adaptation efforts to climate change?', *Annals of Forest Science* 74(2), p. 41 (DOI: 10.1007/s13595-017-0639-9).

Brunette, M. and Couture, S., 2023, 'Forest Insurance for Natural Events: An Overview by Economists', *Forests* 14(2), p. 289 (DOI: 10.3390/f14020289).

Buck et al., 2022, 'Why residual emissions matter right now', *Nature Climate Change 13, pages 351–358. https://doi.org/10.1038/s41558-022-01592-2*.

Buck, H. J., et al., 2020, 'Adaptation and Carbon Removal', *One Earth* 3(4), pp. 425-435 (DOI: 10.1016/j.oneear.2020.09.008).

Buck, H. J., et al., 2023, 'Why residual emissions matter right now', *Nature Climate Change* 13(4), pp. 351-358 (DOI: 10.1038/s41558-022-01592-2).

Buck, H. J. and Palumbo-Compton, A., 2022, 'Soil carbon sequestration as a climate strategy: what do farmers think?', *Biogeochemistry* 161(1), pp. 59-70 (DOI: 10.1007/s10533-022-00948-2).

Buckingham, F. L. and Henderson, G. M., 2024, 'The enhanced weathering potential of a range of silicate and carbonate additions in a UK agricultural soil', *Science of The Total Environment* 907, p. 167701 (DOI: 10.1016/j.scitotenv.2023.167701).

Bui, M., et al., 2018, 'Bio-energy with carbon capture and storage (BECCS): Opportunities for performance improvement', *Fuel* 213, pp. 164-175 (DOI: 10.1016/j.fuel.2017.10.100).

Bukar, A. M. and Asif, M., 2024, 'Technology readiness level assessment of carbon capture and storage technologies', *Renewable and Sustainable Energy Reviews* 200, p. 114578 (DOI: 10.1016/j.rser.2024.114578).

Burke, J. and Gambhir, A., 2022, 'Policy incentives for Greenhouse Gas Removal Techniques: the risks of premature inclusion in carbon markets and the need for a multi-pronged policy framework', *Energy and Climate Change* 3, p. 100074 (DOI: 10.1016/j.egycc.2022.100074).

Burke, J. and Schenuit, F., 2023, *Governing permanence of carbon dioxide removal: a typology of policy measures*, Policy Report, CO2RE - The Greenhouse Gas Removal Hub (https://co2re.org/wp-content/uploads/2023/11/CO2RE_Report_CDR_Permanence-FINAL-v7.pdf) accessed 3 September 2024.

Burke, J. and Schenuit, F., 2024, 'Conditional fungibility: sequencing permanent removals into emissions trading systems', *Environmental Research Letters* 19(11), p. 111002 (DOI: 10.1088/1748-9326/ad796b).

Canning, A. D., et al., 2021, 'Financial incentives for large-scale wetland restoration: Beyond markets to common asset trusts', *One Earth* 4(7), pp. 937-950 (DOI: 10.1016/j.oneear.2021.06.006).

Cao, L. and Caldeira, K., 2010, 'Can ocean iron fertilization mitigate ocean acidification?', *Climatic Change* 99(1), pp. 303-311 (DOI: 10.1007/s10584-010-9799-4).

Capocelli, M. and De Falco, M., 2022, 'Generalized penalties and standard efficiencies of carbon capture and storage processes', *International Journal of Energy Research* 46(4), pp. 4808-4824 (DOI: 10.1002/er.7474).

Capponi, G., et al., 2022, 'Breakthrough innovations and where to find them', *Research Policy* 51(1), p. 104376 (DOI: 10.1016/j.respol.2021.104376).

Carattini, S., et al., 2019, 'How to win public support for a global carbon tax', *Nature* 565(7739), pp. 289-291 (DOI: 10.1038/d41586-019-00124-x).

Carbon Gap, 2024, Integrating GGRs in the UK Emissions Trading Scheme: Carbon Gap's response, (https://carbongap.org/integrating-ggrs-in-the-uk-emissions-trading-scheme-carbon-gaps-response/).

Carbonplan, 2021, 'A buyer's guide to soil carbon offsets', carbonplan.org (https://carbonplan.org/research/soil-protocols-explainer) accessed 14 February 2025.

Carl, J. and Fedor, D., 2016, 'Tracking global carbon revenues: A survey of carbon taxes versus cap-and-trade in the real world', *Energy Policy* 96, pp. 50-77 (DOI: 10.1016/j.enpol.2016.05.023).

Carton, W., et al., 2021, 'Undoing Equivalence: Rethinking Carbon Accounting for Just Carbon Removal', *Frontiers in Climate* 3, p. 664130 (DOI: 10.3389/fclim.2021.664130).

Carton, W., et al., 2023, 'Is carbon removal delaying emission reductions?', *WIREs Climate Change* (DOI: 10.1002/wcc.826).

Carver, T., et al., 2022, 'Including forestry in an emissions trading scheme: Lessons from New Zealand', *Frontiers in Forests and Global Change* 5, p. 956196 (DOI: 10.3389/ffgc.2022.956196).

Caserini, S., et al., 2022, 'The Availability of Limestone and Other Raw Materials for Ocean Alkalinity Enhancement', *Global Biogeochemical Cycles* 36(5), p. e2021GB007246 (DOI: 10.1029/2021GB007246).

CCUS Forum, 2023a, *A Vision for Carbon Capture, Utilisation and Storage in the EU* (https://circabc.europa.eu/ui/group/75b4ad48-262d-455d-997a-7d5b1f4cf69c/library/594e5e2f-1d3b-4e9d-afaa-6f6657c7ee3a/details).

CCUS Forum, 2023b, *An Interoperable CO2 Transport Network – Towards Specifications for the Transport of Impure CO2*, CCUS Forum Working Group on CO2 Infrastructure (https://circabc.europa.eu/ui/group/75b4ad48-262d-455d-997a-7d5b1f4cf69c/library/13c2a475-c705-432d-8ca3-17ce799ba502/details).

CCUS Forum, 2023c, *Towards a European cross-border CO2 transport and storage infrastructure: Recommendations ahead of the EU Industrial Carbon Management Strategy*, CCUS Forum Working Group on CO2 Infrastructure (https://circabc.europa.eu/ui/group/75b4ad48-262d-455d-997a-7d5b1f4cf69c/library/435ae9cd-1cb6-49a9-9311-f77c21c64d82/details).

Chan, T., et al., 2023, Corruption and integrity risks in climate solutions: an emerging global challenge, (https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2023/10/Corruption-and-integrity-risks-in-climate-solutions.pdf), The Centre for Climate Change Economics and Policy (CCCEP) and The Grantham Research Institute on Climate Change and the Environment.

Cherubini, F., et al., 2011, 'CO2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming', *GCB Bioenergy* 3(5), pp. 413-426 (DOI: https://doi.org/10.1111/j.1757-1707.2011.01102.x).

Chiti, T., et al., 2024, *Carbon farming in the European forestry sector*, From Science to Policy, European Forest Institute (https://efi.int/publications-bank/carbon-farming-european-forestry-sector) accessed 15 November 2024.

Christianson, A. B., et al., 2022, 'The Promise of Blue Carbon Climate Solutions: Where the Science Supports Ocean-Climate Policy', *Frontiers in Marine Science* 9, p. 851448 (DOI: 10.3389/fmars.2022.851448).

CINEA, 2023, *Connecting Europe Facility (CEF): energy 2023: latest achievements and way forward.*, Publications Office, LU.

CIRCABC, 2015, 'Summary Report', conference paper presented at: Workshop on coordinated implementation of nature, biodiversity, marine and water policies 2-3 December 2014, Brussels, 30 January 2015.

Clausen, L. P. W., et al., 2023, 'How environmental regulation can drive innovation: Lessons learned from a systematic review', *Environmental Policy and Governance* 33(4), pp. 364-373 (DOI: 10.1002/eet.2035).

Clean Air Task Force, 2024a, Designing Carbon Contracts for Difference, (https://cdn.catf.us/wp-content/uploads/2024/02/15092725/Carbon-Contracts-for-Difference-Policy-Brief.pdf).

Clean Air Task Force, 2024b, Europe Carbon Capture Activity and Project Map, (https://www.catf.us/ccsmapeurope/).

Climate Resilience Dialogue, 2024, *Climate Resilience Dialogue Final Report*, European Commission, Brussels (https://climate.ec.europa.eu/eu-action/adaptation-climate-change/climate-resilience-dialogue_en) accessed 25 August 2024.

Climeworks, 2025, *Mammoth: our newest facility* (https://climeworks.com/plant-mammoth).

Cliquet, A., et al., 2024, 'The negotiation process of the EU Nature Restoration Law Proposal: bringing nature back in Europe against the backdrop of political turmoil?', *Restoration Ecology*, p. e14158 (DOI: 10.1111/rec.14158).

Coffman, D. and Lockley, A., 2017, 'Carbon dioxide removal and the futures market', *Environmental Research Letters* 12(1), p. 015003 (DOI: 10.1088/1748-9326/aa54e8).

Collins, H. and McFetridge, A., 2021, *The impact of afforestation on rural communities: A case study in the Tararua District of New Zealand*, No TUR_1BT_2020_035, Tararua District Council, Dannevirke, New Zealand (https://www.tararuadc.govt.nz/__data/assets/pdf_file/0022/14980/The-Impacts-of-Afforestation-on-Rural-Communities-in-the-Tararua-District-March-2021.pdf).

CONCITO, 2023, *The potential and risks of carbon dioxide removal based on carbon capture and storage in the EU*, CONCITO (https://concito.dk/en/udgivelser/the-future-role-of-beccs-and-daccs-in-the-eu-potential-and-risks) accessed 23 November 2023.

Cornillie, J., et al., 2024, *A clean industrial deal delivering decarbonisation and competitiveness*, European University Institute.

Cotella, G., 2020, 'How Europe hits home? The impact of European Union policies on territorial governance and spatial planning', *Géocarrefour* 94(3) (DOI: 10.4000/geocarrefour.15648).

Cott, G. M., et al., 2021, *Blue carbon and marine carbon sequestration in Irish waters and coastal habitats*, Marine Institute, Ireland.

Cox, E., et al., 2024, 'Public attitudes and emotions toward novel carbon removal methods in alternative sociotechnical scenarios', *Environmental Research Letters* 19(8), p. 084026 (DOI: 10.1088/1748-9326/ad5dd0).

CREDIBLE, 2024, *Minimum requirements to ensure carbon delivers sustainability benefits*, Project CREDIBLE (https://www.project-credible.eu/consultations/FG_21).

Crooks, S., et al., 2019, 'Defining Blue Carbon - The Emergence of a Climate Context for Coastal Carbon Dynamics', in: *A Blue Carbon Primer: the State of Coastal Wetland Carbon Science, Practice and Policy*, CRC Press, Boca Raton, FL, pp. 1-8.

CRS, 2023, *Carbon Dioxide (CO2) Pipeline Development: Federal Initiatives*, Congressional Research Service (https://crsreports.congress.gov/product/pdf/IN/IN12169).

Daniels, S., et al., 2023, *Deep Geological Storage of CO2 on the UK Continental Shelf*.

Danish Climate Council, 2024, *Climate-friendly food and consumer behaviour | Klimarådet*, Danish Climate Council (https://klimaraadet.dk/en/analyser/climate-friendly-food-and-consumer-behaviour) accessed 7 January 2025.

Davies, G., 2020, 'Climate Change and Reversed Intergenerational Equity: the Problem of Costs Now, for Benefits Later', *Climate Law* 10(3-4) (DOI: 10.1163/18786561-10030002).

De Jong, M., et al., 2021, 'Paludiculture as paludifuture on Dutch peatlands: An environmental and economic analysis of Typha cultivation and insulation production', *Science of The Total Environment* 792, p. 148161 (DOI: 10.1016/j.scitotenv.2021.148161).

De Perthuis, C. and Trotignon, R., 2014, 'Governance of CO2 markets: Lessons from the EU ETS', *Energy Policy* 75, pp. 100-106 (DOI: 10.1016/j.enpol.2014.05.033).

Delbeke, J., ed., 2024, *Delivering a climate neutral Europe*, Routledge, New York, NY.

Delbeke, J. and Vis, P., 2021, 'Climate Policy Architecture in the EU', *EAERE Magazine*, 2021 (https://cadmus.eui.eu/bitstream/handle/1814/72260/ClimatePolicyArchitectureEU_Delbeke_Vis.pdf?sequence=1&isAllowed=y).

Deng, H., et al., 2017, 'Leakage risks of geologic CO2 storage and the impacts on the global energy system and climate change mitigation', *Climatic Change* 144(2), pp. 151-163 (DOI: 10.1007/s10584-017-2035-8).

De Rosa, D., et al., 2024, 'Soil organic carbon stocks in European croplands and grasslands: How much have we lost in the past decade?', *Global Change Biology* 30(1), p. e16992 (DOI: 10.1111/gcb.16992).

DESNZ, 2023, *Carbon Capture, Usage and Storage An update on the business model for Transport and Storage - explanatory note and indicative heads of terms*, UK government - Department for Energy Security & Net Zero (https://assets.publishing.service.gov.uk/media/6581d936fc07f3000d8d4517/ccus-heads-of-terms-december-2023-412234454.1.pdf).

DG AGRI, 2024, Catalogue of CAP interventions, CAP 2023-2027, (https://agridata.ec.europa.eu/extensions/DataPortal/pmef_indicators.html) accessed 18 February 2025.

Dingwall, J., 2020, 'Commercial Mining Activities in the Deep Seabed beyond National Jurisdiction: the International Legal Framework', in: Banet, C. (ed.), *The Law of the Seabed*, Brill | Nijhoff, pp. 139-162.

Dixon, T., et al., 2015, 'Legal and Regulatory Developments on CCS', *International Journal of Greenhouse Gas Control* 40, pp. 431-448 (DOI: 10.1016/j.ijggc.2015.05.024).

Doblinger, C., et al., 2019, 'Governments as partners: The role of alliances in U.S. cleantech startup innovation', *Research Policy* 48(6), pp. 1458-1475 (DOI: 10.1016/j.respol.2019.02.006).

Doelman, J. C., et al., 2019, 'Making the Paris agreement climate targets consistent with food security objectives', *Global Food Security* 23, pp. 93-103 (DOI: 10.1016/j.gfs.2019.04.003).

Doelman, J. C., et al., 2020, 'Afforestation for climate change mitigation: Potentials, risks and trade-offs', *Global Change Biology* 26(3), pp. 1576-1591 (DOI: 10.1111/gcb.14887).

Dolphin, G., et al., 2022, *A net-zero target compels a backwards induction approach to climate policy*, Resources for the Future (https://media.rff.org/documents/WP_22-18.pdf) accessed 11 February 2025.

Dolphin, G., et al., 2023, 'A net-zero target compels a backward induction approach to climate policy', *Nature Climate Change* 13(10), pp. 1033-1041 (DOI: 10.1038/s41558-023-01798-y).

Domorenok, E., 2024, 'Chapter 20: Integrating EU climate action into Cohesion Policy: instruments, developments and challenges',.

Douenne, T. and Fabre, A., 2022, 'Yellow Vests, Pessimistic Beliefs, and Carbon Tax Aversion', *American Economic Journal: Economic Policy* 14(1), pp. 81-110.

Draghi, M., 2024, *The future of European competitiveness - A competitiveness strategy for Europe*.

Drax, 2022, 'Drax invests in 30 new rail wagons supporting energy security and jobs whilst cutting supply chain emissions', Drax UK (https://www.drax.com/uk/press_release/drax-invests-in-30-new-rail-wagons-supporting-energy-security-and-jobs-whilst-cutting-supply-chain-emissions/) accessed 21 January 2025.

Duan, L. and Caldeira, K., 2024, 'Implications of uncertainty in technology cost projections for least-cost decarbonized electricity systems', *iScience* 27(1), p. 108685 (DOI: 10.1016/j.isci.2023.108685).

Dubash, N. K., 2021, 'Varieties of climate governance: the emergence and functioning of climate institutions', *Environmental Politics* 30(sup1), pp. 1-25 (DOI: 10.1080/09644016.2021.1979775).

Duesberg, S., et al., 2013, 'To plant or not to plant—Irish farmers' goals and values with regard to afforestation', *Land Use Policy* 32, pp. 155-164 (DOI: 10.1016/j.landusepol.2012.10.021).

Dusík, J. and Bond, A., 2022, 'Environmental assessments and sustainable finance frameworks: will the EU Taxonomy change the mindset over the contribution of EIA to sustainable development?', *Impact Assessment and Project Appraisal* 40(2), pp. 90-98 (DOI: 10.1080/14615517.2022.2027609).

Dziejarski, B., et al., 2023, 'Current status of carbon capture, utilization, and storage technologies in the global economy: A survey of technical assessment', *Fuel* 342, p. 127776 (DOI: 10.1016/j.fuel.2023.127776).

EASAC, 2022a, *Forest bioenergy update: BECCS and its role in integrated assessment models*, European Academies Science Advisory Council (https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_BECCS_Commentary_2022_WEB_final.pdf).

EASAC, 2022b, *Regenerative agriculture in Europe: a critical analysis of contributions to European Union Farm to Fork and Biodiversity Strategies*, No EASAC policy report 44, German National Academy of Sciences Leopoldina (https://easac.eu/fileadmin/PDF_s/reports_statements/Regenerative_Agriculture/EASAC_RegAgri_Web_290422.pdf).

EC, 2003, Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council Directive 96/61/EC, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32003L0087), European Commision.

EC, 2008, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0098).

EC, 2016, *Fitness Check of the EU Nature Legislation (Birds and Habitats Directives). Directive 2009/147/EC of the European Parliament and of the COuncil of 30 November 2009 on the conservation of wild birds and COuncil Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora*, Commission Staff Working Document No SWD(2016) 472 final, European Commission, Brussels.

EC, 2018, Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and amending Commission Regulation (EU) No 601/2012 (OJ L 334, 31.12.2018, pp. 1–93).

EC, 2020a, *Analytical support for the operationalisation of an EU carbon farming initiative*, EC (https://climate.ec.europa.eu/document/download/b0fc5b79-92b3-4ec1-89ba-3846158e904a_en?filename=policy_forest_carbon_report_en.pdf) accessed 1 August 2025.

EC, 2020b, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS - A Farm to Fork Strategy for a fair, healthy and environmentally-friendly food system (COM(2020) 381 final), (https://eur-lex.europa.eu/resource.html?uri=cellar:ea0f9f73-9ab2-11ea-9d2d-01aa75ed71a1.0001.02/DOC_1&format=PDF).

EC, 2020c, *EU Biodiversity Strategy for 2030: Bringing nature back into our lives*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions No COM(2020) 380 final, European Commission, Brussels (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52020DC0380).

EC, 2021a, *BECCS Stockholm: delivering net carbon removals with clean energy* (https://cinea.ec.europa.eu/featured-projects/beccs-stockholm-delivering-net-carbon-removals-clean-energy_en).

EC, 2021b, Commission Delegated Regulation (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives (OJ L 442, 9.12.2021, p. 1–349).

EC, 2021c, Commission Notice - Technical guidance on climate proofing of infrastructure in the period 2021-2027 (C/2021/5430) (OJ C 373, 16.9.2021, p. 1–92).

EC, 2021d, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee of the Regions 'New EU Forest Strategy for 2030'.

EC, 2021e, Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions 'Sustainable carbon cycles' (COM(2021)800).

EC, 2021f, 'EU Forest Strategy' (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12674-Forests-new-EU-strategy_en) accessed 8 March 2023.

EC, 2021g, European Missions: A Soil Deal for Europe 100 living labs and lighthouses to lead the transition towards healthy soils by 2030 - Implementation Plan, (https://research-and-innovation.ec.europa.eu/document/download/1517488e-767a-4f47-94a0-bd22197d18fa_en?filename=soil_mission_implementation_plan_final.pdf).

EC, 2021h, *Impact Assessment Report accompanying the document Proposal for a Regulation of the European Parliament and the Council amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review*, No SWD(2021) 609 final (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=SWD:2021:609:FIN).

EC, 2021i, *New EU Forest Strategy for 2030*, No COM/2021/572 (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572) accessed 23 August 2023.

EC, 2021j, 'New European Bauhaus' (https://europa.eu/new-european-bauhaus/about/about-initiative_en) accessed 28 June 2021.

EC, et al., 2022a, *Biodiversity financing and tracking: final report.*, Publications Office, LU.

EC, 2022a, *CARBONCAPS - Efficient and verifiable carbon removal with ecosystem co-benefits.* (https://cordis.europa.eu/project/id/190108904).

EC, 2022b, Commission Notice on the Guidance to Member States for the update of the 2021-2030 national energy and climate plans (2022/C 495/02), (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A52022XC1229%2802%29&from=EN).

EC, 2022c, Communication and annex - Guidance on cost-benefit sharing in CB RES cooperation projects, (https://energy.ec.europa.eu/publications/communication-and-annex-guidance-cost-benefit-sharing-cb-res-cooperation-projects_en).

EC, et al., 2022b, *Financing Natura 2000: EU funding opportunities in 2021 2027*, Publications Office, LU.

EC, 2022d, *Impact Assessment Report accompanying the document Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals*, Commission Staff Working Document No SWD(2022) 378 final, European Commission, Brussels.

EC, 2023a, *'Better regulation' toolbox*, EC, Brussels (https://commission.europa.eu/document/download/9c8d2189-8abd-4f29-84e9-abc843cc68e0_en?filename=BR%20toolbox%20-%20Jul%202023%20-%20FINAL.pdf) accessed 26 January 2024.

EC, 2023b, Commission Staff Working Document Assessment of progress towards the objectives of the Energy Union and Climate Action Accompanying the document Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Commitee of the Regions State of the Energy Union 2023 Report (pursuant to Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action) {COM(2023) 650 final}, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=SWD%3A2023%3A646%3AFIN&qid=1698236844015).

EC, 2023c, Commission Staff Working Document 'Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity' (SWD(2023) 68 final), (https://single-market-economy.ec.europa.eu/system/files/2023-03/SWD_2023_68_F1_STAFF_WORKING_PAPER_EN_V4_P1_2629849.PDF), European Commission.

EC, 2023d, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS EU-wide assessment of the draft updated National Energy and Climate Plans An important step towards the more ambitious 2030 energy and climate objectives under the European Green Deal and RePowerEu, (https://eur-lex.europa.eu/resource.html?uri=cellar:bb8fb395-9d9c-11ee-b164-01aa75ed71a1.0001.02/DOC_1&format=PDF).

EC, 2023e, *EU missions assessment report: Mission A Soil Deal for Europe.*, Publications Office, LU.

EC, 2023f, *EU Missions two years on: assessment of progress and way forward*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions No COM(2023) 457 final, European Commission, Brussels (https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX%3A52023DC0457).

EC, et al., 2023, *Impact assessment study to support the development of legally binding EU nature restoration targets: final report.*, Impact assessment report, European Commission - DG Environment, LU (https://data.europa.eu/doi/10.2779/275295) accessed 2 May 2024.

EC, 2023g, Just Transition Platform Working Groups Implementation Plan, (https://ec.europa.eu/regional_policy/sources/funding/just-transition-fund/working-groups-implementation-plan.pdf).

EC, 2023h, 'Nature Restoration Law and Commission's proposal', European Commission - European Commission (https://ec.europa.eu/commission/presscorner/detail/en/SPEECH_22_3968) accessed 16 March 2023.

EC, 2023i, Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on Soil Monitoring and Resilience (Soil Monitoring Law) COM/2023/416 final.

EC, 2023j, Proposal for a Directive of the European Parliament and of the Council on substantiation and communication of explicit environmental claims (Green Claims Directive) (COM/2023/166 final).

EC, 2023k, Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act) (COM(2023) 161 final).

EC, 2023l, Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on a monitoring framework for resilient European forests COM/2023/728 final.

EC, 2023m, Report from the Commission to the European Parliament and the Council on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide, COM(2023) 657 final, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2023%3A657%3AFIN).

EC, 2023n, Report from the Commission to the European Parliament and the Council on the functioning of the European carbon market in 2022 COM(2023) 654 final, (https://climate.ec.europa.eu/system/files/2023-10/COM_2023_654_1_EN_ACT_part1_CMR%2BSWD.pdf).

EC, 2023o, Review of certification methodologies for carbon farming – survey results and first assessment of coverage of the QU.A.L.ITY criteria, (https://climate.ec.europa.eu/document/download/456ef0dd-5614-4643-99d6-dd531921658e_en?filename=policy_carbon_expert_carbon_farming_en.pdf).

EC, 2023p, Support to the development of methodologies for the certification of industrial carbon removals with permanent storage: Review of certification methodologies and relevant EU legislation, (https://climate.ec.europa.eu/document/download/28698b02-7624-4709-9aec-379b26273bc0_en?filename=policy_carbon_expert_carbon_removals_with_permanent_storage_en.pdf).

EC, 2024a, *Annex to the Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee, and the Committee of the Regions: State of the Energy Union Report 2024* (https://energy.ec.europa.eu/document/download/9bff5d03-3c7b-475e-bb09-1eb4df893ea5_en?filename=Annex.pdf).

EC, 2024b, Answer given by Ms Simson on behalf of the European Commission, (https://www.europarl.europa.eu/doceo/document/E-9-2024-001152-ASW_EN.html).

EC, 2024c, 'Biodiversity research policy' (https://research-and-innovation.ec.europa.eu/research-area/environment/biodiversity/biodiversity-research-policy_en).

EC, 2024d, 'Commission approves €3 billion Swedish State aid scheme to support the roll-out of biogenic carbon dioxide capture and storage', European Commission (https://ec.europa.eu/commission/presscorner/detail/en/ip_24_3583) accessed 15 July 2024.

EC, 2024e, Commission Delegated Regulation (EU) 2024/1235 of 12 March 2024 amending Commission Delegated Regulation (EU) 2022/126 supplementing Regulation (EU) 2021/2115 of the European Parliament and of the Council as regards the rules on the ratio for the good agricultural and environmental condition (GAEC) standard 1 (OJ L, 2024/1235, 26.4.2024).

EC, 2024f, Commission Delegated Regulation (EU) 2024/2620 of 30 July 2024 supplementing Directive 2003/87/EC of the European Parliament and of the Council as regards the requirements for considering that greenhouse gases have become permanently chemically bound in a product, C/2024/5294 (OJ L, 2024/2620, 4.10.2024).

EC, 2024g, Commission Recommendation (EU) 2024/1343 of 13 May 2024 on speeding up permit-granting procedures for renewable energy and related infrastructure projects C/2024/2660, (https://eur-lex.europa.eu/eli/reco/2024/1343/oj).

EC, 2024h, Commission sets out how to sustainably capture, store and use carbon to reach climate neutrality by 2050 - press release, (https://ec.europa.eu/commission/presscorner/api/files/document/print/en/ip_24_585/IP_24_585_EN.pdf).

EC, 2024i, *Commission Staff Working Document - Impact Assessment Report Part 1-5 with supplementary information accompanying the communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: Securing our future Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society, COM(2024) 63 final, SWD(2024) 63 final* (https://climate.ec.europa.eu/document/download/768bc81f-5f48-48e3-b4d4-e02ba09faca1_en).

EC, 2024j, Communication from the Commission: Guidance on collaborative investment frameworks for offshore energy projects C(2024) 3998 final.

EC, 2024k, 'Corporate sustainability due diligence' (https://commission.europa.eu/business-economy-euro/doing-business-eu/sustainability-due-diligence-responsible-business/corporate-sustainability-due-diligence_en).

EC, 2024l, *DACCS and BECCS for CO2 removal/negative emissions* (https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/HORIZON-CL5-2024-D3-02-12?utm_content=bufferc8034&utm_medium=social&utm_source=linkedin.com&utm_campaign=buffer).

EC, 2024m, 'EU delivers on its global financing commitments to protect nature at COP 16' (https://international-partnerships.ec.europa.eu/news-and-events/news/eu-delivers-its-global-financing-commitments-protect-nature-cop-16-2024-10-31_en).

EC, 2024n, Guidance document 1 CO2 storage life cycle and risk management framework, (https://climate.ec.europa.eu/document/download/951d14ea-ce0f-4753-92dd-35ba88920888_en?filename=ccs-implementation_gd1_en_0.pdf).

EC, 2024o, Guidance Document 2 Characterisation of the Storage Complex, CO2 Stream Composition, Monitoring and Corrective Measures, (https://climate.ec.europa.eu/document/download/6f19cb98-b791-466d-8f3c-32c5bb12be2d_en?filename=ccs-implementation_gd2_en..pdf).

EC, 2024p, *Impact Assessment accompanying Europe's 2040 climate target and path to climate neutrality by 2050 building a sustainable, just and prosperous society*, No SWD(2024) 63 final, European

Commission, Brussels, Belgium (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A52024SC0063) accessed 25 October 2024.

EC, 2024q, Innovation Fund (InnovFund): Methodology for calculation of GHG emission avoidance, (https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/innovfund/guidance/ghg-emission-avoidance-methodology_innovfund_en.pdf).

EC, 2024r, 'Just Transition Fund' (https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/just-transition-fund_en) accessed 27 July 2024.

EC, 2024s, 'Net-Zero Industry Act - European Commission' (https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/green-deal-industrial-plan/net-zero-industry-act_en) accessed 30 April 2024.

EC, 2024t, *Peatlands – Technical Assessment Paper* (https://climate.ec.europa.eu/document/download/95f2f80b-2b7f-42e2-a627-9c070d8090c3_en?filename=policy_carbon_expert_tap_peatlands_en.pdf&prefLang=lv).

EC, 2024u, Register of Commission Expert Groups and Other Similar Entities Expert Group on Carbon Removals (E03861), (https://ec.europa.eu/transparency/expert-groups-register/screen/expert-groups/consult?lang=en&groupID=3861).

EC, 2024v, *State of the Energy Union Report 2024*, No COM(2024) 404 final, European Commission, Brussels (https://energy.ec.europa.eu/publications/state-energy-union-report-2024_en).

EC, 2024w, 'Sustainable agricultural practices and methods' (https://agriculture.ec.europa.eu/sustainability/environmental-sustainability/sustainable-agricultural-practices-and-methods_en).

EC, 2024x, *The Strategic Dialogue on the Future of EU Agriculture: A shared prospect for farming and food in Europe*, European Commission (https://agriculture.ec.europa.eu/document/download/171329ff-0f50-4fa5-946f-aea11032172e_en?filename=strategic-dialogue-report-2024_en.pdf) accessed 18 December 2024.

EC, 2024y, *Towards an ambitious Industrial Carbon Management for the EU*, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions No COM(2024) 62 final, European Commission, Brussels (https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52024DC0062).

EC, 2024z, Towards an ambitious Industrial Carbon Management for the EU - Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2024:62:FIN).

EC, 2025a, *Cluster 5: Climate, Energy and Mobility* (https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/cluster-5-climate-energy-and-mobility_en#:~:text=This%20cluster%20aims%20to%20fight%20climate%20change%20by,efficient%20and%20competitive%2C%20smarter%2C%20safer%20and%20more%20resilient.).

EC, 2025b, *Dashboard of all grants managed by the CINEA* (https://dashboard.tech.ec.europa.eu/qs_digit_dashboard_mt/public/sense/app/3744499f-670f-42f8-9ef3-0d98f6cd586f/sheet/4c9ea8df-f0f9-4c0d-b26b-99fc0218d9d9/state/analysis).

EC, 2025c, Electricity production capacities for renewables and wastes, Statistics nrg_inf_epcrw (https://ec.europa.eu/eurostat/databrowser/view/nrg_inf_epcrw__custom_14900007/default/table?lang=en) accessed 1 August 2025.

EC, 2025d, *Horizon Europe work programmes* (https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/horizon-europe-work-programmes_en).

EC, 2025e, *Innovation Fund - Performance* (https://commission.europa.eu/strategy-and-policy/eu-budget/performance-and-reporting/programme-performance-statements/innovation-fund-performance_en).

EC, 2025c, *Innovation Fund - Portfolio of signed projects* (https://dashboard.tech.ec.europa.eu/qs_digit_dashboard_mt/public/sense/app/6e4815c8-1f4c-4664-b9ca-8454f77d758d/sheet/bac47ac8-b5c7-4cd1-87ad-9f8d6d238eae/state/analysis).

EC and Ramboll, 2017, *Analysis of the use of auction revenues by the member states*, Final report, European Commission, Brussels (https://climate.ec.europa.eu/document/download/4d598efa-42b7-4793-99ea-e50167a09f60_en?filename=auction_revenues_report_2017_en.pdf).

ECA, 2013, *Has the environment component of the LIFE programme been effective?*, Special Report No 15/2013, European Court of Auditors, LU (https://data.europa.eu/doi/10.2865/75865) accessed 30 April 2024.

ECA, 2016, *The EU system for the certification of sustainable biofuels*, Special Report No 18, European Court of Auditors, Luxembourg (https://www.eca.europa.eu/Lists/ECADocuments/SR16_18/SR_BIOFUELS_EN.pdf) accessed 29 March 2019.

ECA, 2018, *Combating desertification in the EU: a growing threat in need of more action*, Special Report No 33, European Court of Auditors, Luxembourg (https://www.eca.europa.eu/Lists/ECADocuments/SR18_33/SR_DESERTIFICATION_EN.pdf).

ECA, 2020, *Biodiversity on farmland: CAP contribution has not halted the decline*, Special Report No 13, European Court of Auditors (https://www.eca.europa.eu/Lists/ECADocuments/SR20_13/SR_Biodiversity_on_farmland_EN.pdf).

ECA, 2021, *Common agricultural policy and climate: Half of EU climate spending but farm emissions are not decreasing*, Special Report No 16, European Court of Auditors (https://www.eca.europa.eu/Lists/ECADocuments/SR21_16/SR_CAP-and-Climate_EN.pdf) accessed 8 November 2021.

ECA, 2023, *The EU's support for sustainable biofuels in transport An unclear route ahead - special report*, No 29, European Court of Auditors (https://www.eca.europa.eu/ECAPublications/SR-2023-29/SR-2023-29_EN.pdf).

ECB, 2024, *Massive investment needs to meet EU green and digital targets*, European Central Bank (https://www.ecb.europa.eu/press/fie/box/html/ecb.fiebox202406_01.en.html) accessed 31 October 2024.

Ecologic, 2015, *Regional cooperation in the context of the new 2030 energy governance* (https://www.ecologic.eu/sites/default/files/publication/2015/regional-cooperation-energy-2030.pdf).

Ecologic, 2022a, 'Ecologic' (https://ecologic.rec.ro/lorand-arpad-fulop-cand-schimbi-sase-presedinti-in-doi-ani-este-clar-ca-lucrurile-nu-pot-functiona/).

Ecologic, 2022b, *The use of auctioning revenues from the EU ETS for climate action: an analysis based on eight selected case studies*, Ecologic Institute, Berlin (https://www.ecologic.eu/sites/default/files/publication/2022/EcologicInstitute-2022-UseAucRevClimate-FullReport.pdf).

Ecologic, 2023, *Certification of carbon dioxide removals: Evaluation of the Commission proposal*, Interim Report, German Environment Agency (https://www.ecologic.eu/sites/default/files/publication/2023/50122-certification-of-carbon-dioxide-removals.pdf).

Ecologic and Oeko-Institut, 2023a, *EU 2040 Climate Target and Framework: The Role of Carbon Removals - Potentials, incentives, and regulation*, Ecologic Institute & Oko-Institut.

Ecologic and Oeko-Institut, 2023b, *QU.A.L.ITY soil carbon removals? Assessing the EU Framework for Carbon Removal Certification from a climate-friendly soil management perspective*, Berlin (https://www.ecologic.eu/sites/default/files/publication/2023/50061-QUALITY-soil-carbon-removals.pdf).

Edelenbosch, O. Y., et al., 2024, 'Reducing sectoral hard-to-abate emissions to limit reliance on carbon dioxide removal', *Nature Climate Change* 14(7), pp. 715-722 (DOI: 10.1038/s41558-024-02025-y).

Edenhofer, O., et al., 2021, 'Pigou in the 21st Century: a tribute on the occasion of the 100th anniversary of the publication of The Economics of Welfare', *International Tax and Public Finance* 28(5), pp. 1090-1121 (DOI: 10.1007/s10797-020-09653-y).

Edenhofer, O., et al., 2023, 'On the governance of carbon dioxide removal - a public economics perspective'.

Edenhofer, O., et al., 2024a, 'On the Governance of Carbon Dioxide Removal – A Public Economics Perspective', *FinanzArchiv* 80(1), p. 70 (DOI: 10.1628/fa-2023-0012).

Edenhofer, O., et al., 2024b, 'The Economics of Carbon Dioxide Removal: A Governance Perspective' (https://www.ssrn.com/abstract=5053587) accessed 10 February 2025.

Edenhofer, O. and Kalkuhl, M., 2024, 'Planetarische Müllabfuhr – Gamechanger der Klimapolitik?: Thünen-Vorlesung 2024', *Perspektiven der Wirtschaftspolitik* (DOI: 10.1515/pwp-2024-0028).

Edenhofer, O. and Leisinger, C., 2024, 'Das Klimaschutzprogramm der EU und Bundesregierung', in: *Warnsignal Kilma. Herausforderung Wetterextreme*, , pp. 345-351.

Edwards, D. P., et al., 2017, 'Climate change mitigation: potential benefits and pitfalls of enhanced rock weathering in tropical agriculture', *Biology Letters* 13(4), p. 20160715 (DOI: 10.1098/rsbl.2016.0715).

EEA, 2011, *Air pollution impacts from carbon capture and storage (CCS)*, EEA Technical Report No 14/2011, European Environment Agency (https://www.eea.europa.eu/publications/carbon-capture-and-storage) accessed 18 January 2019.

EEA, 2020, *State of nature in the EU: results from reporting under the nature directives 2013 2018*, EEA Report No 10/2020, European Environment Agency (https://data.europa.eu/doi/10.2800/088178) accessed 30 October 2020.

EEA, 2022, *Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?*,.

EEA, 2023a, *Annual European Union greenhouse gas inventory 1990-2021 and inventory report 2023. Submission to the UNFCCC Secretariat*, No EEA/PUBL/2023/044, European Envionment Agency.

EEA, 2023b, *European Union 8th Environment Action Programme* (https://www.eea.europa.eu/en/analysis/publications/european-union-8th-environment-action-programme).

EEA, 2023c, Greenhouse gas emissions from land use, land use change and forestry in Europe, (https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emissions-from-land#:~:text=The%20land%20use%2C%20land%20use,EU's%20annual%20greenhouse%20gas%20emissions.).

EEA, 2023d, 'Natura 2000 network's contribution to good status' (https://www.eea.europa.eu/en/topics/at-a-glance/nature/state-of-nature-in-europe-a-health-check/natura-2000-networks-contribution-to-good-status).

EEA, 2023e, *The European biomass puzzle*, No EEA Report No 8/2023, EEA (https://www.eea.europa.eu/publications/the-european-biomass-puzzle).

EEA, 2023f, *The European Biomass Puzzle*, No EEA Report No 8/2023, European Environment Agency (https://www.eea.europa.eu/publications/the-european-biomass-puzzle) accessed 22 November 2023.

EEA, 2023g, *Trends and projections in Europe 2023*, No 11/2024, European Environment Agency, Copenhagen, Denmark.

EEA, 2024a, *European climate risk assessment*, EEA report No 01/2024, European Environment Agency, Copenhagen, Denmark (https://www.eea.europa.eu/publications/european-climate-risk-assessment) accessed 12 March 2024.

EEA, 2024b, *European climate risk assessment — Executive summary*, No EEA Report No 1/2024, European Environment Agency (https://www.eea.europa.eu/publications/european-climate-risk-assessment).

EEA, 2024c, 'Greenhouse gases — data viewer', European Environment Agency (https://www.eea.europa.eu/en/analysis/maps-and-charts/greenhouse-gases-viewer-data-viewers) accessed 27 November 2024.

EEA, 2024d, *Handbook of the updated LULUCF Regulation EU 2018/841: Guidance and orientation for the implementation of the updated Regulation*, No EEA/CET/22/001, European Environment Agency, Copenhagen.

EEA, 2024e, *Trends and projections in Europe 2024*, EEA Report No 11/2024, European Environment Agency, Luxembourg (https://www.eea.europa.eu/en/analysis/publications/trends-and-projections-in-europe-2024) accessed 15 January 2025.

EEA, forthcoming, 'Approximated EU GHG inventory: proxy GHG estimates for 2023', European Environment Agency.

EEA and ACER, 2023, *Flexibility solutions to support a decarbonised and secure EU Electricity System*, European Environmental Agency, EU Agency for the Cooperation of Energy Regulators, Luxembourg (https://www.eea.europa.eu/en/newsroom/news/rapid-growth-in-renewables-calls).

EEB, et al., 2024, *Call for a dedicated EU nature restoration fund*, European Environmental Bureau.

EFI, 2021, *Key questions on forests in the EU*, Knowledge to Action, European Forest Institute (https://efi.int/publications-bank/key-questions-forests-eu) accessed 8 January 2025.

Efstathiou, K. and Wolff, G., 2023, 'What drives implementation of the European Union's policy recommendations to its member countries?', *Journal of Economic Policy Reform* 26(2), pp. 177-198 (DOI: 10.1080/17487870.2022.2056461).

EIB, 2021, *Investment report 2020/2021: Building a smart and green Europe in the COVID-19 era*, European Investment Bank, Luxembourg.

EIB, 2024, 'Innovation Fund - Project Development Assistance' (https://www.eib.org/en/products/mandates-partnerships/innovation-fund/index).

EIOPA, 2023, *European Insurance Overview 2023*, Frankfurt (https://www.eiopa.europa.eu/publications/european-insurance-overview-report-2023_en).

Ekardt, F., et al., 2023, 'Legally binding and ambitious biodiversity protection under the CBD, the global biodiversity framework, and human rights law', *Environmental Sciences Europe* 35(1), p. 80 (DOI: 10.1186/s12302-023-00786-5).

Ekholm, T., 2020, 'Optimal forest rotation under carbon pricing and forest damage risk', *Forest Policy and Economics* 115, p. 102131 (DOI: 10.1016/j.forpol.2020.102131).

Emerson, D., et al., 2023, 'A cost model for ocean iron fertilization as a means of carbon dioxide removal that compares ship- and aerial-based delivery, and estimates verification costs.', Oceanography (https://eartharxiv.org/repository/view/5272/) accessed 4 February 2025.

Enríquez-de-Salamanca, Á., 2022, 'Climate Change Mitigation in Forestry: Paying for Carbon Stock or for Sequestration?', *Atmosphere* 13(10), p. 1611 (DOI: 10.3390/atmos13101611).

EnTEC, et al., 2023, *EU regulation for the development of the market for CO2 transport and storage*, Publications Office, LU.

Eory, V., et al., 2015, *Review and update the UK Agriculture Marginal Abatement Cost Curve to assess the greenhouse gas abatement potential for the 5th carbon budget period and to 2050*, Committee on Climate Change (https://www.theccc.org.uk/wp-content/uploads/2015/11/Scotland%E2%80%99s-Rural-Collage-SRUC-Ricardo-Energy-and-Environment-2015-Review-and-update-of-the-UK-agriculture-MACC-to-assess-abatement-potential-for-the-fifth-carbon-budget-period-and-to-2050.pdf).

Erans, M., et al., 2022, 'Direct air capture: process technology, techno-economic and socio-political challenges', *Energy & Environmental Science* 15(4), pp. 1360-1405 (DOI: 10.1039/D1EE03523A).

Ernst, A., et al., 2023, 'Carbon pricing, border adjustment and climate clubs: Options for international cooperation', *Journal of International Economics* 144, p. 103772 (DOI: 10.1016/j.jinteco.2023.103772).

Escobar, D., et al., 2022, 'Back to the Future: Restoring Northern Drained Forested Peatlands for Climate Change Mitigation', *Frontiers in Environmental Science* 10, p. 834371 (DOI: 10.3389/fenvs.2022.834371).

ESMA, 2022, *Final Report Emission allowances and associated derivatives*, European Securitites and Markets Authority (https://www.esma.europa.eu/sites/default/files/library/esma70-445-38_final_report_on_emission_allowances_and_associated_derivatives.pdf).

EU, 2001, Directive 2001/42/EC of the European Parliament and of the Council of 27 June 2001 on the assessment of the effects of certain plans and programmes on the environment (OJ L 197, 21.7.2001, p. 30-37).

EU, 2003, Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC (OJ L 275 25.10.2003, p. 32).

EU, 2008a, Consolidated version of the Treaty on the Functioning of the European Union EUR-Lex - 12008E002 - EN, text/html; charset=UTF-8 (https://eur-lex.europa.eu/eli/treaty/tfeu_2008/art_2/oj/eng) accessed 7 January 2025, OPOCE.

EU, 2008b, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance) (OJ L 312, 22.11.2008, pp. 3–30).

EU, 2009a, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC (OJ L 140, 5.6.2009, p. 16-62).

EU, 2009b, Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (OJ L 140, 5.6.2009, p. 114–135).

EU, 2010, Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) (recast) (Text with EEA relevance) (OJ L 334, 17.12.2010, pp. 17–119).

EU, 2011, Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC (OJ L 88, 4.4.2011, p. 5–43).

EU, 2012, Directive 2011/92/EU of the European Parliament and of the Council of 13 December 2011 on the assessment of the effects of certain public and private projects on the environment (OJ L 26, 28.01.2012, p. 1-21).

EU, 2016, Consolidated version of the Treaty on the European Union (OJ C 202 7.6.2016, p. 13).

EU, 2018a, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (OJ L 328, 21.12.2018, p. 82-209).

EU, 2018b, Regulation (EU) 2018/841 of the European Parliament and of the Council on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending REgulation (EU) No 525/2013 and Decision No 529/2013/EU (OJ L 156, 19.6.2018).

EU, 2018c, Regulation (EU) 2018/1999 of the European Parliament and of the Council of 11 December 2018 on the Governance of the Energy Union and Climate Action (OJ L 328, 21.12.2018, p. 1-77).

EU, 2020, Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088 (OJ L 198, 22.6.2020, p. 13–43).

EU, 2021a, Regulation (EU) 2021/1060 of the European Parliament and of the Council of 24 June 2021 laying down common provisions on the European Regional Development Fund, the European Social Fund Plus, the Cohesion Fund, the Just Transition Fund and the European Maritime, Fisheries and Aquaculture Fund and financial rules for those and for the Asylum, Migration and Integration Fund, the Internal Security Fund and the Instrument for Financial Support for Border Management and Visa Policy (OJ L 231, 30.6.2021, p. 159–706).

EU, 2021b, Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law') (OJ L 243, 9.7.2021, p. 1-17).

EU, 2022, Regulation (EU) 2022/869 of the European Parliament and of the Council of 30 May 2022 on guidelines for trans-European energy infrastructure (OJ L 152, 3.6.2022, p. 45–102).

EU, 2023a, Commission Delegated Regulation (EU) 2023/2486 of 27 June 2023 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to the sustainable use and protection of water and marine resources, to the transition to a circular economy, to pollution prevention and control, or to the protection and restoration of biodiversity and ecosystems and for determining whether that economic activity causes no significant harm to any of the other environmental objectives and amending Commission Delegated Regulation (EU) 2021/2178 as regards specific public disclosures for those economic activities (OJ L, 2023/2486, 21.11.2023).

EU, 2023b, Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system.

EU, 2023c, Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast) (OJ L 231, 20.9.2023, pp. 1-111).

EU, 2023d, Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652 (OJ L, 2023/2413).

EU, 2023e, European Union. 2023 Common Reporting Format (CRF) Table, (https://unfccc.int/documents/627830).

EU, 2023f, Regulation (EU) 2023/839 of the European Parliament and of the Council of 19 April 2023 amending Regulation (EU) 2018/841 as regards the scope, simplifying the reporting and compliance rules, and setting out the targets of the Member States for 2030, and Regulation (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review.

EU, 2023g, Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010 (Regulation (EU) 2023/1115).

EU, 2023h, Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Regulation (EU) 2023/1805).

EU, 2023i, Regulation (EU) 2023/2405 of the European Parliament and of the Council of 18 October 2023 on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation) (Regulation (EU) 2023/2405).

EU, 2024a, Consolidated text: Council Regulation (EU) No 833/2014 of 31 July 2014 concerning restrictive measures in view of Russia's actions destabilising the situation in Ukraine.

EU, 2024b, Directive (EU) 2024/1760 of the European Parliament and of the Council of 13 June 2024 on corporate sustainability due diligence and amending Directive (EU) 2019/1937 and Regulation (EU) 2023/2859 (OJ L, 2024/1760, 5.7.2024,).

EU, 2024c, 'Financing the EU budget', Consilium (https://www.consilium.europa.eu/en/policies/financing-the-eu-budget/) accessed 12 February 2025.

EU, 2024d, Interinstitutional Agreement on the Proposal for a Regulation of the European Parliament and of the Council establishing a Union certification framework for carbon removals (7514/24).

EU, 2024e, Regulation (EU) 2024/1735 of the European Parliament and of the Council of 13 June 2024 on establishing a framework of measures for strengthening Europe's net-zero technology manufacturing ecosystem and amending Regulation (EU) 2018/1724 (OJ L, 2024/1735, 28.6.2024).

EU, 2024f, Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869 (2022/0195(COD)).

EU, 2024g, Regulation (EU) 2024/3012 of the European Parliament and of the Council of 27 November 2024 establishing a Union certification framework for permanent carbon removals, carbon farming and carbon storage in products (OJ L, 2024/3012).

EU, 2024h, 'Types of institutions and bodies' (https://european-union.europa.eu/institutions-law-budget/institutions-and-bodies/types-institutions-and-bodies_en).

EU and OACPS, 2023, Partnership Agreement between the European Union and its Member States, of the one part, and the Members of the Organisation of African, Caribbean and Pacific States, of the other part (OJ L, 2023/2862, 28.12.2023).

Eurofound, 2021, *Distributional impacts of climate policies in Europe*, Luxembourg (https://www.eurofound.europa.eu/en/publications/2021/distributional-impacts-climate-policies-europe).

European Biochar Industry, 2023, *European Biochar: Market Report 2022-2023* (https://www.biochar-industry.com/wp-content/uploads/2023/03/European-Biochar-Market-Report_20222023.pdf) accessed 27 November 2023.

European Forest Institute, 2023, *2023 Annual Report* (https://efi.int/publications-bank/2023-annual-report).

European Ombudsman, 2022, Decision on the European Commission's refusal to grant public access to documents concerning compliance with biofuels sustainability criteria under the Renewable Energy Directive (case 1527/2020/DL), (https://www.ombudsman.europa.eu/en/decision/en/153581).

Eurostat, 2021, *Accounting for ecosystems and their services in the European Union (INCA): final report from phase II of the INCA project aiming to develop a pilot for an integrated system of ecosystem accounts for the EU*, Publications Office of the European Union, Luxembourg.

Eurostat, 2022, Farms and farmland in the European Union - statistics, (https://ec.europa.eu/eurostat/statistics-explained/SEPDF/cache/73319.pdf) accessed 6 March 2023.

Eurostat, 2023, Roundwood, fuelwood and other basic products, for_basic (https://ec.europa.eu/eurostat/databrowser/view/for_basic__custom_12944338/default/table?lang=en).

Eurostat, 2024a, GDP and main components (output, expenditure and income), nama_10_gdp.

Eurostat, 2024b, Production of electricity and derived heat by type of fuel, nrg_bal_peh (https://ec.europa.eu/eurostat/databrowser/view/nrg_bal_peh__custom_10906388/default/table?lang=en).

Faaij, A. P. C., 2022, 'Repairing What Policy Is Missing Out on: A Constructive View on Prospects and Preconditions for Sustainable Biobased Economy Options to Mitigate and Adapt to Climate Change', *Energies* 15(16), p. 5955 (DOI: 10.3390/en15165955).

Fajardy, M., et al., 2019, *BECCS deployment: a reality check*, Grantham Insititute (https://www.imperial.ac.uk/media/imperial-college/grantham-institute/public/publications/briefing-papers/BECCS-deployment---a-reality-check.pdf).

Fajardy, M. and Dowell, N. M., 2017, 'Can BECCS deliver sustainable and resource efficient negative emissions?', *Energy & Environmental Science* 10(6), pp. 1389-1426 (DOI: 10.1039/C7EE00465F).

FAO, 2023, *Estimating emissions and removals from forest degradation*, FAO (http://www.fao.org/documents/card/en/c/cc5803en) accessed 24 October 2024.

Farrell, C. A., et al., 2024, 'Charting a course for peatland restoration in Ireland: a case study to support restoration frameworks in other regions', *Restoration Ecology* 32(7), p. e14216 (DOI: 10.1111/rec.14216).

Fasihi, M., et al., 2019, 'Techno-economic assessment of CO2 direct air capture plants - ScienceDirect', *Journal of Cleaner Production* 224, pp. 957-980.

Fassnacht, F. E., et al., 2024, 'Remote sensing in forestry: current challenges, considerations and directions' Achim, A. (ed.), *Forestry: An International Journal of Forest Research* 97(1), pp. 11-37 (DOI: 10.1093/forestry/cpad024).

Fawzy, S., et al., 2022, 'Atmospheric carbon removal via industrial biochar systems: A techno-economic-environmental study', *Journal of Cleaner Production* 371, p. 133660 (DOI: 10.1016/j.jclepro.2022.133660).

Feindt, S., et al., 2021, 'Understanding regressivity: Challenges and opportunities of European carbon pricing', *Energy Economics* 103, p. 105550 (DOI: 10.1016/j.eneco.2021.105550).

Feng, E. Y., et al., 2016, 'Could artificial ocean alkalinization protect tropical coral ecosystems from ocean acidification?', *Environmental Research Letters* 11(7), p. 074008 (DOI: 10.1088/1748-9326/11/7/074008).

Field, J. L., et al., 2020, 'Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels', *Proceedings of the National Academy of Sciences* 117(36), pp. 21968-21977 (DOI: 10.1073/pnas.1920877117).

Filipović, S., et al., 2022, 'The green deal – just transition and sustainable development goals Nexus', *Renewable and Sustainable Energy Reviews* 168, p. 112759 (DOI: 10.1016/j.rser.2022.112759).

FISE, 2024, *Unlocking the Vast Potential of Remote Sensing to Monitor Forests and Forest Disturbances*, Forest Information System for Europe (https://forest.eea.europa.eu/knowledge/research-highlights).

Fléchard, M.-C., et al., 2007, 'The changing relationships between forestry and the local community in rural northwestern Ireland', *Canadian Journal of Forest Research* 37(10), pp. 1999-2009 (DOI: 10.1139/X07-060).

Forzieri, G., et al., 2021, 'Emergent vulnerability to climate-driven disturbances in European forests', *Nature Communications* 12(1), p. 1081 (DOI: 10.1038/s41467-021-21399-7).

Frank, S., et al., 2015, 'The dynamic soil organic carbon mitigation potential of European cropland', *Global Environmental Change* 35, pp. 269-278 (DOI: 10.1016/j.gloenvcha.2015.08.004).

Franks, M., et al., 2022, 'Pigou's Advice and Sisyphus' Warning: Carbon Pricing with Non-Permanent Carbon-Dioxide Removal', Munich (https://www.cesifo.org/en/publications/2022/working-paper/pigous-advice-and-sisyphus-warning-carbon-pricing-non-permanent).

Franks, M., et al., 2023, 'Optimal pricing for carbon dioxide removal under inter-regional leakage', *Journal of Environmental Economics and Management* 117, p. 102769 (DOI: 10.1016/j.jeem.2022.102769).

Frederiksen, P., et al., 2017, 'Misfits and compliance patterns in the transposition and implementation of the Habitats Directive—four cases', *Land Use Policy* 62, pp. 337-350 (DOI: 10.1016/j.landusepol.2016.12.010).

Fridahl, M., et al., 2023, 'Novel carbon dioxide removals techniques must be integrated into the European Union's climate policies', *Communications Earth & Environment* 4(1), p. 459 (DOI: 10.1038/s43247-023-01121-9).

Fuss, S., et al., 2018, 'Negative emissions—Part 2: Costs, potentials and side effects', *Environmental Research Letters* 13(6), p. 063002 (DOI: 10.1088/1748-9326/aabf9f).

G7 Carbon Market Platform, 2024, Summary: 9 th Strategic Dialogue of the Carbon Market Platform, (https://www.oecd.org/content/dam/oecd/en/networks/carbon-market-platform/co-chair-summary-9th-cmp-strategic-dialogue-2024.pdf).

Gattuso, J.-P., et al., 2021, 'The Potential for Ocean-Based Climate Action: Negative Emissions Technologies and Beyond', *Frontiers in Climate* 2, p. 575716 (DOI: 10.3389/fclim.2020.575716).

Geels, F. W., et al., 2017, 'Sociotechnical transitions for deep decarbonization', *Science* 357(6357), pp. 1242-1244 (DOI: 10.1126/science.aao3760).

Geels, F. W., 2018, 'Disruption and low-carbon system transformation: Progress and new challenges in socio-technical transitions research and the Multi-Level Perspective', *Energy Research & Social Science* 37, pp. 224-231 (DOI: 10.1016/j.erss.2017.10.010).

German Environment Agency, et al., 2022, *Role of soils in climate change mitigation*, Role of soils in climate change mitigation No 56/2022, German Environment Agency (https://www.ecologic.eu/sites/default/files/publication/2023/50061-role-of-soils-in-climate-change-mitigation.pdf).

GESMAP, 2019, *High Level Review of a Wide Range of Proposed Marine Geoengineering Techniques* (http://www.gesamp.org/publications/high-level-review-of-a-wide-range-of-proposed-marine-geoengineering-techniques) accessed 7 January 2025.

Gholami, R., et al., 2021, 'Leakage risk assessment of a CO2 storage site: A review', *Earth-Science Reviews* 223, p. 103849 (DOI: 10.1016/j.earscirev.2021.103849).

Gidden, M. J., et al., 2023, 'Aligning climate scenarios to emissions inventories shifts global benchmarks', *Nature* 624(7990), pp. 102-108 (DOI: 10.1038/s41586-023-06724-y).

Gillingham, K. and Stock, J. H., 2018, 'The Cost of Reducing Greenhouse Gas Emissions', *Journal of Economic Perspectives* 32(4), pp. 53-72 (DOI: 10.1257/jep.32.4.53).

Goldstein, A., et al., 2020a, 'Patenting and business outcomes for cleantech startups funded by the Advanced Research Projects Agency-Energy', *Nature Energy* 5(10), pp. 803-810 (DOI: 10.1038/s41560-020-00683-8).

Goldstein, A., et al., 2020b, 'Protecting irrecoverable carbon in Earth's ecosystems', *Nature Climate Change* 10(4), pp. 287-295 (DOI: 10.1038/s41558-020-0738-8).

Golub, A., et al., 2023, *Pricing Forest Carbon*, No DEP/2511/NA, United Nations Environment Programme, Geneva (https://www.un-redd.org/sites/default/files/2023-02/ForestCarbonPricing_Report_16Feb_FINAL.pdf) accessed 29 November 2023.

Gopal, B., 2009, 'Biodiversity in Wetlands', in: Maltby, E. and Barker, T. (eds), *The wetlands handbook*, Wiley-Blackwell, Chichester, UK; Hoboken, NJ, pp. 65-95.

Gordeeva, E., et al., 2022, 'The New EU Forest Strategy for 2030—An Analysis of Major Interests', *Forests* 13(9), p. 1503 (DOI: 10.3390/f13091503).

Gough, C. M., 2011, 'Terrestrial primary production: fuel for life' (https://www.nature.com/scitable/knowledge/library/terrestrial-primary-production-fuel-for-life-17567411/) accessed 7 March 2023.

Goulder, L. H. and Schein, A. R., 2013, 'Carbon taxes vs cap and trade: a critical review', *Climate Change Economics* 04(03), p. 1350010 (DOI: 10.1142/s2010007813500103).

Grafton, R. Q., et al., 2021, *A Global Analysis of the Cost-Efficiency of Forest Carbon Sequestration*, Environment Working Paper No 185, OECD Environment Directorate (https://one.oecd.org/document/ENV/WKP(2021)17/En/pdf).

Grassi, G., et al., 2008, 'Applying the conservativeness principle to REDD to deal with the uncertainties of the estimates', *Environmental Research Letters* 3(3), p. 035005 (DOI: 10.1088/1748-9326/3/3/035005).

Gren, I.-M., 2024, 'A trading market for uncertain carbon removal by land use in the EU', *Forest Policy and Economics* 159, p. 103127 (DOI: 10.1016/j.forpol.2023.103127).

Griscom, B. W., et al., 2017, 'Natural climate solutions', *Proceedings of the National Academy of Sciences of the United States of America* 114(44), pp. 11645-11650 (DOI: 10.1073/pnas.1710465114).

Groom, B. and Venmans, F., 2024, 'The social value of temporary carbon removals and delayed emissions', National Bureau of Economic Research.

Grossmann, M. and Dietrich, O., 2012, 'SOCIAL BENEFITS AND ABATEMENT COSTS OF GREENHOUSE GAS EMISSION REDUCTIONS FROM RESTORING DRAINED FEN WETLANDS: A CASE STUDY FROM THE ELBE RIVER BASIN (GERMANY)', *Irrigation and Drainage* 61(5), pp. 691-704 (DOI: 10.1002/ird.1669).

Grubb, M., et al., 2021, 'Induced innovation in energy technologies and systems: a review of evidence and potential implications for CO2 mitigation', *Environmental Research Letters* 16(4), p. 043007 (DOI: 10.1088/1748-9326/abde07).

Grubb, M., et al., 2022, 'Carbon Leakage, Consumption, and Trade', *Annual Review of Environment and Resources* 47(1), pp. 753-795 (DOI: 10.1146/annurev-environ-120820-053625).

Grubb, M., 2022, *Navigating the crises in European energy: Price Inflation, Marginal Cost Pricing, and Principles for Electricity Market Redesign in an Era of Low-Carbon Transition*, Institute for New Economic Thinking Working Paper Series (https://www.ineteconomics.org/research/research-papers/navigating-the-crises-in-european-energy) accessed 8 October 2022.

Grubert, E. and Talati, S., 2024, 'The distortionary effects of unconstrained for-profit carbon dioxide removal and the need for early governance intervention', *Carbon Management* 15(1), p. 2292111 (DOI: 10.1080/17583004.2023.2292111).

Grundnig, P. W., et al., 2006, 'Influence of air humidity on the suppression of fugitive dust by using a water-spraying system', *China Particuology* 4(5), pp. 229-233 (DOI: 10.1016/S1672-2515(07)60265-6).

Günther, A., et al., 2020, 'Prompt rewetting of drained peatlands reduces climate warming despite methane emissions', *Nature Communications* 11(1), p. 1644 (DOI: 10.1038/s41467-020-15499-z).

Günther, P., et al., 2024, 'Carbon farming, overestimated negative emissions and the limits to emissions trading in land-use governance: the EU carbon removal certification proposal', *Environmental Sciences Europe* 36(1), p. 72 (DOI: 10.1186/s12302-024-00892-y).

Hardaker, A., 2018, 'Is forestry really more profitable than upland farming? A historic and present day farm level economic comparison of upland sheep farming and forestry in the UK', *Land Use Policy* 71, pp. 98-120 (DOI: 10.1016/j.landusepol.2017.11.032).

Hartmann, J., et al., 2023, 'Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches – consequences for durability of CO_2 storage', *Biogeosciences* 20(4), pp. 781-802 (DOI: 10.5194/bg-20-781-2023).

Haya, B. K., et al., 2023, 'Comprehensive review of carbon quantification by improved forest management offset protocols', *Frontiers in Forests and Global Change* 6, p. 958879 (DOI: 10.3389/ffgc.2023.958879).

Healey, P., et al., 2024, 'Responsible innovation in CDR: designing sustainable national Greenhouse Gas Removal policies in a fragmented and polycentric governance system', *Frontiers in Climate* 5, p. 1293650 (DOI: 10.3389/fclim.2023.1293650).

Heck, V., et al., 2018, 'Biomass-based negative emissions difficult to reconcile with planetary boundaries', *Nature Climate Change* 8(2), pp. 151-155 (DOI: 10.1038/s41558-017-0064-y).

Heffron, R. J., et al., 2018, 'Ownership, risk and the law for a CO2 transport network for carbon capture and storage in the European Union', *Journal of Energy & Natural Resources Law* 36(4), pp. 433-462 (DOI: 10.1080/02646811.2018.1442215).

Hegger, D. L. T., et al., 2017, 'The Roles of Residents in Climate Adaptation: A systematic review in the case of the Netherlands', *Environmental Policy and Governance* 27(4), pp. 336-350 (DOI: 10.1002/eet.1766).

Henderson, B., et al., 2022, *Soil carbon sequestration by agriculture: Policy options*, OECD Food, Agriculture and Fisheries Papers No 174 (https://www.oecd-ilibrary.org/agriculture-and-food/soil-carbon-sequestration-by-agriculture_63ef3841-en) accessed 25 October 2024.

Henry, B., et al., 2022, 'Creating framework to foster soil carbon sequestration', in: Rumpel, C. (ed.), *Understanding and fostering soil carbon sequestration*, Burleigh Dodds Science Publishing, pp. 767-808.

Hepburn, C., et al., 2019, 'The technological and economic prospects for CO2 utilization and removal', *Nature* 575(7781), pp. 87-97 (DOI: 10.1038/s41586-019-1681-6).

Hermawan, S., et al., 2023, 'Institutional layering in climate policy: Insights from REDD+ governance in Indonesia', *Forest Policy and Economics* 154, p. 103037 (DOI: 10.1016/j.forpol.2023.103037).

Hermoso, V., et al., 2022, 'The EU Biodiversity Strategy for 2030: Opportunities and challenges on the path towards biodiversity recovery', *Environmental Science & Policy* 127, pp. 263-271 (DOI: 10.1016/j.envsci.2021.10.028).

Hickey, C., et al., 2023, 'A review of commercialisation mechanisms for carbon dioxide removal', *Frontiers in Climate* 4, p. 1101525 (DOI: 10.3389/fclim.2022.1101525).

Hoek, N., 2022, 'A Critical Analysis of the Proposed EU Regulation on Nature Restoration: Have the Problems Been Resolved?', *European Energy and Environmental Law Review* 31(Issue 5), pp. 320-333 (DOI: 10.54648/EELR2022021).

Holz, F., et al., 2021, 'A 2050 perspective on the role for carbon capture and storage in the European power system and industry sector', *Energy Economics* 104, p. 105631 (DOI: 10.1016/j.eneco.2021.105631).

Honegger, M., et al., 2021a, 'Potential implications of carbon dioxide removal for the sustainable development goals', *Climate Policy* 21(5), pp. 678-698 (DOI: 10.1080/14693062.2020.1843388).

Honegger, M., et al., 2021b, 'Who Is Paying for Carbon Dioxide Removal? Designing Policy Instruments for Mobilizing Negative Emissions Technologies', *Frontiers in Climate* 3, p. 672996 (DOI: 10.3389/fclim.2021.672996).

Honegger, M., 2023, 'Toward the effective and fair funding of CO2 removal technologies', *Nature Communications* 14(1), p. 534 (DOI: 10.1038/s41467-023-36199-4).

Howell, S. T., 2017, 'Financing Innovation: Evidence from R&D Grants', *American Economic Review* 107(4), pp. 1136-1164 (DOI: 10.1257/aer.20150808).

Howley, P., et al., 2015, 'Explaining the economic "irrationality" of farmers' land use behaviour: The role of productivist attitudes and non-pecuniary benefits', *Ecological Economics* 109, pp. 186-193 (DOI: 10.1016/j.ecolecon.2014.11.015).

Hummel, K. and Bauernhofer, K., 2024, 'Consequences of sustainability reporting mandates: evidence from the EU taxonomy regulation', *Accounting Forum* 48(3), pp. 374-400 (DOI: 10.1080/01559982.2024.2301854).

Humpenöder, F., et al., 2020, 'Peatland protection and restoration are key for climate change mitigation', *Environmental Research Letters* 15(10), p. 104093 (DOI: 10.1088/1748-9326/abae2a).

Huuskonen, S., et al., 2021, 'What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia?', *Forest Ecology and Management* 479, p. 118558 (DOI: 10.1016/j.foreco.2020.118558).

Hyyrynen, M., et al., 2023, 'European forest sinks and climate targets: past trends, main drivers, and future forecasts', *European Journal of Forest Research* 142(5), pp. 1207-1224 (DOI: 10.1007/s10342-023-01587-4).

Ibrahim, E. A., et al., 2022, 'Effects of biochar on soil properties, heavy metal availability and uptake, and growth of summer squash grown in metal-contaminated soil', *Scientia Horticulturae* 301, p. 111097 (DOI: 10.1016/j.scienta.2022.111097).

IEA, 2011, *Combining Bioenergy with CCS: Reporting and Accounting for Negative Emissions under UNFCCC and the Kyoto Protocol*, Working Paper (https://iea.blob.core.windows.net/assets/989e0be2-6025-40ca-a81c-482a685feb94/CombiningBioenergywithCCS.pdf).

IEA, 2022a, *CO2 storage resources and their development, An IEA CCUS Handbook*, International Energy Agency, Paris (https://www.iea.org/reports/co2-storage-resources-and-their-development).

IEA, 2022b, *Legal and Regulatory Frameworks for CCUS*, International Energy Agency, Paris (https://iea.blob.core.windows.net/assets/bda8c2b2-2b9c-4010-ab56-b941dc8d0635/LegalandRegulatoryFrameworksforCCUS-AnIEACCUSHandbook.pdf).

IEA, 2023a, 'Bioenergy with Carbon Capture and Storage' (https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/bioenergy-with-carbon-capture-and-storage).

IEA, 2023b, CCUS Projects Explorer.

IEA, 2025, *Direct Air Capture 2022* (https://www.iea.org/reports/direct-air-capture-2022).

IEAGHG, 2019, *Towards Zero Emissions CCS from Power Stations using Higher Capture Rates or Biomass* (https://ieaghg.org/publications/towards-zero-emissions-ccs-from-power-stations-using-higher-capture-rates-or-biomass/) accessed 6 January 2025.

IEAGHG, 2024, *Measurement, reporting and verification and accounting for carbon dioxide removal in the context of both project-based approaches and national greenhouse gas inventories* (https://ieaghg.org/publications/measurement-reporting-and-verification-and-accounting-for-carbon-dioxide-removal/).

IEEFA, 2022, 'The carbon capture crux: Lessons learned' (https://ieefa.org/resources/carbon-capture-crux-lessons-learned) accessed 6 January 2025.

IEEP and WWF, 2021, *Climate mitigation of large-scale nature restoration in Europe: Analysis of the climate mitigation potential of restoring habitats listsed in Annex I of the Habitats Directive*, Policy Report, Institute for Environmental Policy, Brussels (https://ieep.eu/publications/climate-mitigation-potential-of-large-scale-nature-restoration-in-europe/).

IMO, 2013, Resolution LP.4(8) on the amendment to the London Protocol to regulate the placement of matter for ocean fertilization and other marine geoengineering activities.

IMO, 2023, Marine geoengineering - assessing the impacts on the marine environment, (https://www.imo.org/en/MediaCentre/Pages/WhatsNew-1854.aspx).

IMO, 2024, 'London Protocol and Carbon Capture and Storage (CCS) at Sea', presentation given at: LC-SG 47 Science Day, London, April 2024.

IPCC, 2005, *IPCC Special Report on carbon dioxide capture and storage*, Cambridge Univ. Press, Cambridge.

IPCC, 2006, IPCC Guidelines for National Greenhouse Gas Inventories - Volume 5, (http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol5.html).

IPCC, 2019, *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*, The Intergovernmental Panel on Climate Change, Geneva, Switzerland (https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/).

IPCC, 2021, *AR6 WGI Report – Chapter 7: The Earth's energy budget, climate feedbacks, and climate sensitivity - Supplementary Material*, Intergovernmental Panel on Climate Change (https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf).

IPCC, 2022a, *Agriculture, Forestry and Other Land Uses (AFOLU). Chapter 7 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (doi: 10.1017/9781009157926.009).

IPCC, 2022b, *Annex: Glossary, in: Climate Change 2022, Mitigation of Climate Change*, Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IPCC, 2022c, 'Annex II: Glossary', in: *Climate change 2022: impacts, adaptation and vulnerability. Contribution of Working Group II to the sixth assessment report of the Intergovernmental Panel on Climate Change*, Intergovernmental Panel on Climate Change, p. AII/1-AII/51.

IPCC, 2022d, 'Chapter 3: Mitigation Pathways Compatible with Long-term Goals', in: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*,.

IPCC, 2022e, *'Chapter 12: Cross sectoral perspectives', in: Climate Change 2022: Mitigation of Climate Change*, Intergovernmental Panel on Climate Change, Geneva, Switzerland.

IPCC, 2022f, 'Chapter 13: National and sub-national policies and institutions', in: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*,.

IPCC, 2022g, 'Climate Change 2022: Impacts, Adaptation and Vulnerability' (https://www.ipcc.ch/report/ar6/wg2/) accessed 9 May 2023.

IPCC, 2022h, *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC, 2022i, *Climate change 2022: mitigation of climate change*, Intergovernmental Panel on Climate Change (https://www.ipcc.ch/report/sixth-assessment-report-working-group-3/) accessed 28 November 2022.

IPCC, 2022j, *Climate Change and Land: IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems*, Cambridge University Press.

IPCC, 2022k, *Cross-sectoral perspectives. Chapter 12 in Climate Change 2022: mitigation of climate change* (doi: 10.1017/9781009157926.005).

IPCC, 2022l, 'Demand, Services and Social Aspects of Mitigation', in: *Climate Change 2022: Mitigation of Climate Change AR 6 WGIII*,.

IPCC, 2022m, *Energy Systems. Chapter 6 in Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the IPCC* (doi: 10.1017/9781009157926.008).

IPCC, 2022n, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change -Summary for Policy Makers.

IPCC, ed., 2023a, 'Accelerating the Transition in the Context of Sustainable Development', in: *Climate Change 2022 - Mitigation of Climate Change*, Cambridge University Press, pp. 1727-1790.

IPCC, ed., 2023b, 'Agriculture, Forestry and Other Land Uses (AFOLU)', in: *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, pp. 747-860.

IPCC, 2023c, *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press.

IPCC, ed., 2023d, 'Energy Systems', in: *Climate Change 2022 - Mitigation of Climate Change*, Cambridge University Press, pp. 613-746.

IPCC, ed., 2023e, 'Innovation, Technology Development and Transfer', in: *Climate Change 2022 - Mitigation of Climate Change*, Cambridge University Press, pp. 1641-1726.

IPCC, ed., 2023f, 'Urban Systems and Other Settlements', in: *Climate Change 2022 - Mitigation of Climate Change*, Cambridge University Press, pp. 861-952.

IPCC, 2024, Call for nomination of experts to Scoping Meeting for Methodology Report on Carbon Dioxide Removal Technologies and Carbon Capture Utilization and Storage, (https://www.ipcc.ch/2024/06/18/nominations-scoping-meeting-cdr/).

ITLOS, 2024, Advisory Opinion of the International Tribunal for the Law of the Sea no 31, (https://www.itlos.org/fileadmin/itlos/documents/cases/31/Advisory_Opinion/C31_Adv_Op_21.05.2024_corr.pdf).

Izikowitz, D., 2021, 'Carbon Purchase Agreements, Dactories, and Supply-Chain Innovation: What Will It Take to Scale-Up Modular Direct Air Capture Technology to a Gigatonne Scale', *Frontiers in Climate* 3 (DOI: 10.3389/fclim.2021.636657).

Jactel, H., et al., 2018, 'Positive biodiversity–productivity relationships in forests: climate matters', *Biology Letters* 14(4), p. 20170747 (DOI: 10.1098/rsbl.2017.0747).

Jaiswal, S., et al., 2024, 'Projecting a food insecure world: Equity implications of land-based mitigation in IPCC mitigation pathways', *Environmental Science & Policy* 155, p. 103724 (DOI: 10.1016/j.envsci.2024.103724).

Jakob, M., 2021, 'Climate policy and international trade – A critical appraisal of the literature', *Energy Policy* 156, p. 112399 (DOI: 10.1016/j.enpol.2021.112399).

Jeffery, S., et al., 2011, 'A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis', *Agriculture, Ecosystems & Environment* 144(1), pp. 175-187 (DOI: 10.1016/j.agee.2011.08.015).

Jenkins, S., et al., 2021, 'Upstream decarbonization through a carbon takeback obligation: An affordable backstop climate policy', *Joule* 5(11), pp. 2777-2796 (DOI: 10.1016/j.joule.2021.10.012).

Jenkins, S., et al., 2023, 'Extended producer responsibility for fossil fuels', *Environmental Research Letters* 18(1), p. 011005 (DOI: 10.1088/1748-9326/aca4e8).

Jeszke, R., et al., 2024, 'VIIEW on EU ETS 2050: Exploring synergies between the EU ETS and other EU climate policy measures - carbon removal, hydrogen, and sectoral transport policy', (DOI: 10.13140/RG.2.2.26320.93443).

Jones, C., 2023, The future regulatory framework applicable to Carbon Capture and Storage Infrastructure - issues for discussion, (https://cadmus.eui.eu/bitstream/handle/1814/76181/RSC_PB_2023_23.pdf?sequence=1&isAllowed=y), EUI Florence School of Regulation.

Jonsson, R., et al., 2021, 'Boosting the EU forest-based bioeconomy: Market, climate, and employment impacts', *Technological Forecasting and Social Change* 163, p. 120478 (DOI: 10.1016/j.techfore.2020.120478).

Joseph, S., et al., 2021, 'How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar', *GCB Bioenergy* 13(11), pp. 1731-1764 (DOI: 10.1111/gcbb.12885).

Joskow, P. L., 2007, 'Chapter 16 Regulation of Natural Monopoly', in: *Handbook of Law and Economics*, Elsevier, pp. 1227-1348.

JRC, 2021a, *Forest reference levels under Regulation (EU) 2018/841 for the period 2021–2025: overview and main findings of the technical assessment.*, Publications Office, LU (https://data.europa.eu/doi/10.2760/0521) accessed 22 October 2024.

JRC, 2021b, *Study on certification and verification schemes in the forest sector and for wood-based products.*, Publications Office, LU (https://data.europa.eu/doi/10.2779/126030) accessed 20 November 2024.

JRC, 2022, *Clean Energy Technology Observatory, Clean energy outlooks: analysis and critical review: status report on technology development, trends, value chains and markets: 2022*, Joint Research Centre (https://data.europa.eu/doi/10.2760/309952).

JRC, 2024a, *Exploring foresight scenarios for the EU bioeconomy: report from a series of workshops with the Scenario Exploration System foresight tool.*, Publications Office, LU (https://data.europa.eu/doi/10.2760/874111) accessed 19 September 2024.

JRC, 2024b, *Shaping the future CO2 transport network for Europe.*, Publications Office, LU.

JRC, 2024c, *The state of soils in Europe* (https://publications.jrc.ec.europa.eu/repository/handle/JRC137600) accessed 11 November 2024.

Jutz, S. and Milagro-Pérez, M. P., 2020, 'Copernicus: the European Earth Observation programme', *Revista de Teledetección* (56) (DOI: 10.4995/raet.2020.14346).

Kaplan, R. S., et al., 2023, 'Accounting for Carbon Offsets – Establishing the Foundation for Carbon-Trading Markets', *SSRN Electronic Journal* (DOI: 10.2139/ssrn.4362921).

Kay, S., et al., 2019, 'Agroforestry creates carbon sinks whilst enhancing the environment in agricultural landscapes in Europe', *Land Use Policy* 83, pp. 581-593 (DOI: 10.1016/j.landusepol.2019.02.025).

Kelley, L. A., et al., 2024, 'Changes in soil N2O emissions and nitrogen use efficiency following long-term soil carbon storage: Evidence from a mesocosm experiment', *Agriculture, Ecosystems & Environment* 370, p. 109054 (DOI: 10.1016/j.agee.2024.109054).

Kenneth Möllersten, 2022, 'Assessment of classes of CDR methods: Technology Readiness, Costs, Impacts and Practical Limitations of Biochar as Soil Additive and BECCS', *14th International Conference on Applied Energy*.

Kerner, C., et al., 2023, 'Carbon dioxide removal to combat climate change? An expert survey on perception and support', *Environmental Research Communications* 5(4), p. 041003 (DOI: 10.1088/2515-7620/accc72).

Kettunen, M., et al., 2017, *Summary report - Integration approach to EU biodiversity financing: evaluation of results and analysis of options for the future*, No Project ENV.B.3/ETU/2015/0014, Institute for European Environmental Policy, Brussels / London.

Kilgallon, R., et al., 2015, 'Odourisation of CO2 pipelines in the UK: Historical and current impacts of smell during gas transport', *International Journal of Greenhouse Gas Control* 37, pp. 504-512 (DOI: 10.1016/j.ijggc.2015.04.010).

Kim, D., 2008, Preliminary life cycle analysis of modular and conventional housing in Benton Harbor, University of Michigan, MI, USA.

Kloo, Y., et al., 2024, 'Reaching net-zero in the chemical industry—A study of roadmaps for industrial decarbonisation', *Renewable and Sustainable Energy Transition* 5, p. 100075 (DOI: 10.1016/j.rset.2023.100075).

Knill, C., et al., 2020, 'Policy Integration: Challenges for Public Administration', in: *Oxford Research Encyclopedia of Politics*, Oxford University Press.

Köhler, A. R. and Som, C., 2014, 'Risk preventative innovation strategies for emerging technologies the cases of nano-textiles and smart textiles', *Risk and Uncertainty Management in Technological Innovation* 34(8), pp. 420-430 (DOI: 10.1016/j.technovation.2013.07.002).

Kolesnikov, S., et al., 2024, 'A framework and methodology for analyzing technology spillover processes with an application in solar photovoltaics', *Technovation* 134, p. 103048 (DOI: 10.1016/j.technovation.2024.103048).

Kongsager, R., 2018, 'Linking Climate Change Adaptation and Mitigation: A Review with Evidence from the Land-Use Sectors', *Land* 7(4), p. 158 (DOI: 10.3390/land7040158).

Koponen, K., et al., 2024, 'Responsible carbon dioxide removals and the EU's 2040 climate target', *Environmental Research Letters* 19(9), p. 091006 (DOI: 10.1088/1748-9326/ad6d83).

Kornek, U. and Edenhofer, O., 2020, 'The strategic dimension of financing global public goods', *European Economic Review* 127, p. 103423 (DOI: 10.1016/j.euroecorev.2020.103423).

Korosuo, A., et al., 2023, 'The role of forests in the EU climate policy: are we on the right track?', *Carbon Balance and Management* 18(1), p. 15 (DOI: 10.1186/s13021-023-00234-0).

Kortleve, A. J., et al., 2024, 'Over 80% of the European Union's Common Agricultural Policy supports emissions-intensive animal products', *Nature Food* 5(4), pp. 288-292 (DOI: 10.1038/s43016-024-00949-4).

Kotz, M., et al., 2024, 'The economic commitment of climate change', *Nature* 628(8008), pp. 551-557 (DOI: 10.1038/s41586-024-07219-0).

Krause-Jensen, D., et al., 2022, 'Nordic Blue Carbon Ecosystems: Status and Outlook', *Frontiers in Marine Science* 9, p. 847544 (DOI: 10.3389/fmars.2022.847544).

Krey, V., et al., 2019, 'Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models', *Energy* 172, pp. 1254-1267 (DOI: 10.1016/j.energy.2018.12.131).

Kumar, T. R., et al., 2023, 'Plant and system-level performance of combined heat and power plants equipped with different carbon capture technologies', *Applied Energy* 338, p. 120927 (DOI: 10.1016/j.apenergy.2023.120927).

Kwasiborska, A., et al., 2023, 'The Influence of Visibility on the Opportunity to Perform Flight Operations with Various Categories of the Instrument Landing System', *Sensors* 23(18), p. 7953 (DOI: 10.3390/s23187953).

Kwiatkowski, L., et al., 2023, 'Contrasting carbon dioxide removal potential and nutrient feedbacks of simulated ocean alkalinity enhancement and macroalgae afforestation', *Environmental Research Letters* 18(12), p. 124036 (DOI: 10.1088/1748-9326/ad08f9).

La Hoz Theuer, S., et al., 2021, *Emissions Trading Systems and Net Zero: Trading Removals*, International Carbon Action Partnership, Berlin (https://adelphi.de/en/system/files/mediathek/bilder/ICAP%20NetZeroPaper_final.pdf).

Lamb, W. F., et al., 2024, 'Countries need to provide clarity on the role of carbon dioxide removal in their climate pledges', *Environmental Research Letters* (DOI: 10.1088/1748-9326/ad91c7).

Lamb, W. F., 2024, 'The size and composition of residual emissions in integrated assessment scenarios at net-zero CO_2', *Environmental Research Letters* 19(4), p. 044029 (DOI: 10.1088/1748-9326/ad31db).

Lanigan, G. J., et al., 2023, *MACC 2023: An updated analysis of the grenhouse gas abatement potential of the Irish agriculture and land-use sectors between 2021 and 2030*, Teagasc, Carlow.

Larsen, S. V., et al., 2018, 'The role of EIA and weak assessments of social impacts in conflicts over implementation of renewable energy policies', *Energy Policy* 115, pp. 43-53 (DOI: 10.1016/j.enpol.2018.01.002).

Lebling, K., et al., 2022, 'Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities', *World Resources Institute* (DOI: 10.46830/wrirpt.21.00090).

Lebling, K. and Riedl, D., 2023, 'Lessons from California's Carbon Dioxide Removal Policies', World Resources Institute (https://www.wri.org/insights/california-carbon-dioxide-removal-policies).

Lee, H., et al., 2019, 'Implementing land-based mitigation to achieve the Paris Agreement in Europe requires food system transformation', *Environmental Research Letters* 14(10), p. 104009 (DOI: 10.1088/1748-9326/ab3744).

Lefebvre, D., et al., 2023, 'Biomass residue to carbon dioxide removal: quantifying the global impact of biochar', *Biochar* 5(1), p. 65 (DOI: 10.1007/s42773-023-00258-2).

Lefvert, A. and Grönkvist, S., 2024, 'Lost in the scenarios of negative emissions: The role of bioenergy with carbon capture and storage (BECCS)', *Energy Policy* 184, p. 113882 (DOI: 10.1016/j.enpol.2023.113882).

Lehmann, J., et al., 2015, 'Persistence of biochar in soil', in: *Biochar for environmental management*, Routledge, London New York.

Lehtilä, A., et al., 2023, *Quantitiative assessment of NEGEM scenarios with TIMES-VTT*, NEGEM Project No D8.2 (https://www.negemproject.eu/wp-content/uploads/2023/11/NEGEM_D8.2_NEGEM-scenarios.pdf).

Lemoine, D., 2020, 'Incentivizing Negative Emissions through Carbon Shares', National Bureau of Economic Research.

Lessmann, K., et al., 2024, 'Emissions trading with clean-up certificates: deterring mitigation or increasing ambition?' (https://cesifo.org/en/publications/2024/working-paper/emissions-trading-clean-certificates-deterring-mitigation-or) accessed 18 July 2024.

Lezaun, J., et al., 2021, 'Governing Carbon Dioxide Removal in the UK: Lessons Learned and Challenges Ahead', *Frontiers in Climate* 3, p. 673859 (DOI: 10.3389/fclim.2021.673859).

Liang, J., et al., 2016, 'Positive biodiversity-productivity relationship predominant in global forests', *Science* 354(6309), aaf8957 (DOI: 10.1126/science.aaf8957).

Liebe, M. and Howarth, D., 2020, 'The European Investment Bank as Policy Entrepreneur and the Promotion of Public-Private Partnerships', *New Political Economy* 25(2), pp. 195-212 (DOI: 10.1080/13563467.2019.1586862).

Lienhoop, N. and Brouwer, R., 2015, 'Agri-environmental policy valuation: Farmers' contract design preferences for afforestation schemes', *Land Use Policy* 42, pp. 568-577 (DOI: 10.1016/j.landusepol.2014.09.017).

Lier, M., et al., 2022, 'The New EU Forest Strategy for 2030: A New Understanding of Sustainable Forest Management?', *Forests* 13(2), p. 245 (DOI: 10.3390/f13020245).

Lin, X., et al., 2023, 'Biochar-cement concrete toward decarbonisation and sustainability for construction: Characteristic, performance and perspective', *Journal of Cleaner Production* 419, p. 138219 (DOI: 10.1016/j.jclepro.2023.138219).

Liu, Y., et al., 2021, 'Influences of environmental impact assessment on public acceptance of waste-to-energy incineration projects', *Journal of Cleaner Production* 304, p. 127062 (DOI: 10.1016/j.jclepro.2021.127062).

Liu, Z., et al., 2015, 'Four system boundaries for carbon accounts', *Ecological Modelling* 318, pp. 118-125 (DOI: 10.1016/j.ecolmodel.2015.02.001).

Lloyd, I. L., et al., 2023, 'State of Knowledge on UK Agricultural Peatlands for Food Production and the Net Zero Transition', *Sustainability* 15(23), p. 16347 (DOI: 10.3390/su152316347).

Lovec, M., et al., 2024, 'External shocks, policy spillovers, and veto players: (post)exceptionalist common agricultural policy and the case of the 2023-2027 reform', *Journal of European Integration* 46(4), pp. 433-453 (DOI: 10.1080/07036337.2023.2300366).

Low, S., et al., 2024, 'Public perceptions on carbon removal from focus groups in 22 countries', *Nature Communications* 15(1), p. 3453 (DOI: 10.1038/s41467-024-47853-w).

Luderer, G., et al., 2022, 'Impact of declining renewable energy costs on electrification in low-emission scenarios', *Nature Energy* 7(1), pp. 32-42 (DOI: 10.1038/s41560-021-00937-z).

Lugato, E., et al., 2014, 'Potential carbon sequestration of European arable soils estimated by modelling a comprehensive set of management practices', *Global Change Biology* 20(11), pp. 3557-3567 (DOI: 10.1111/gcb.12551).

Lugato, E., et al., 2020, 'Maximising climate mitigation potential by carbon and radiative agricultural land management with cover crops', *Environmental Research Letters* 15(9), p. 094075 (DOI: 10.1088/1748-9326/aba137).

Lund, J. F., et al., 2023, 'Net zero and the unexplored politics of residual emissions', *Energy Research & Social Science* 98, p. 103035 (DOI: 10.1016/j.erss.2023.103035).

Lundberg, L. and Fridahl, M., 2022, 'The missing piece in policy for carbon dioxide removal: reverse auctions as an interim solution', *Discover Energy* 2(1), p. 3 (DOI: 10.1007/s43937-022-00008-8).

Lux, B., et al., 2023, 'Potentials of direct air capture and storage in a greenhouse gas-neutral European energy system', *Energy Strategy Reviews* 45, p. 101012 (DOI: 10.1016/j.esr.2022.101012).

Lyngfelt, A., et al., 2024, 'FinanceForFuture: Enforcing a CO2 emitter liability using atmospheric CO2 removal deposits (ACORDs) to finance future negative emissions', *Energy Research & Social Science* 107, p. 103356 (DOI: 10.1016/j.erss.2023.103356).

Mac Dowell, N., et al., 2022, 'Comparing approaches for carbon dioxide removal', *Joule* 6(10), pp. 2233-2239 (DOI: 10.1016/j.joule.2022.09.005).

Maes, J. and et al., 2023, 'Accounting for forest condition in Europe based on an international statistical standard', *Nature Communications* 14(1), p. 3723 (DOI: 10.1038/s41467-023-39434-0).

Mai-Moulin, T., et al., 2021, 'Effective sustainability criteria for bioenergy: Towards the implementation of the european renewable directive II', *Renewable and Sustainable Energy Reviews* 138, p. 110645 (DOI: 10.1016/j.rser.2020.110645).

Malak, D., et al., 2021, *Carbon pools and sequestration potential of wetlands in the European Union.*, ETC/ULS Report No 10/2021, European Topic Centre on Urban, Land and Soil Systems (https://www.eionet.europa.eu/etcs/etc-uls/products/etc-uls-reports/etc-uls-report-10-2021-carbon-pools-and-sequestration-potential-of-wetlands-in-the-european-union) accessed 4 July 2023.

Malhotra, A. and Schmidt, T. S., 2020, 'Accelerating Low-Carbon Innovation', *Joule* 4(11), pp. 2259-2267 (DOI: 10.1016/j.joule.2020.09.004).

Maltby, E. and Acreman, M. C., 2011, 'Ecosystem services of wetlands: pathfinder for a new paradigm', *Hydrological Sciences Journal* 56(8), pp. 1341-1359 (DOI: 10.1080/02626667.2011.631014).

Mannion, P., et al., 2023, *Carbon removals: how to scale a new gigaton industry*, McKinsey Sustainability.

Markusson, N., et al., 2018, 'Towards a cultural political economy of mitigation deterrence by negative emissions technologies (NETs)', *Global Sustainability* 1, p. e10 (DOI: 10.1017/sus.2018.10).

Martin-Roberts, E., et al., 2021, 'Carbon capture and storage at the end of a lost decade', *One Earth* 4(11), pp. 1569-1584 (DOI: 10.1016/j.oneear.2021.10.002).

Material Economics, 2021, *EU biomass use in a net-zero economy — a course correction for EU biomass* (https://materialeconomics.com/publications/eu-biomass-use) accessed 7 March 2023.

Mazzucato, M., 2015, 'Innovation, the state and patient capital', *Political Quarterly* 86, pp. 98-118.

Mazzucato, M., 2024, Theory meets practice: Getting missions right, (https://marianamazzucato.substack.com/p/theory-meets-practice-getting-missions).

Mazzucato, M. and Semieniuk, G., 2017, 'Public financing of innovation: new questions', *Oxford Review of Economic Policy* 33(1), pp. 24-48.

McCauley, D. and Heffron, R., 2018, 'Just transition: Integrating climate, energy and environmental justice', *Energy Policy* 119, pp. 1-7 (DOI: 10.1016/j.enpol.2018.04.014).

McGrath, M. J., et al., 2023, 'The consolidated European synthesis of CO_2 emissions and removals for the European Union and United Kingdom: 1990–2020', *Earth System Science Data* 15(10), pp. 4295-4370 (DOI: 10.5194/essd-15-4295-2023).

McLaren, D., 2020, 'Quantifying the potential scale of mitigation deterrence from greenhouse gas removal techniques', *Climatic Change* 162(4), pp. 2411-2428 (DOI: 10.1007/s10584-020-02732-3).

McLaren, D. P., et al., 2019, 'Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions', *Frontiers in Climate* 1, p. 4 (DOI: 10.3389/fclim.2019.00004).

Meckling, J., et al., 2017, 'Policy sequencing toward decarbonization', *Nature Energy* 2(12), pp. 918-922 (DOI: 10.1038/s41560-017-0025-8).

Meckling, J., et al., 2022, 'Energy innovation funding and institutions in major economies', *Nature Energy* 7(9), pp. 876-885 (DOI: 10.1038/s41560-022-01117-3).

Meeus, L. and Keyaerts, N., 2015, *First series of cross-border cost allocation decisions for projects of common interest: main lessons learned*,.

Mendes, A., et al., 2023, 'Towards a legal definition of ecological restoration: Reviewing international, European and Member States' case law', *Review of European, Comparative & International Environmental Law* 32(1), pp. 3-17 (DOI: 10.1111/reel.12476).

Meng, J., et al., 2021, 'Comparing expert elicitation and model-based probabilistic technology cost forecasts for the energy transition', *Proceedings of the National Academy of Sciences* 118(27), p. e1917165118 (DOI: 10.1073/pnas.1917165118).

Mercer, L., et al., 2024, *Towards improved cost estimates for monitoring, reporting and verification of carbon dioxide removal - policy report* (https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2024/10/Towards-improved-cost-estimates-for-monitoring-reporting-and-verification-of-carbon-dioxide-removal-.pdf).

Mercer, L. and Burke, J., 2023, *Strengthening MRV standards for greenhouse gas removals to improve climate change governance*, Policy Report, Grantham Research Institute on Climate Change and the Environment & Centre for Climate Change Economic and Policy (https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2023/05/Strengthening-MRV-standards-for-greenhouse-gas-removals-.pdf).

Merfort, A., et al., 2024, 'Separating CO2 emission from removal targets comes with limited cost impacts' (https://www.researchsquare.com/article/rs-4572047/v1) accessed 20 August 2024.

Merk, C., et al., 2023, 'German citizens' preference for domestic carbon dioxide removal by afforestation is incompatible with national removal potential', *Communications Earth & Environment* 4(1), pp. 1-9 (DOI: 10.1038/s43247-023-00713-9).

Meyer-Ohlendorf, N., 2023, *Making Carbon Removals a Real Climate Solution - How to integrate carbon removals into EU Climate Policies*, Ecologi Institute (c).

Meysman, F. J. R. and Montserrat, F., 2017, 'Negative CO2 emissions via enhanced silicate weathering in coastal environments', *Biology Letters* 13(4), p. 20160905 (DOI: 10.1098/rsbl.2016.0905).

Michaelowa, A., et al., 2019, 'Additionality revisited: guarding the integrity of market mechanisms under the Paris Agreement', *Climate Policy* 19(10), pp. 1211-1224 (DOI: 10.1080/14693062.2019.1628695).

Minx et al., 2018, 'Negative emissions—Part 1: Research landscape and synthesis', (Environ. Res. Lett. 13 063001.) (DOI: 10.1088/1748-9326/aabf9b.).

Misch, F. and Wingender, P., 2024, 'Revisiting carbon leakage', *Energy Economics* 140, p. 107786 (DOI: 10.1016/j.eneco.2024.107786).

Mitchell, S. R., et al., 2012, 'Carbon debt and carbon sequestration parity in forest bioenergy production', *GCB Bioenergy* 4(6), pp. 818-827 (DOI: 10.1111/j.1757-1707.2012.01173.x).

Möller, T., et al., 2024, 'Achieving net zero greenhouse gas emissions critical to limit climate tipping risks', *Nature Communications* 15(1), p. 6192 (DOI: 10.1038/s41467-024-49863-0).

Mongin, M., et al., 2021, 'Reversing ocean acidification along the Great Barrier Reef using alkalinity injection', *Environmental Research Letters* 16(6), p. 064068 (DOI: 10.1088/1748-9326/ac002d).

Montserrat, F., et al., 2017, 'Olivine Dissolution in Seawater: Implications for CO2 Sequestration through Enhanced Weathering in Coastal Environments', *Environmental Science & Technology* 51(7), pp. 3960-3972 (DOI: 10.1021/acs.est.6b05942).

Moosmann, D., et al., 2020, 'Strengths and gaps of the EU frameworks for the sustainability assessment of bio-based products and bioenergy', *Energy, Sustainability and Society* 10(1), p. 22 (DOI: 10.1186/s13705-020-00251-8).

Morin, X., et al., 2018, 'Long-term response of forest productivity to climate change is mostly driven by change in tree species composition', *Scientific Reports* 8(1), 5627 (DOI: 10.1038/s41598-018-23763-y).

Moser, C. and Leipold, S., 2021, 'Toward "hardened" accountability? Analyzing the European Union's hybrid transnational governance in timber and biofuel supply chains', *Regulation & Governance* 15(1), pp. 115-132 (DOI: 10.1111/rego.12268).

Mosquera-Losada, M. R., et al., 2018, 'Agroforestry in the European common agricultural policy', *Agroforestry Systems* 92(4), pp. 1117-1127 (DOI: 10.1007/s10457-018-0251-5).

Nabuurs, G.-J., et al., 2013, 'First signs of carbon sink saturation in European forest biomass', *Nature Climate Change* 3(9), pp. 792-796 (DOI: 10.1038/nclimate1853).

Nabuurs, G.-J., et al., 2017, 'By 2050 the Mitigation Effects of EU Forests Could Nearly Double through Climate Smart Forestry', *Forests* 8(12), p. 484 (DOI: 10.3390/f8120484).

Nagelkerken, I., et al., 2008, 'The habitat function of mangroves for terrestrial and marine fauna: A review', *Aquatic Botany* 89(2), pp. 155-185 (DOI: 10.1016/j.aquabot.2007.12.007).

Nawaz, S., et al., 2023, 'An independent public engagement body is needed to responsibly scale carbon removal in the US', *Environmental Research Letters* 19(1), p. 011002 (DOI: 10.1088/1748-9326/ad1081).

Nawaz, S., et al., 2024a, *Agenda for a progressive political economy of carbon removal*, Institute for Responsible Carbon Removal, Washington D.C. (https://www.american.edu/sis/centers/carbon-removal/upload/agenda-for-a-progressive-political-economy-of-carbon-removal.pdf).

Nawaz, S., et al., 2024b, 'Carbon removal for a just transition', *Climate Policy*, pp. 1-12 (DOI: 10.1080/14693062.2024.2418305).

Nemet, G. F., et al., 2018a, 'Negative emissions—Part 3: Innovation and upscaling', *Environmental Research Letters* 13(6), p. 063003 (DOI: 10.1088/1748-9326/aabff4).

Nemet, G. F., et al., 2018b, 'The valley of death, the technology pork barrel, and public support for large demonstration projects', *Energy Policy* 119, pp. 154-167 (DOI: 10.1016/j.enpol.2018.04.008).

Nesbitt, L., et al., 2019, 'Who has access to urban vegetation? A spatial analysis of distributional green equity in 10 US cities', *Landscape and Urban Planning* 181, pp. 51-79 (DOI: 10.1016/j.landurbplan.2018.08.007).

Nijnik, M., et al., 2013, 'An economic analysis of the establishment of forest plantations in the United Kingdom to mitigate climatic change', *Forest Policy and Economics* 26, pp. 34-42 (DOI: 10.1016/j.forpol.2012.10.002).

Nilsson, L. J., et al., 2021, 'An industrial policy framework for transforming energy and emissions intensive industries towards zero emissions', *Climate Policy* 21(8), pp. 1053-1065 (DOI: 10.1080/14693062.2021.1957665).

Niskanen, A., 1999, 'The financial and economic profitability of field afforestation in Finland', *Silva Fennica* 33(2) (DOI: 10.14214/sf.664).

Nolan, C., et al., 2021, *Risk of Drought-Related 'Fodder Crises' in Irish Agriculture under mid-21st Century Climatic Conditions*.

Nolan, C., et al., 2024, 'Additionality, baselines, and the proper accounting for land-based climate change mitigation efforts', *Oxford Open Climate Change* 4(1), p. kgae012 (DOI: 10.1093/oxfclm/kgae012).

Nordic Council of Ministers, 2023, *Regulatory framework for CCS in the Nordic countries* (https://www.norden.org/en/publication/regulatory-framework-ccs-nordic-countries).

Norris, J., et al., 2021, 'Viewpoints on Cooperative Peatland Management: Expectations and Motives of Dutch Farmers', *Land* 10(12), p. 1326 (DOI: 10.3390/land10121326).

Noussia, K., et al., 2022, 'European Regulatory and Insurance Aspects of Carbon Capture and Storage', *European Energy and Environmental Law Review* 31(Issue 6), pp. 383-393 (DOI: 10.54648/EELR2022024).

Oberthür, S. and Dupont, C., 2021, ‘The European Union’s international climate leadership: towards a grand climate strategy?’, *Journal of European Public Policy* 28(7), pp. 1095-1114 (DOI: 10.1080/13501763.2021.1918218).

Oberthur, S. and Von Homeyer, I., 2023, ‘From emissions trading to the European Green Deal: the evolution of the climate policy mix and climate policy integration in the EU’, *Journal of European Public Policy* 30(3), pp. 445-468 (DOI: 10.1080/13501763.2022.2120528).

OECD, 2021, *The design and implementation of mission-oriented innovation policies: A new systemic policy approach to address societal challenges*, OECD Science, Technology and Industry Policy Papers No 100 (https://www.oecd-ilibrary.org/science-and-technology/the-design-and-implementation-of-mission-oriented-innovation-policies_3f6c76a4-en) accessed 11 September 2024.

OECD, 2024, *Considerations for informing, implementing, and investing in the next nationally determined contributions (NDCs)* (https://www.oecd.org/en/publications/considerations-for-informing-implementing-and-investing-in-the-next-nationally-determined-contributions-ndcs_4f014ce6-en.html).

Öko Institut, 2022, *Methodology for assessing the quality of carbon credits* (https://carboncreditquality.org/download/Methodology/CCQI%20Methodology%20-%20Version%203.0.pdf).

Oldfield, E. E., et al., 2022, ‘Crediting agricultural soil carbon sequestration’, *Science* 375(6586), pp. 1222-1225 (DOI: 10.1126/science.abl7991).

Olsson, L., et al., 2019, ‘Land degradation’, in: Shukla, P. R. et al. (eds), *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*, IPCC, Geneva.

O’Neill, C., et al., 2020, ‘Forest regeneration on European sheep pasture is an economically viable climate change mitigation strategy’, *Environmental Research Letters* 15(10), p. 104090 (DOI: 10.1088/1748-9326/abaf87).

OnePointFive, 2025, *STRATOS* (https://www.1pointfive.com/projects/ector-county-tx) accessed 2 October 202AD.

Onyebuchi, V. E., et al., 2018, ‘A systematic review of key challenges of CO2 transport via pipelines’, *Renewable and Sustainable Energy Reviews* 81, pp. 2563-2583 (DOI: 10.1016/j.rser.2017.06.064).

Otto, F. E. L., 2016, ‘Extreme events: the art of attribution’, *Nature Climate Change* 6(4), pp. 342-343 (DOI: 10.1038/nclimate2971).

Owen, A., et al., 2022a, ‘Who pays for BECCS and DACCS in the UK: designing equitable climate policy’, *Climate Policy* 22(8), pp. 1050-1068 (DOI: 10.1080/14693062.2022.2104793).

Owen, J. R., et al., 2022b, ‘Fast track to failure? Energy transition minerals and the future of consultation and consent’, *Energy Research & Social Science* 89, p. 102665 (DOI: 10.1016/j.erss.2022.102665).

Pahle, M., et al., 2018, ‘Sequencing to ratchet up climate policy stringency’, *Nature Climate Change* 8(10), pp. 861-867 (DOI: 10.1038/s41558-018-0287-6).

Pahle, M., et al., 2023, ‘The Emerging Endgame: The EU ETS on the Road Towards Climate Neutrality’, *SSRN Electronic Journal* (DOI: 10.2139/ssrn.4373443).

Paul, A., et al., 2023a, *Who should use NETPS? Managing expectations for NETP demand: considerations for allocating carbon dioxide removals*, NEGEM Project No T6.4 (https://www.negemproject.eu/wp-content/uploads/2023/11/D6.5_Who-should-use-NETPS.pdf).

Paul, C., et al., 2023b, 'Carbon farming: Are soil carbon certificates a suitable tool for climate change mitigation?', *Journal of Environmental Management* 330, p. 117142 (DOI: 10.1016/j.jenvman.2022.117142).

Pe'er, G., et al., 2020, 'Action needed for the EU Common Agricultural Policy to address sustainability challenges' Gaston, K. (ed.), *People and Nature* 2(2), pp. 305-316 (DOI: 10.1002/pan3.10080).

Pellerin, S. and Bamière, L., 2020, *Stocker du carbone dans les sols français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ?*, INRA, France (français, Quel potentiel au regard de l'objectif 4 pour 1000 et à quel coût ?).

Perugini, L., et al., 2017, 'Biophysical effects on temperature and precipitation due to land cover change', *Environmental Research Letters* 12(5), p. 053002 (DOI: 10.1088/1748-9326/aa6b3f).

Pescaroli, G. and Alexander, D., 2018, 'Understanding Compound, Interconnected, Interacting, and Cascading Risks: A Holistic Framework', *Risk Analysis* 38(11), pp. 2245-2257 (DOI: 10.1111/risa.13128).

Petersen, H. I., et al., 2023, 'Molecular structure and long-term stability of biochars', *Bulletin of the Geological Society of Greece* (Special Publication 12).

Petrovics, D., et al., 2024, 'Scaling mechanisms of energy communities: A comparison of 28 initiatives', *Global Environmental Change* 84, p. 102780 (DOI: 10.1016/j.gloenvcha.2023.102780).

Pett-Ridge et al., 2023, *Roads to Removal - Options for carbon dioxide removal in the United States* (https://roads2removal.org/resources/) accessed 7 January 2025.

Pham, H. and Saner, M., 2021, 'A Systematic Literature Review of Inclusive Climate Change Adaption', *Sustainability* 13(19), p. 10617 (DOI: 10.3390/su131910617).

PHMSA, 2022, PHMSA Announces New Safety Measures to Protect Americans From Carbon Dioxide Pipeline Failures After Satartia, MS Leak, (https://www.phmsa.dot.gov/news/phmsa-announces-new-safety-measures-protect-americans-carbon-dioxide-pipeline-failures), The U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration.

Pihl, H., 2020, 'A Climate Club as a complementary design to the UN Paris agreement', *Policy Design and Practice* 3(1), pp. 45-57 (DOI: 10.1080/25741292.2019.1710911).

Pilli, R., et al., 2021, 'Combined effects of natural disturbances and management on forest carbon sequestration: the case of Vaia storm in Italy', *Annals of Forest Science* 78(2), pp. 1-18 (DOI: 10.1007/s13595-021-01043-6).

Pilli, R., et al., 2022, 'The European forest carbon budget under future climate conditions and current management practices', *Biogeosciences* 19(13), pp. 3263-3284 (DOI: 10.5194/bg-19-3263-2022).

Pless, J., 2024, 'Are Complementary Policies Substitutes? Evidence from R&D Subsidies in the UK (conditionally accepted)', *American Economic Journal: Economic Policy*.

Poeplau, C. and Dechow, R., 2023, 'The legacy of one hundred years of climate change for organic carbon stocks in global agricultural topsoils', *Scientific Reports* 13(1), p. 7483 (DOI: 10.1038/s41598-023-34753-0).

Pongratz, J., et al., 2021, 'Land Use Effects on Climate: Current State, Recent Progress, and Emerging Topics', *Current Climate Change Reports* 7(4), pp. 99-120 (DOI: 10.1007/s40641-021-00178-y).

Pototschnig, A. and Rossetto, N., 2024, *Benefit-based remuneration of efficient infrastructure investments*, European University Institute.

Pozvek, M., et al., 2024, 'A Vision for the EU Net-Zero Transition',.

Prado, A. and Mac Dowell, N., 2023, 'The cost of permanent carbon dioxide removal', *Joule* 7(4), pp. 700-712 (DOI: 10.1016/j.joule.2023.03.006).

Prepsoil, 2024, 'Knowledge hub' (https://prepsoil.eu/knowledge-hub).

Probst, B. S., et al., 2024, 'Systematic assessment of the achieved emission reductions of carbon crediting projects', *Nature Communications* 15(1), p. 9562 (DOI: 10.1038/s41467-024-53645-z).

Prütz, R., et al., 2024, 'A taxonomy to map evidence on the co-benefits, challenges, and limits of carbon dioxide removal', *Communications Earth & Environment* 5(1), p. 197 (DOI: 10.1038/s43247-024-01365-z).

Pulles, T., et al., 2022, 'CO2 emissions from biomass combustion Accounting of CO2 emissions from biomass under the UNFCCC', *Carbon Management* 13(1), pp. 181-189 (DOI: 10.1080/17583004.2022.2067456).

Quandt, A., et al., 2023, 'Climate change adaptation through agroforestry: opportunities and gaps', *Current Opinion in Environmental Sustainability* 60, p. 101244 (DOI: 10.1016/j.cosust.2022.101244).

Quiggin, D., 2021, *BECCS deployment: The risks of policies forging ahead of the evidence*, Research Paper, Chatham House, The Royal Institute of International Affairs (https://www.chathamhouse.org/sites/default/files/2021-09/2021-10-01-beccs-deployment-quiggin.pdf) accessed 1 June 2025.

Randazzo, N. A., et al., 2023, 'Improved assessment of baseline and additionality for forest carbon crediting', *Ecological Applications* 33(3), p. e2817 (DOI: 10.1002/eap.2817).

Raschky, P. and Weckhannemann, H., 2007, 'Charity hazard—A real hazard to natural disaster insurance?', *Environmental Hazards* 7(4), pp. 321-329 (DOI: 10.1016/j.envhaz.2007.09.002).

Ravichandran, M., et al., 2024, 'Carbon dioxide capture, sequestration, and utilization models for carbon management and transformation', *Environmental Science and Pollution Research* 31(44), pp. 55895-55916 (DOI: 10.1007/s11356-024-34861-y).

Rayner, T., et al., eds., 2023, *Handbook on European Union Climate Change Policy and Politics*, Edward Elgar Publishing.

Reckien, D., et al., 2023, 'Navigating the continuum between adaptation and maladaptation', *Nature Climate Change* 13(9), pp. 907-918 (DOI: 10.1038/s41558-023-01774-6).

Reisinger, A. and Geden, O., 2023, 'Temporary overshoot: Origins, prospects, and a long path ahead', *One Earth* 6(12), pp. 1631-1637 (DOI: 10.1016/j.oneear.2023.11.008).

Requate, T., 2005, 'Dynamic incentives by environmental policy instruments—a survey', *Ecological Economics* 54(2-3), pp. 175-195 (DOI: 10.1016/j.ecolecon.2004.12.028).

Rickels, W., et al., 2021, 'Integrating Carbon Dioxide Removal Into European Emissions Trading', *Frontiers in Climate* 3, p. 690023 (DOI: 10.3389/fclim.2021.690023).

Rickels, W., et al., 2022, 'Procure, Bank, Release: Carbon Removal Certificate Reserves to Manage Carbon Prices on the Path to Net-Zero', *Energy Research & Social Science* 94, p. 102858 (DOI: 10.1016/j.erss.2022.102858).

Rickels, W., et al., 2023, *Potential efficiency gains from the introduction of an emissions trading system for the buildings and road transport sectors in the European Union*, Working Paper No 2249, Kiel Working Paper (https://www.econstor.eu/handle/10419/273080) accessed 17 October 2023.

Rietig, K. and Dupont, C., 2023, 'Climate policy integration and climate mainstreaming in the EU budget', in: Rayner, T. et al. (eds), *Handbook on European Union Climate Change Policy and Politics*, Edward Elgar Publishing, pp. 246-258.

Rigopoulos, I., et al., 2018, 'Sustainable exploitation of mafic rock quarry waste for carbon sequestration following ball milling', *Resources Policy* 59, pp. 24-32 (DOI: 10.1016/j.resourpol.2018.08.002).

Rinder, T. and von Hagke, C., 2021, 'The influence of particle size on the potential of enhanced basalt weathering for carbon dioxide removal - Insights from a regional assessment', *Journal of Cleaner Production* 315, p. 128178 (DOI: 10.1016/j.jclepro.2021.128178).

Ripple, W. J., et al., 2024, 'The 2024 state of the climate report: Perilous times on planet Earth', *BioScience*, p. biae087 (DOI: 10.1093/biosci/biae087).

Rodemeier, M., 2022, 'Willingness to Pay for Carbon Mitigation: A Field Experiment in the Market for Carbon Offsets', *SSRN Electronic Journal* (DOI: 10.2139/ssrn.4315854).

Roe, S., et al., 2019, 'Contribution of the land sector to a 1.5 °C world', *Nature Climate Change* 9(11), pp. 817-828 (DOI: 10.1038/s41558-019-0591-9).

Roe, S., et al., 2021, 'Land-based measures to mitigate climate change: Potential and feasibility by country', *Global Change Biology* 27(23), pp. 6025-6058 (DOI: 10.1111/gcb.15873).

Rogelj, J., et al., 2021, 'Net-zero emissions targets are vague: three ways to fix', *Nature* 591(7850), pp. 365-368 (DOI: 10.1038/d41586-021-00662-3).

Romanak, K. and Dixon, T., 2022, 'CO2 storage guidelines and the science of monitoring: Achieving project success under the California Low Carbon Fuel Standard CCS Protocol and other global regulations', *International Journal of Greenhouse Gas Control* 113, p. 103523 (DOI: 10.1016/j.ijggc.2021.103523).

Rosa, L., et al., 2021a, 'Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe', *Energy & Environmental Science* 14(5), pp. 3086-3097 (DOI: 10.1039/D1EE00642H).

Rosa, L., et al., 2021b, 'The water footprint of carbon capture and storage technologies', *Renewable and Sustainable Energy Reviews* 138, p. 110511 (DOI: 10.1016/j.rser.2020.110511).

Rosa, L. and Mazzotti, M., 2022, 'Potential for hydrogen production from sustainable biomass with carbon capture and storage', *Renewable and Sustainable Energy Reviews* 157, p. 112123 (DOI: 10.1016/j.rser.2022.112123).

Rowan, N. J., et al., 2022, ‘Digital transformation of peatland eco-innovations (“Paludiculture”): Enabling a paradigm shift towards the real-time sustainable production of “green-friendly” products and services’, *Science of The Total Environment* 838, p. 156328 (DOI: 10.1016/j.scitotenv.2022.156328).

Runge-Metzger, A., et al., 2022, *Certifying land-use based carbon dioxide removals - outline of a strawman proposal*, Policy Brief No 2022/11, European University Institute - School of Transitional Governance, Florence (https://cadmus.eui.eu/bitstream/handle/1814/74473/PB_2022_11_STG.pdf?sequence=4).

Russell, L. M., et al., 2012, ‘Ecosystem Impacts of Geoengineering: A Review for Developing a Science Plan’, *AMBIO* 41(4), pp. 350-369 (DOI: 10.1007/s13280-012-0258-5).

Ryan, M., et al., 2022, ‘Understanding planting preferences – A case-study of the afforestation choices of farmers in Ireland’, *Land Use Policy* 115, p. 105982 (DOI: 10.1016/j.landusepol.2022.105982).

Salzman, J. and Weisbach, D., 2024, ‘The additionality double standard’, *Harvard Environmental Law Review* 48(1), pp. 117-152.

Sandalow, D., et al., 2018, *Direct Air Capture of Carbon Dioxide* (https://www.ourenergypolicy.org/resources/direct-air-capture-of-carbon-dioxide/) accessed 7 January 2025.

Sanei, H., et al., 2024, ‘Assessing biochar’s permanence: An inertinite benchmark’, *International Journal of Coal Geology* 281, p. 104409 (DOI: 10.1016/j.coal.2023.104409).

SBTi, 2024, *Aligning corporate value chains to global climate goals*, SBTi Research: Scope 3 Discussion Paper, Science Based Targets initiative.

Schäfer, S., et al., 2015, ‘The European Transdisciplinary Assessment of Climate Engineering (EuTRACE)’,.

Schenuit et al., 2023, ‘“Carbon Management” Opportunities and risks for ambitious climate policy’, SWP Comment 2023/C 29 (DOI: 10.18449/2023C29).

Schenuit, F., et al., 2024a, *Chapter 5: Policy and governance. in The State of Carbon Dioxide Removal 2024 – 2nd Edition n (eds. Smith, S. M. et al.)* (https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/665ed5f9e05d5b3cc21a2e1d/1717491199286/Chapter+5-The+State+of+Carbon+Dioxide+Removal+2ED.pdf).

Schenuit, F., et al., 2024b, ‘Five principles for robust carbon dioxide removal policy in the G7’, *One Earth* 7(9), pp. 1487-1491 (DOI: 10.1016/j.oneear.2024.08.015).

Schirmer, J. and Bull, L., 2014, ‘Assessing the likelihood of widespread landholder adoption of afforestation and reforestation projects’, *Global Environmental Change* 24, pp. 306-320 (DOI: 10.1016/j.gloenvcha.2013.11.009).

Schleussner, C.-F., et al., 2024, ‘Overconfidence in climate overshoot’, *Nature* 634(8033), pp. 366-373 (DOI: 10.1038/s41586-024-08020-9).

Schuett, L., 2024, ‘Permanence and Liability: Legal Considerations on the Integration of Carbon Dioxide Removal into the EU Emissions Trading System’, *Transnational Environmental Law* 13(1), pp. 87-110 (DOI: 10.1017/S2047102524000013).

Schwarze, R. and Sushchenko, O., 2022, ‘Climate insurance for agriculture in Europe: on the merits of smart contracts and Distributed Ledger Technologies’, *Journal of Risk and Financial Management* 15(5), p. 211 (DOI: 10.3390/jrfm15050211).

Shackley, S., et al., 2011, 'The feasibility and costs of biochar deployment in the UK', *Carbon Management* 2(3), pp. 335-356 (DOI: 10.4155/cmt.11.22).

Shahbaz, M., et al., 2024, 'Evaluating negative emission technologies in a circular carbon economy: A holistic evaluation of direct air capture, bioenergy carbon capture and storage and biochar', *Journal of Cleaner Production* 466, p. 142800 (DOI: 10.1016/j.jclepro.2024.142800).

Sievert, K., et al., 2024, 'Considering technology characteristics to project future costs of direct air capture', *Joule* 8(4), pp. 979-999 (DOI: 10.1016/j.joule.2024.02.005).

Sikkema, R., et al., 2021, 'How can solid biomass contribute to the EU's renewable energy targets in 2020, 2030 and what are the GHG drivers and safeguards in energy- and forestry sectors?', *Renewable Energy* 165, pp. 758-772 (DOI: 10.1016/j.renene.2020.11.047).

Sikow-Magny, C., 2024, Making TEN-E into a truly European project, (https://data.europa.eu/doi/10.2870/3422035) accessed 3 February 2025, Publications Office.

Simonsen, K. R., et al., 2024, 'Challenges in CO2 transportation: Trends and perspectives', *Renewable and Sustainable Energy Reviews* 191, p. 114149 (DOI: 10.1016/j.rser.2023.114149).

Singh, N., et al., 2016, *MRV 101: Understanding measurement, reporting, and verification of climate change mitigation*, Working Paper, World Resources Institute, Washington DC (https://transparency-partnership.net/sites/default/files/mrv_101_0.pdf).

Smith et al., 2023, *State of Carbon Dioxide Removal - 1st Edition*, The State of Carbon Dioxide Removal, Open Science Framework.

Smith, P., 2012, 'Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years?', *Global Change Biology* 18(1), pp. 35-43 (DOI: 10.1111/j.1365-2486.2011.02517.x).

Smith, P., 2014, 'Do grasslands act as a perpetual sink for carbon?', *Global Change Biology* 20(9), pp. 2708-2711 (DOI: 10.1111/gcb.12561).

Smith, P., et al., 2016a, 'Biophysical and economic limits to negative CO2 emissions', *Nature Climate Change* 6(1), pp. 42-50 (DOI: 10.1038/nclimate2870).

Smith, P., et al., 2016b, 'Preliminary assessment of the potential for, and limitations to, terrestrial negative emission technologies in the UK', *Environmental Science: Processes & Impacts* 18(11), pp. 1400-1405 (DOI: 10.1039/C6EM00386A).

Smith, P., 2016, 'Soil carbon sequestration and biochar as negative emission technologies', *Global Change Biology* 22(3), pp. 1315-1324 (DOI: 10.1111/gcb.13178).

Smith, P., et al., 2019, 'Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals', *Annual Review of Environment and Resources* 44(Volume 44, 2019), pp. 255-286 (DOI: 10.1146/annurev-environ-101718-033129).

Smith, S., et al., 2024, *The State of Carbon Dioxide Removal - 2nd Edition* (https://static1.squarespace.com/static/633458017a1ae214f3772c76/t/665ed1e2b9d34b2bf8e17c63/1717490167773/The-State-of-Carbon-Dioxide-Removal-2Edition.pdf) accessed 26 June 2024.

Smyth, M.-A., et al., 2015, *Developing Peatland Carbon Metrics and Financial Modelling to Inform the Pilot Phase UK Peatland Code*, No Report to Defra for Project NR0165, Crichton Carbon Centre, Dumfries.

Söderberg, C. and Eckerberg, K., 2013, 'Rising policy conflicts in Europe over bioenergy and forestry', *Forest Policy and Economics* 33, pp. 112-119 (DOI: 10.1016/j.forpol.2012.09.015).

Sollen-Norrlin, M., et al., 2020, 'Agroforestry Benefits and Challenges for Adoption in Europe and Beyond', *Sustainability* 12(17), p. 7001 (DOI: 10.3390/su12177001).

Sovacool, B. K., et al., 2023, 'Six bold steps towards net-zero industry', *Energy Research & Social Science* 99, p. 103067 (DOI: 10.1016/j.erss.2023.103067).

Stephan, A., et al., 2021, 'How has external knowledge contributed to lithium-ion batteries for the energy transition?', *iScience* 24(1), p. 101995 (DOI: 10.1016/j.isci.2020.101995).

Stojilovska, A., et al., 2022, 'Energy poverty and emerging debates: Beyond the traditional triangle of energy poverty drivers', *Energy Policy* 169, p. 113181 (DOI: 10.1016/j.enpol.2022.113181).

Stuart-Smith, R. F., et al., 2023, 'Legal limits to the use of CO2 removal', *Science* 382(6672), pp. 772-774 (DOI: 10.1126/science.adi9332).

Sultani, D., et al., 2024, 'Sequencing Carbon Dioxide Removal into the EU ETS', CEPR Press, Paris & London (https://cepr.org/publications/dp19179).

Tahvonen, O. and Rautiainen, A., 2017, 'Economics of forest carbon storage and the additionality principle', *Resource and Energy Economics* 50, pp. 124-134 (DOI: 10.1016/j.reseneeco.2017.07.001).

Tan, R. R., et al., 2022, 'Optimization of enhanced weathering networks with alternative transportation modes', *Carbon Resources Conversion* 5(2), pp. 167-176 (DOI: 10.1016/j.crcon.2022.04.002).

Tang, K., et al., 2016, 'Carbon farming economics: What have we learned?', *Journal of Environmental Management* 172, pp. 49-57 (DOI: 10.1016/j.jenvman.2016.02.008).

Tanneberger, F., et al., 2021a, 'Mires in Europe—Regional Diversity, Condition and Protection', *Diversity* 13(8) (DOI: 10.3390/d13080381).

Tanneberger, F., et al., 2021b, 'The Power of Nature-Based Solutions: How Peatlands Can Help Us to Achieve Key EU Sustainability Objectives', *Advanced Sustainable Systems* 5(1), p. 2000146 (DOI: 10.1002/adsu.202000146).

Tanzer, S. E. and Ramírez, A., 2019, 'When are negative emissions negative emissions?', *Energy & Environmental Science* 12(4), pp. 1210-1218 (DOI: 10.1039/C8EE03338B).

Tavoni, A. and Winkler, R., 2021, 'Domestic Pressure and International Climate Cooperation', *Annual Review of Resource Economics* 13(1), pp. 225-243 (DOI: 10.1146/annurev-resource-101420-105854).

Terlouw, T., et al., 2021, 'Life cycle assessment of carbon dioxide removal technologies: a critical review', *Energy & Environmental Science* 14(4), pp. 1701-1721 (DOI: 10.1039/D0EE03757E).

Thorsdottir, G., et al., 2024, *Navigating Governance of CDR Certification in the Voluntary Carbon Market: Insights and Perspectives*, sus.lab ETH Zurich (https://e5216549-8c87-430e-bfe5-ddee2ea5091e.usrfiles.com/ugd/f8fdcc_e3c2f23f5d91421daf881f6418573e5a.pdf).

Tisserant, A., et al., 2023, 'Biochar and Its Potential to Deliver Negative Emissions and Better Soil Quality in Europe', *Earth's Future* 11(10), p. e2022EF003246 (DOI: 10.1029/2022EF003246).

Tisserant, A. and Cherubini, F., 2019, 'Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation', *Land* 8(12), p. 179 (DOI: 10.3390/land8120179).

Torralba, M., et al., 2016, 'Do European agroforestry systems enhance biodiversity and ecosystem services? A meta-analysis', *Agriculture, Ecosystems & Environment* 230, pp. 150-161 (DOI: 10.1016/j.agee.2016.06.002).

Trinomics, 2023a, *Assessment of the potential of sustainable fuels in transport*, Study requested by the TRAN Committee, European Parliament (https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733103/IPOL_STU(2023)733103_EN.pdf).

Trinomics, 2023b, *Pricing agricultural emissions and rewarding climate action in the agri-food value chain*, Trinomics, Rotterdam (https://www.ecologic.eu/19482) accessed 15 April 2024.

UBA, et al., 2021, *Certification of carbon removals - Part 1: Synoptic review of carbon removal solutions*, No REP-0796, Umweltbundesamt, Vienna (https://www.ecologic.eu/sites/default/files/publication/2022/50035-Certification-of-carbon-removal-part-2-web.pdf).

UBA, 2023, *Sustainability criteria for carbon dioxide removals: Requirements for sustainability criteria in the EU CRCF proposal and elements to be included in a delegated act*, Umweltbundesamt (https://www.ecologic.eu/sites/default/files/publication/2024/50122-fact-sheet-sustainability-criteria-for-carbon-dioxid-removals.pdf).

UK Environment Agency, 2024, *Post-combustion carbon dioxide capture: emerging techniques* (https://www.gov.uk/guidance/post-combustion-carbon-dioxide-capture-best-available-techniques-bat).

UK Government, 2024, *Integrating Greenhouse Gas Removals in the UK Emissions Trading Scheme - a joint consultation of the UK Government, the Scottish Government, the Welsh Government and the Department of Agriculture, Environment and Rural Affairs for Northern Ireland*, Consultation (https://www.gov.uk/government/consultations/integrating-greenhouse-gas-removals-in-the-uk-emissions-trading-scheme) accessed 8 July 2024.

Umweltbundesamt, 2023, *Entwicklung des Abfallvermeidungsprogrammes 2023 - Österreich*, No REP-0835 (https://www.umweltbundesamt.at/fileadmin/site/publikationen/rep0835.pdf) accessed 29 April 2024.

UN, 1982, United Nations Convention on the Law of the Sea.

UNDRR, 2023, *Designing a climate resilience classification framework. To facilitate investment in climate resilience through capital markets* (https://www.climatebonds.net/files/reports/resiliencewhitepaper_climatebondsinitiative_undrr.pdf).

UNECE, 1991, Convention on Environmental Impact Assessment in a Transboundary Context (Espoo Convention).

UNFCCC and art. 6.4 Supervisory Body, 2024, Removal activities under the Article 6.4 mechanism - information note - A6.4-SB002-AA-A06 Version 01.0, (https://unfccc.int/sites/default/files/resource/a64-sb002-aa-a06.pdf).

Upton, V., et al., 2013, 'The Potential Economic Returns of Converting Agricultural Land to Forestry: An Analysis of System and Soil Effects from 1995 to 2009', *Irish Forestry* 70, pp. 61-74.

U.S. DOE, 2024, Primer on Carbon Dioxide Removal Credits, (https://www.energy.gov/sites/default/files/2024-10/Primer%20on%20CDR%20Credits_Oct%202024%20FINAL.pdf), U.S. Department of Energy.

USDA, 2024, *European Union: Wood Pellets Annual*, U.S. Department of Agriculture (https://fas.usda.gov/data/european-union-wood-pellets-annual-0).

USITC, 2024, *EU Wood Pellet Imports After Russia's Invasion of Ukraine*, Executive Briefings on Trade, United States International Trade Commission (https://www.usitc.gov/publications/332/executive_briefings/ebot_eu_wood_pellet_imports_after_russia_invasion_of_ukraine.pdf).

van Teeffelen, A., et al., 2014, 'How climate proof is the European Union's biodiversity policy?', *Regional Environmental Change* 15(6), pp. 997-1010 (DOI: 10.1007/s10113-014-0647-3).

Verkerk, P. J., et al., 2020, 'Climate-Smart Forestry: the missing link', *Forest Policy and Economics* 115, p. 102164 (DOI: 10.1016/j.forpol.2020.102164).

Verkerk, P. J., et al., 2022, *Forest-based climate change mitigation and adaptation in Europe*, From Science to Policy, European Forest Institute (https://efi.int/publications-bank/forest-based-climate-change-mitigation-and-adaptation-europe) accessed 21 December 2022.

Vivian, C. and Savio, L. D., 2024, 'The London Convention and Protocol: Adapting to Address the Ocean-Climate Crisis', (DOI: 10.1163/15718085-bja10178).

Vogelpohl, T., 2021, 'Transnational sustainability certification for the bioeconomy? Patterns and discourse coalitions of resistance and alternatives in biomass exporting regions', *Energy, Sustainability and Society* 11(1), p. 3 (DOI: 10.1186/s13705-021-00278-5).

Voicu-Dorobanțu, R., et al., 2021, 'Tackling Complexity of the Just Transition in the EU: Evidence from Romania', *Energies* 14(5), p. 1509 (DOI: 10.3390/en14051509).

Volpi, M. P. C., et al., 2024, 'Review of the Current State of Pyrolysis and Biochar Utilization in Europe: A Scientific Perspective', *Clean Technologies* 6(1), pp. 152-175 (DOI: 10.3390/cleantechnol6010010).

Vos, E., 2016, 'EU Agencies and Independence', in: Ritleng, D. (ed.), *Independence and Legitimacy in the Institutional System of the European Union*, Oxford University Press, pp. 206-228.

Vrebos, D., et al., 2017, 'The impact of policy instruments on soil multifunctionality in the European Union', *Sustainability* 9(3), p. 407 (DOI: 10.3390/su9030407).

Wang, R., 2024, 'Status and perspectives on CCUS clusters and hubs', *Unconventional Resources* 4, p. 100065 (DOI: 10.1016/j.uncres.2023.100065).

Wang, Y., et al., 2023, 'Risk to rely on soil carbon sequestration to offset global ruminant emissions', *Nature Communications* 14(1), p. 7625 (DOI: 10.1038/s41467-023-43452-3).

Watari, T., et al., 2023, 'Feasible supply of steel and cement within a carbon budget is likely to fall short of expected global demand', *Nature Communications* 14(1), p. 7895 (DOI: 10.1038/s41467-023-43684-3).

Way, R., et al., 2022, 'Empirically grounded technology forecasts and the energy transition', *Joule* Volume 6, issue 9, pp. 2057-2082.

Webb, R., et al., 2021, *Removing Carbon Dioxide Through Ocean Alkalinity Enhancement: Legal Challenges and Opportunities*, Sabin Center for Climate Change Law, Columbia Law School (https://scholarship.law.columbia.edu/faculty_scholarship/2981).

Webb, R., 2024, *International governance of ocean-based carbon dioxide removal: recent developments and future directions*, Sabin Center for Climate Change Law, Columbia Law School, New York (https://scholarship.law.columbia.edu/cgi/viewcontent.cgi?article=1217&context=sabin_climate_change).

Whitehead, D., 2011, 'Forests as carbon sinks—benefits and consequences', *Tree Physiology* 31(9), pp. 893-902 (DOI: 10.1093/treephys/tpr063).

Wildenborg, T., et al., 2013, 'Key Messages from Active CO2 Storage Sites', *Energy Procedia* 37, pp. 6317-6325 (DOI: 10.1016/j.egypro.2013.06.560).

Wilkin, R. T. and Digiulio, D. C., 2010, 'Geochemical impacts to groundwater from geologic carbon sequestration: controls on pH and inorganic carbon concentrations from reaction path and kinetic modeling', *Environmental Science & Technology* 44(12), pp. 4821-4827 (DOI: 10.1021/es100559j).

Williamson, P., 2016, 'Emissions reduction: Scrutinize CO2 removal methods', *Nature* 530(7589), pp. 153-155 (DOI: 10.1038/530153a).

Williamson, P. and Gattuso, J.-P., 2022, 'Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, With Questionable Climatic Cost-Effectiveness', *Frontiers in Climate* 4, p. 853666 (DOI: 10.3389/fclim.2022.853666).

Wilson, D., et al., 2016, 'Greenhouse gas emission factors associated with rewetting of organic soils', *Mires and Peat* (17), pp. 1-28 (DOI: 10.19189/MaP.2016.OMB.222).

Winkel, G., et al., 2022, 'Governing Europe's forests for multiple ecosystem services: Opportunities, challenges, and policy options', *Forest Policy and Economics* 145, p. 102849 (DOI: 10.1016/j.forpol.2022.102849).

Wise Europa, 2021, *Regional cooperation for CCS/CCU deployment* (https://ccs4cee.eu/wp-content/uploads/2021/11/CCS4CEE-regional-analysis.pdf).

WKR, 2024, *Clearing the air? Advice for principles and policy for governing carbon dioxide removal Advisory report*, the Netherlands Scientific Climate Council (https://english.wkr.nl/projects/documents/kamerstukken/2024/07/18/wkr-report-002-clearing-the-air).

Wonka, A. and Rittberger, B., 2010, 'Credibility, Complexity and Uncertainty: Explaining the Institutional Independence of 29 EU Agencies', *West European Politics* 33(4), pp. 730-752 (DOI: 10.1080/01402381003794597).

Woolf, D., et al., 2016, 'Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration', *Nature Communications* 7(1), p. 13160 (DOI: 10.1038/ncomms13160).

Woolf, D., et al., 2021, 'Greenhouse Gas Inventory Model for Biochar Additions to Soil', *Environmental Science & Technology* 55(21), pp. 14795-14805 (DOI: 10.1021/acs.est.1c02425).

Woziwoda, B. and Kopeć, D., 2014, 'Afforestation or natural succession? Looking for the best way to manage abandoned cut-over peatlands for biodiversity conservation', *Ecological Engineering* 63, pp. 143-152 (DOI: 10.1016/j.ecoleng.2012.12.106).

WRI, 2023, '7 Things to Know About Carbon Capture, Utilization and Sequestration' (https://www.wri.org/insights/carbon-capture-technology) accessed 6 January 2025.

Wu, H., et al., 2017, 'The interactions of composting and biochar and their implications for soil amendment and pollution remediation: a review', *Critical Reviews in Biotechnology* 37(6), pp. 754-764 (DOI: 10.1080/07388551.2016.1232696).

Wu, Z. and Zhai, H., 2021, 'Consumptive life cycle water use of biomass-to-power plants with carbon capture and sequestration', *Applied Energy* 303, p. 117702 (DOI: 10.1016/j.apenergy.2021.117702).

Wüstenhagen, R., et al., 2007, 'Social acceptance of renewable energy innovation: An introduction to the concept', *Energy Policy* 35(5), pp. 2683-2691 (DOI: 10.1016/j.enpol.2006.12.001).

Wüstenhagen, R. and Menichetti, E., 2012, 'Strategic choices for renewable energy investment: conceptual framework and opportunities for further research', *Energy Policy* 40, pp. 1-10.

Xiang, L., et al., 2021, 'Potential hazards of biochar: The negative environmental impacts of biochar applications', *Journal of Hazardous Materials* 420, p. 126611 (DOI: 10.1016/j.jhazmat.2021.126611).

Yanagi, K., et al., 2019, 'The importance of designing a comprehensive Strategic Environmental Assessment (SEA) & Environmental Impact Assessment (EIA) for carbon capture and storage in Japan', *International Journal of Greenhouse Gas Control* 91, p. 102823 (DOI: 10.1016/j.ijggc.2019.102823).

Younger, P. L., et al., 2004, 'Mining Impacts on the Fresh Water Environment: Technical and Managerial Guidelines for Catchment Scale Management', *Mine Water and the Environment* 23(1), pp. s2-s80 (DOI: 10.1007/s10230-004-0028-0).

ZEP, 2023, ZEP supports interim solution to the London Protocol – unblocking regulatory barrier to CCS!, (https://zeroemissionsplatform.eu/wp-content/uploads/ZEP-London-Protocol-position-paper.pdf), Zero Emissions Technology and Innovation Platform.

Źróbek-Różańska, A., et al., 2014, 'Financial Dilemmas Associated with the Afforestation of Low-Productivity Farmland in Poland', *Forests* 5(11), pp. 2846-2864 (DOI: 10.3390/f5112846).

2023, Aalborg Declaration on enabling cross-border carbon capture utilisation and storage (CCUS) in Europe, (https://www.kefm.dk/Media/638366861585598350/EU%20CCUS%20Aalborg%20declaration%20231127%20SEFR.pdf).

Consulted organisations and experts

During the analysis, the Advisory Board consulted the following organisations and experts:

- European Commission Directorate-General for Climate Action,
- European Environment Agency,
- Belgian Presidency of the Council of the European Union,
- Netherlands Ministry of Economic Affairs and Climate Policy,
- Netherlands Scientific Climate Council,
- Finnish Climate Change Panel,
- France High Council on Climate,
- Danish Council on Climate Change,
- Swedish Climate Policy Council,
- Lund University,
- University of Copenhagen,
- Imperial College,
- Cambridge University,
- Potsdam Institute for Climate Impact Research,
- Mercator Research Institute on Global Commons and Climate Change,
- Carbon Market Watch,
- Bellona Europa,
- Clean Air Taskforce,
- World Wide Fund for Nature,
- Concito,
- CAN Europe,
- European Climate Foundation,
- CCUS Forum,
- ecoLocked,
- Maersk and
- Cambridge Carbon Capture.

Annex I - Detailed assessment of individual removal methods: potential volumes and costs

This section provides a detailed assessment of the literature on individual removal methods. It reviews studies regarding the potential and costs of individual removal methods at a European level where possible, which forms the basis of the assessment contained in **Chapter 2**.

While estimates from literature reviews were prioritised where possible, for most methods, there were a lack of large-scale literature reviews at an EU level. For estimates of future potential, approximate ranges were therefore largely assessed based on ranges from individual studies and scenarios at an EU level. For some removal methods, a limited number of studies or wide disparities between available studies limited the confidence in these estimates. Where possible, estimates are for 2050, although some studies do not have a particular reference year (particularly those based on technical potential). However, explicitly short-term estimates (e.g. for 2030) were generally excluded from the analysis.

Cost estimates are largely derived from global estimates and literature reviews, as few EU-wide or EU-specific cost estimates were available. While these global ranges may be appropriate for some methods, they may underestimate or overestimate the costs for others, particularly those in the land sectors where there can be major differences in land and labour costs. Therefore, these global cost ranges were supplemented by other studies for comparative purposes, generally marginal abatement cost studies from individual EU or European countries, to assess the applicability of these global estimates. Given the different currencies and time horizons of these estimates, cost estimates were converted into common EUR 2015 values.

Afforestation and reforestation

Several studies have estimated the potential removals from afforestation and reforestation in the EU or Europe. A literature review by Verkerk et al. (2022) assessed potential additional removals from afforestation and reforestation in the EU at 49 $MtCO_2$ per year on average by 2050, with a range across studies of 17-75 $MtCO_2$ per year, which they note to include both technical and economic potential. The scale of individual technical potential estimates vary based on authors' assumptions on land use. For example, Nabuurs et al. (2017) assumes that the afforestation of 15 Mha of unprofitable EU farmland (~10% of EU agricultural land area) could deliver 64 $MtCO_2$ per year of additional removals by 2050. The European Commission (EC, 2021i) estimated that afforestation of 2 Mha (~1-2% of land area) to deliver the EU forest strategy's target for 3 billion trees by 2030 could remove approximately 4 $MtCO_2$ per year by 2030, or 15 $MtCO_2$ per year by 2050; corresponding to a sink of about 4.5 tCO_2/ha/year 10 years after planting, and 7.8 tCO_2/ha/year 20 years after planting on average. As posited by several authors, the availability of land for sequestration can be mitigated by dietary changes. A number of scenarios have been proposed which demonstrate that a reduction in livestock production, coupled with a transition towards a greater reliance on plant-based diets, has the potential to free up land, thereby facilitating the implementation of practices like afforestation and BECCS (Doelman et al., 2020, 2019; Lee et al., 2019; Lehtilä et al., 2023). Enhancing crop yields and productivity also has the capacity to free up land for the purpose of increased carbon sequestration (Lee et al., 2019; Smith et al., 2016a). While these represent changes that could be used to mitigate the land use pressure of removal methods, it is likely that enabling policies would be required for them to be implemented.

Estimates of economic potential are generally much lower for afforestation (Verkerk et al., 2022), suggesting a need for substantial investments. Roe et al. (2021) also estimated the technical potential of afforestation and reforestation for EU countries to be 75 $MtCO_2e$ per year by 2050, although with a lower cost-effective potential of 18 $MtCO_2e$ per year (i.e. below a carbon price of USD 100 per tCO_2, 24% of the technical potential). The European Commission has also carried out several analyses and impact assessments on the potential contribution of afforestation and reforestation to EU climate and land use policies. In its impact assessment for the Carbon Removals Certification Framework (EC, 2022d), the Commission estimated the future potentials from afforestation and reforestation at 18-36 $MtCO_2e$ per year, which appears to be based on previous modelling carried out as part of its in-depth analysis for the 'Clean Planet for All Communication' (EC, 2018). This analysis found potential "sink enhancement" from afforestation of up to 36 $MtCO_2e$ per year by 2050 at a carbon price of EUR 150 per tCO_2, 32 $MtCO_2e$ per year at a carbon price of EUR 100 per tCO_2, and 23 $MtCO_2e$ per year at a carbon price of EUR 50 per tCO_2. However, in the more recent impact assessment accompanying the 2040 target communication, the cost-effective mitigation potential from afforestation and reforestation was assessed at lower levels still, ranging from just under 2 $MtCO_2$ per year by 2050 at a mitigation cost of EUR 20 per tCO_2 or less, to 7$MtCO_2$ per year at a cost of EUR 100 per tCO_2.

Table 42: Estimates of future removal or mitigation potential from afforestation and reforestation

Study	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Verkerk et al. (2022)	EU	Literature review, average (range) in literature	49 (17-75)
Nabuurs et al. (2017)	EU	Technical, afforestation of 15 Mha	64
European Commission (EC, 2021i)	EU	Technical, afforestation of 3 billion trees	15
Roe et al. (2021)	EU	Technical	75
Roe et al. (2021)	EU	Cost-effective, at costs of less than USD 100 per tCO_2	18
European Commission (2018, 2022)	EU	Cost-effective, at carbon prices of EUR 50-150 per tCO_2e	18-36
European Commission (2024)	EU	Cost-effective, at carbon prices of EUR 20-100 per tCO_2e	2-7

Note: Estimates in the LULUCF sector may include both removal and mitigation potential (i.e. enhancement of the net sink)

The costs of afforestation and reforestation can include the direct costs of planting (e.g. materials, labour, land), ongoing maintenance, MRV, as well as the opportunity costs of alternative land uses. As a result, the literature reports a wide range of cost estimates that vary significantly depending on the project and the methodology/scope of costs by indivi19dual authors (Golub et al., 2023). While A/R is often regarded as a relatively low-cost mitigation strategy in literature, costs and cost-optimal mitigation potential from global assessments are often weighted towards countries in the tropics and in the global south (Doelman et al., 2020; Fuss et al., 2018), making these estimates not directly comparable to the European context where costs are generally higher and per-hectare sequestration rates lower. Given differences in methods and locations, Fuss et al. (2018) reported global A/R costs in the literature over a wide range of USD 0-240 per tCO_2e, and assessed a likely range of USD 5-50 per tCO_2e. Although they note that the lower end of this range tends to be weighted towards studies from land in the global south, they also highlight 'high agreement' of maximum A/R costs being around USD 100 per tCO_2e.

Doelman et al. (2020) estimated potentials and costs from A/R at a regional level, with most of the 2050 mitigation potential for Europe occurring between costs of USD 50-150 per tCO_2e. Including private benefits from the sale of timber, Grafton et al. (2021) estimated a global maximum cost range of USD 12-169 per tCO_2e for A/R, with average costs of USD 34-57 per tCO_2e based on assumptions of a 100-year contract length. For the fifty most cost-effective countries (a category which includes EU countries Latvia, Lithuania, Estonia, Ireland and Bulgaria), the average A/R cost was found to be lower at USD 16-

25 per tCO_2e. These costs were compared with select country-level estimates in the EU or other European countries, which often reveal differences depending on the time horizon. For Ireland, the marginal abatement costs of afforestation have been estimated at 237 EUR/tCO_2e between 2021-2030, reflecting the limited growth and sequestration that would occur in such a short time horizon. However, over a longer 30-year timeframe, afforestation becomes a more cost-effective option, with estimates of EUR 34 per tCO_2e over 2021-2050 (Lanigan et al., 2023). Similarly in Slovakia, the short-term marginal abatement cost of afforestation has been estimated at approximately 93 EUR per tCO_2e up to 2030 (Bárány et al., 2022). Several European studies come from the UK: Eory et al. (2015) estimated average afforestation costs of GBP 16-51 per tCO_2e across different UK regions and discount rates and assuming a 100-year project period, while Nijnik et al. (2013) have estimated average costs ranging from GBP 15-76 GBP/tC (or 4-21 GBP/tCO_2e) according to the type of agricultural system replaced. While noting the relatively high costs of land in the UK, they note differences in productivity: livestock systems on poor quality land are associated with the lowest opportunity costs, while at the higher end is afforestation on prime arable land. They also estimate costs according to different discount rates of between 3.5 and 7%, with costs of up to GBP 160 per tC (GBP 44 per tCO_2e). Rämö et al. similarly estimated necessary subsidies for afforestation to occur on different farm types in Finland, finding that for cereal farms, subsidies would need to be EUR 27-54 per tCO_2e for afforestation to occur, while for high-productivity dairy farms, these subsidies would need to be up to EUR 164 per tCO_2e for afforestation to become more profitable.

Table 43: Cost estimates and conversions for afforestation

Study	Region (details)	Original estimate	EUR_{2015} estimate
Fuss et al. (2018)	Global, full range	0-240 USD_{2015}	0-216
Grafton et al. (2021)	Global, full range	12-169 USD_{2017}	11-150
Fuss et al. (2018)	Global, likely range	5-100 USD_{2015}	5-90
Grafton et al. (2021)	Global, average	34-57 USD_{2017}	30-50
Grafton et al. (2021)	Global, 50 most cost-effective countries	16-25 USD_{2017}	14-22
Doelman et al. (2020)	Europe	50-150 USD_{2010}	49-147
Lanigan et al. (2023)	Ireland, 2021-2030	237 EUR_{2022}*	205
Lanigan et al. (2023)	Ireland (2021-2050)	34 EUR_{2022}*	29
Bárany et al. (2022)	Slovakia (2030)	93 EUR_{2022}*	81
Eory et al. (2015)	UK	16-51 GBP_{2015}*	22-70
Nijnik et al. (2013)	UK, over different agricultural land types	4-44 GBP_{2010}	6-66
Rämö et al. (2022)	Finland, necessary afforestation subsidies over different land use types	27-164 EUR_{2015}	25-152

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

Improved forest management and harvested wood products

Improved forest management describes sustainable practices aimed at increasing the carbon stock of existing managed forests, such as longer rotation lengths, changes in harvests, continuous cover forestry, conservation or species selection – among others (IPCC, 2022a). A literature review by Verkerk et al. (2022) estimated the average additional mitigation potential of forest management activities to range between 53 to 70 $MtCO_2e$/year 2050 in the EU-27, with an additional 10 $MtCO_2e$/year from avoided deforestation. The authors note that different forest management practices may conflict with one another and therefore present the potentials in three illustrative 'bundles' of practices, as shown in the table below. At the lower end of this range representing an entirely conservation-based approach (e.g.

set-aside zones), and the upper range more active management approaches. Separate estimates for afforestation & reforestation activities are presented in the previous section.

Table 44 Assessment of future mitigation or removal of forest management activities by Verkerk et al. (2022)

Practice	2050 estimate ($MtCO_2$/year)
Avoiding deforestation	10
Forest conservation (Bundle 1)	53 (41-63)
Active management (other than harvesting) (Bundle 2)	65 (10-169)
Decreased forest harvesting (Bundle 3)	70 (1-259)

Source: Table 8, Verkerk et al. (2022)

Other studies also estimate the EU potential from improved forest management activities. In addition to the A/R figures described in the previous section, Nabuurs et al. (2017) estimated that implementing 'climate smart forestry' management practices in EU-28 forests could deliver a further 129 $MtCO_2e$/year of removals by 2050. This figure comprises 56 $MtCO_2e$/year from replacing low productivity coppice forests with more productive species, 38 $MtCO_2e$/year from enhanced productivity and management, 35 $MtCO_2e$/year from management practices to reduce the impact of natural disturbances[43]. They also identified additional potential of 64 $MtCO_2e$/year from setting aside additional forest reserves. Roe et al. (2021) estimated the additional technical potential from improved forest management in EU countries (e.g. reduced impact logging, longer harvest rotations, set-aside areas etc.) at between 52-266 $MtCO_2e$/year, and a cost-effective potential of between 19-60 $MtCO_2e$/year. In its impact assessment accompanying the communication on a 2040 climate target, the European Commission found improved forest management to have the greatest additional mitigation potential of examined LULUCF practices, with potential of 31 $MtCO_2e$ per year at a carbon price of EUR 20 per tCO_2, 44 $MtCO_2e$/year at EUR 50 per tonne, and 46 $MtCO_2e$ per year at EUR 100 per tonne.

Table 45: Estimates of future mitigation or removal potential from improvement forest management practices

Study	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Verkerk et al. (2022)	EU-27	Literature review, range over three illustrative practice bundles	53-70
Nabuurs et al. (2017)	EU-28	Technical, based on 'climate smart forestry' management practices	129
Roe et al. (2021)	*EU-27*	Technical	52-266
Roe et al. (2021)	EU-27	Cost-effective, at costs of less than USD 100 per tCO_2	19-60
European Commission (2024i)	EU-27	Cost-effective, at carbon prices of EUR 20-100 per tCO_2e	31-46

Note: Estimates in the LULUCF sector may include both removal and mitigation potential (i.e. enhancement of the net sink)

In comparison to afforestation, the costs of improved forest management activities is generally assumed to be lower in most countries, which underscores the relatively high levels of economic potential found by Roe et al. (Roe et al., 2019) and EU Commission (EC, 2024p). The results from the European Commission's impact assessment (referenced above) indicated that most of the mitigation potential from improved forest management could be delivered at carbon prices of less than EUR 50 per tCO_2e. Other global and European estimates generally appear to fall within this range. For instance, Grafton et

[43] This includes 20 Mt from reduced drainage from forest soils, which may include overlap with estimates from other removal categories included in this report, particularly wetlands / peatlands. Excluding this from the total figure would reduce the potential from Forest Management activities to 109 Mt.

al. (2021) also estimated relatively low forest conservation/management costs globally, with a global average of USD 13 to 24 per tCO_2e and an average of USD 4 to 9 USD per tCO_2e within the fifty most cost-effective countries, a category which included EU countries like Ireland, the Baltic states and Bulgaria. Analysis of bottom-up studies by Bottcher et al. (2022) suggested the potential for regional variation, with lower costs of EUR 20-50 per tCO_2e in Finland, and higher costs of up to 0-130 EUR per tCO_2e for Germany.

Table 46: Cost estimates and conversions for improved forest management practices

Study	Region (details)	Original value	EUR_{2015} estimate
European Commission (EC, 2024p)	EU-27	0-50 EUR_{2023}	0-44
Grafton et al. (2021)	Global average	13-24 USD_{2017}	11-21
Grafton et al. (2021)	Global cost-effective	4-9 USD_{2017}	4-8
Bottcher et al. (2022)	Finland (bottom-up)	20-50 EUR_{2022}*	17-44
Bottcher et al. (2022)	Germany (bottom-up)	0-130 EUR_{2022}*	0-113

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

A smaller number of studies also estimated the additional mitigation provided by carbon storage in harvested wood products, with estimates of between 14 $MtCO_2e$/year (Verkerk et al., 2022) and 43 $MtCO_2e$/year (Nabuurs et al., 2013). It should be noted that these estimates generally include emission reductions due to substitution effects, and do not necessarily represent additional removals. Verkerk et al. (Verkerk et al., 2022) note possible trade- offs in potentials between forest management activities (which aim to increase carbon stocks in living biomass and soils) and harvested wood products, although some studies support the use of practices that can both increase the forest sink.

Soil carbon sequestration

Soil carbon sequestration (SCS) refers to management practices aimed at increasing the sequestration and storage of carbon in croplands and grasslands. This can include practices like the conversion of cropland to grassland, crop rotation, cover cropping, reduced or no tillage – among others. Given the diversity of potential practices, estimates of the potential for SCS techniques to sequester carbon in the EU vary significantly in the literature. Roe et al. (2021) estimated relatively high technical and cost-effective potential for SCS practices in EU countries, with technical potential of 122.1 $MtCO_2e$/year (77 $MtCO_2e$ in croplands and 45 $MtCO_2e$ in grasslands) and cost-effective potential of 96.4 $MtCO_2e$/year (70 $MtCO_2e$ in croplands and 27 $MtCO_2e$ in grasslands). The European Commission's (2024i) impact assessment for the 2040 target proposal also assessed the 2050 mitigation potential of agricultural soil carbon sequestration practices, with estimates of 11, 22 and 37 $MtCO_2e$ per year at carbon prices of EUR 20, 50 and 100 per tCO_2e, respectively.

Lugato et al. (2014) simulated the potentials of alternative SCS practices and scenarios, such as reduced tillage, cover crops, and conversion from arable land to grassland. Across all practices, they found median sequestration rates of 0.1 t C ha^{-1} yr^{-1} (0.367 tCO_2e) by 2020, and 0.04 t C ha^{-1} yr^{-1} (0.1468) by 2050, with the highest potential coming from the conversion of arable land to grasslands. Overall sequestration rates were 0-2 tCO_2e per hectare per year across different management practices, although they note significant heterogeneity across individual practices and regions. Upscaling this to European potentials, they found additional carbon sequestration potentials of between 23-58 $MtCO_2e$/year by 2050 in three scenarios applied to arable land.

Based on an upscaling of Pellerin et al.'s (2020) estimates for France, Bellassen et al. (2022) estimated the EU potential for SCS within a similar range at 90 $MtCO_2e$/year, comprising 45 Mt from cover crops and 45 Mt from substituting maize with grass as fodder crops. Lugato et al. (2020) estimated the *total* sequestration potential from the full application of cover crops in the EU to be 1,336 $MtCO_2e$ by 2050, which corresponds to or average annual sequestration rate of approximately 35 $MtCO_2e$/year. Frank et al. (2015) estimated the potential sequestration from applying conservation tillage in EU-28 croplands at 9, 28 and 38 $MtCO_2e$/year by 2050 based on carbon prices of 10, 50 and 100 USD tCO_2e^{-1} respectively. Smith (2012) reported that while some studies have suggested a technical potential from agricultural SCS practices of up to 200 $MtCO_2e$/year in the Europe, the economic potential is considered to be much at around 20 $MtCO_2e$/year for the EU-27 (UK, excluding Croatia), largely based on more limited geographic area and adoption rate than assumed in other studies.

Table 47: Estimates of future mitigation or removal potential from soil carbon sequestration practices

Study	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Roe et al. (2021)	EU-27	Technical potential	122
Roe et al. (2021)	EU-27	Cost-effective potential, at costs of less than USD 100 per tCO_2	*96*
European Commission (EC, 2024p)	EU-27	Cost-effective potential at carbon prices of EUR 20-100 per tCO_2e	11-37
Lugato et al. (2014)	EU-28	Technical potential across several practices and three land deployment scenarios	23-58
Bellassen et al. (2022)**	EU-28	Technical potential from cover crops, and maize-grass substitution	90
Lugato et al. (2020)	EU-27	Technical, application of cover crops	35
Frank et al. (2015)	EU-28	Technical potential from conservation tillage practices	9-38
Smith (2012)**	EU-27*	Economic potential (EU)	20

*Note EU-27 refers to composition in 2012 ** Not linked to specific year, depends on timing of implementation

While some of these estimates imply promising potential from SCS, it should be cautioned that SCS is generally considered to offer only short-term removals: as the total storage capacity of a particular soil carbon sink is finite, it will stop actively removing carbon after this saturation point is reached (Wang et al., 2023; Smith, 2014). Fuss et al. (2018) note that although the exact saturation point varies depending on the location, climate, soil types and baseline conditions, SCS practices generally only provide active removals for a matter of decades after implementation, with an IPCC default saturation time assuming that SCS is only effective for 20 years. Furthermore, they highlight that management practices often must continue indefinitely to prevent the rerelease of sequestered soil carbon, which may have additional implications for the long-term cost of SCS.

Fuss et al. (2018) found costs of SCS to be generally low, albeit very practice- and context-dependent, with a likely global cost range of USD 0-100 per tCO_2e and a full cost range of around USD -45-100 per tCO_2e. The negative value at the lower end implies cost savings, which mainly arises from the benefits of some SCS practices (e.g. improved soil fertility, crop yields etc.), although they noted that cost estimates are heavily practice- and context-dependent. Tang et al. (2016) assessed the costs of several individual SCS practices from the literature, including USD 12-25 per tCO_2e for conservation tillage, 20 USD per tCO_2e for continuous cropping and USD 52-130 per tCO_2e for crop rotation limit.

A limited number of estimates were found at the EU level or for EU countries, which fall into the ranges cited by Fuss et al. (2018), including with some estimates of cost savings in certain contexts. For example, Bamière et al. (2023) estimated both marginal abatement costs for a range of agricultural practices in France over a 30-year timeframe, including for some SCS practices, with average costs estimated at EUR 51 per tCO_2e for cover crops, EUR 101 per tCO_2e for expansion of temporary grasslands, and EUR 70 per tCO_2e for organic C inputs). Similarly, for Spain, negative costs (including transaction costs) were estimated for crop rotation at EUR -43 per tCO_2e indicating the potential for savings in some European countries, and minimal costs at approximately EUR 2 EUR per tCO_2e for minimum tillage (Baccour et al., 2021).

Table 48: Cost estimates and conversions for soil carbon sequestration

Study	Region (details)	Original value	EUR_{2015} estimate
Fuss et al. (2018)	Global (likely)	0-100 USD_{2015}	0-90
Fuss et al. (2018)	Global (full cost range)	-45-100 USD_{2015}	-42-90
Tang et al. (2016)	Global, across several SCS practices	12-130 USD_{2012}	10-123
Bamière et al. (2023)	France, across several SCS practices	41-101 EUR_{2022}	44-87
Baccour et al. (2021)	Spain	-43-2 EUR_{2011}	-45-2

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

Agroforestry

As the term agroforestry can encompass an array of different agricultural practices, estimates of sequestration potential from the literature show similarly wide ranges. Focusing on European agricultural land in 'priority areas' (areas subject to multiple environmental pressures - approximately 9% of the total agricultural area) for example, Kay et al. (2019) estimated the potential removals from agroforestry to range from 0.09 to 7.29 tC ha^{-1} yr^{-1}, or 7.7 to 234.8 $MtCO_2e$ yr^{-1} when aggregated across the EU and Switzerland. The lower end of this range mainly comes from agroforestry systems with lower woody mass density, like hedgerows and field boundaries; the higher end from higher-density silvoarable and silvopastoral systems. At higher densities, the authors note that this would involve trade-offs with food production. Roe et al. (2021) estimated a similar maximum technical potential for agroforestry in the EU of up to 251.8 $MtCO_2e$ per year based on a 50% adoption rate on agricultural lands, and a cost-effective potential of 50.3 $MtCO_2e$ per year based on a 10% adoption rate. Based on an upscaling of Pellerin et al.'s (2020) estimates of the potential for silvoarable agroforestry in France, Bellassen et al. (Bellassen et al., 2022) estimated European potential removals from agroforestry at 60 $MtCO_2e$ per year at a price of EUR 250 per tCO_2e.

Table 49: Estimates of future mitigation or removal potential from agroforestry practices

Study	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Kay et al. (2019)	EU	Technical potentials, range across multiple practices	8-235
Roe et al. (2021)	EU-27	Technical potential	252
Roe et al. (2021)	EU-27	Cost-effective potential, based on a 20% share of technical potential	50
Bellassen et al. (2022)	EU-27	Technical potential	60

The IPCC (2022k) did not report costs for agroforestry, although a limited number of estimates are available at a national level in the European Union. For France, Bamière et al. (2023) has estimated the abatement cost associated with a range of agricultural measures, including average abatement costs of EUR 21 per tCO_2e for agroforestry, and EUR 96 per tCO_2e for hedges. ADEME (2021) also gave a value of approximately EUR 40 EUR per tCO_2e for agroforestry and hedges in France. In the UK, agroforestry marginal abatement costs were estimated at GBP 15 and 30 per tCO_2e when applied to grasslands and arable lands respectively (Eory et al., 2015). Although a lack of EU-wide studies limited the reliability of these assessments, these limited estimates suggests that the cost of agroforestry in the EU may fall within a similar range as that estimated for A/R, of around 20-100 EUR/tCO_2.

Table 50: Cost estimates and conversion for agroforestry practices

Study	Region (details)	Original value	EUR_{2015} estimate
Bamière et al. (2023)	France	21-96 EUR_{2019}	20-91
ADEME (2021)	France	40 EUR_{2023}*	36
Eory et al. (2015)	United Kingdom	15-30 GBP_{2015}*	21-41

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

Terrestrial and coastal wetland restoration

Terrestrial wetlands and peatlands have a high capacity to store carbon, and have among the highest carbon densities per hectare of all habitat types. However, peatlands sequester this carbon slowly over hundreds or thousands of years, meaning that drainage of peatland and organic soils can lead to effectively 'irrecoverable' losses of stored carbon (i.e. in a policy-relevant timeframe) if not halted and reversed (Goldstein et al., 2020b; Olsson et al., 2019). In Europe, peatlands have been extensively drained for agriculture, forestry and fuel extraction, resulting in 50% of EU peatlands being considered degraded (Tanneberger et al., 2021a) and associated annual emissions of 220 Mt. The effects of rewetting of peatland and wetland soils varies over time: in the short-term, rewetting significantly reduces GHG emissions and the continued loss of stored carbon, while in the long-term in restoring their function as a net carbon sink (Humpenöder et al., 2020). The time it takes for this net sink function to be fully re-established in uncertain with some evidence suggesting a timescale of several decades (Bacon et al., 2017; Escobar et al., 2022). While this means that rewetted organic soils generally remain net emitters of GHGs following rewetting in the mid-term (mostly due to increased methane emissions), overall GHG emissions are much lower compared to their previous drained state, delivering significant mitigation benefits and making wetland restoration an important element of climate strategies (Wilson et al., 2016; Günther et al., 2020). Overall, several estimates suggest a mitigation potential of between 2 and 34 $MtCO_2e$ per hectare per year from peatland rewetting (Bellassen et al., 2022).

Within Europe, Abdul Malak et al. (2021) estimated that EU wetlands 'if kept in a good condition or restored' have the potential to sequester between 24 and 144 $MtCO_2e$ annually, approximately 23-138 $MtCO_2e$ of which comes from terrestrial wetlands. They also estimated the total storage potential at 12–31 Gt CO_2. However, it is not clear how much of this represents additional removal or mitigation potential, versus sequestration that is already occurring.

Several EU studies have estimated the additional mitigation potential from peatland and wetlands restoration, which despite its small share of the area, suggest a relatively high mitigation (emission reductions and removals) potential from peatland restoration and rewetting of organic soils. Agora Agriculture (2024) estimated that the rewetting of 80% of agricultural peatlands – or just 2% of the overall land area – could deliver mitigation benefits of 72 $MtCO_2e$ per year by 2045. Other EU technical potential estimates come withing a similar range, including 109 $MtCO_2e$ per year (Bellassen et al., 2022), 101 $MtCO_2e$ per year (Gren, 2024), 48-57 $MtCO_2e$ per year (German Environment Agency et al., 2022). Some estimates also suggest relatively high economic potential. Roe et al. (2021) estimated a maximum technical potential *to reduce emissions* by restoring and rewetting wetlands/peatlands of 195 $MtCO_2e\ yr^{-1}$, and a cost-effective potential of 54 $MtCO_2e\ yr^{-1}$. The European Commission's (2024i) impact assessment for the 2040 target proposal also assessed the 2050 mitigation potential of rewetting organic soil at different carbon prices, with estimates of 1.3, 31 and 48 $MtCO_2e$ per year at carbon prices of EUR 20, 50 and 100 per tCO_2e, respectively.

Table 51 Estimates of future mitigation or removal potential from wetland and peatland restoration

Study	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Abdul Malak et al. (2021)	EU	Technical, sequestration potential of healthy peatlands	23-144
Roe et al (2021)	EU	*Technical potential*	*195*
Roe et al (2021)	EU	Cost-effective potential, at costs of less than USD 100 per tCO_2	54
Agora Agriculture (2024)	EU	Technical potential	72
Bellassen et al. (2022)	EU	Technical potential	109
Gren et al.	EU	Technical potential	101
Verkerk et al. (2022)	EU	Literature review, peatland forest restoration	105
European Commission (2024i)	EU	Cost-effective potential at carbon prices of EUR 20-100 per tCO_2e	1-48

The IPCC (2022k) did not report costs for terrestrial wetland and peatland restoration, although some estimates are available at a national level in Europe. The European Commission's (2024i) impact assessment for the 2040 target modelled the mitigation potentials of LULUCF options at different carbon prices, with their results suggesting that the majority of mitigation potential of rewetting organic soils could be realised at costs of EUR 50 per tCO_2e (EC, 2024p).

A limited number of national estimates generally fall within an average range of approximately EUR 15-75 per tCO_2e. Based on several projects in the Elbe River basin in Germany, Grossman and Dietrich (Grossmann and Dietrich, 2012) estimated relatively low median abatement costs of fen stabilisation and restoration at EUR 7-22 EUR per tCO_2e over a 50-year appraisal period, although noted that more ambitious schemes range lie at the higher end (12-22 EUR per tCO_2e). Böttcher et al. (2022) reviewed the literature and estimated the cost of wetland restoration and rewetting of drained organic soils in Germany to be generally higher at 27-107 EUR per tCO_2e based on bottom-up estimates. For the UK, Smyth et al. (Smyth et al., 2015) estimated the cost of peatland restoration at GBP 10-67 EUR/tCO_2e under three different restoration scenarios.

Table 52: Cost estimates and conversions for terrestrial wetland and peatland restoration

Study	Region (details)	Original value	EUR_{2015} estimate
Grossman and Dietrich (Grossmann and Dietrich, 2012)	Fen stabilisation and restoration projects in Germany	7-22 EUR_{2008}	8-24
Böttcher et al. (2022)	Based on literature review of costs	27-107 EUR_{2012}	28-110
Smyth et al. (Smyth et al., 2015)	Based on three peatland scenarios	11-67 GBP_{2015}*	15-92

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

In the scientific literature, the term 'blue carbon management' usually refers to management coastal vegetated ecosystems - particularly mangroves, seagrasses and saltmarshes – and efforts to restore these ecosystems to sequester and store carbon (IPCC, 2022k; Crooks et al., 2019). Blue carbon can sometimes refer more broadly to the ocean carbon cycle, whereby CO_2 is absorbed from the atmosphere via chemical and biological processes (the 'solubility' and 'biological pumps'), and stored in the form of dissolved organic/inorganic carbon, marine lifeforms or on the sediment floor (Christianson et al., 2022). Removal methods that aim to enhance the ability of the ocean carbon cycle to sequester carbon are detailed further under 'ocean fertilisation' and 'ocean alkalinity enhancement.

While coastal and blue carbon habitats are largely excluded from national GHG inventories, some removals may be included in EU member states' inventory submissions under the wetlands category (mostly in the form of salt marshes) although these levels are difficult to estimate explicitly (EEA, 2023a). Estimates are generally limited, although some regional estimates suggest low sequestration rates, but potentially high carbon stocks. Krause-Jensen et al. (2022) estimated that Nordic blue carbon habitats, including salt marshes, seagrass meadows and macroalgal habitats could sequester approximately 2 $MtCO_2$ per annum. Cott et al. (2021) similarly estimated carbon sequestration potential from saltmarsh and seagrass habitats in Irish waters at 0.03 MtC (0.11 $MtCO_2$ per annum). However, carbon stocks are much higher, with the potential to avoid emissions of approximately 38.5 $MtCO_2$ through conservation of these habitats.

Globally and in the EU, estimates of the removal potential from restoration of coastal wetlands and blue carbon ecosystems are limited, with significant uncertainties. Reviewing the literature on coastal and blue carbon ecosystem restoration as a removal strategy, Williamson and Gattuso (2022) highlight low confidence in estimates of removal potential found in the literature. Global restoration cost estimates from Williamson and Gattuso (2022) and Gattuso et al. (2021) also show significant variability depending on the type of ecosystem concerned, with median costs of USD 240, 30,000, and 7,800 USD per tCO_2 for mangroves, salt marsh and seagrass habitats (respectively). Few estimates of EU costs and potentials were found. One EU-focused study from Malak et al. (Malak et al., 2021) suggests limited carbon sequestration potential overall from healthy coastal wetlands at just 2-5 $MtCO_2$ per annum. Regional estimates also generally show low, but uncertain sequestration levels. Overall, Gattuso et al. (2021) and Williamson and Gattuso (2022)'s assessments suggest that while such marine ecosystems can hold large standing carbon stocks, challenges in carbon accounting, high variability and errors in carbon burial (removal) rates across studies and ecosystem types, and low cost-effectiveness per tCO_2 compared to other removal methods makes it 'uncertain and unreliable' as an explicit removal strategy. Limited European estimates found in the literature largely align with this assessment. However, coastal and blue carbon ecosystems still hold significant carbon stocks and provide many additional benefits, making practices like conservation, restoration of coastal and marine habitats, and reducing pollution and overexploitation 'low regret' options (Williamson and Gattuso, 2022).

Biochar

Tisserant et al. (2023) estimated the EU potential for biochar under 'low' and 'high' supply scenarios: the low scenario representing a 'sustainable removal rate' of residues from mainly crop residues and forest residues; and a high scenario combining the overall technical removal rate from crop and forest residues. Under the low supply scenario, they estimated the potential of biochar in the EU at 73.8 $MtCO_2e\ yr^{-1}$, compared to 169 $MtCO_2e$ per year under the high supply scenario, although they note that the high scenario may involve trade-offs with other activities. Roe et al. (2021) also estimate the technical potential from biochar (produced from crop residues) in EU countries at 102 $MtCO_2e$ per year, with a cost-effective potential of 79 $MtCO_2e$ per year. Lefebvre et al. (2023) estimated the technical potential for biochar from residual feedstocks, namely crop residues, animal manure, forestry wood residues and wastewater, at 197 $MtCO_2e$ per year.

Table 53: Estimates of future removal potential from biochar

Author	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Tisserant et al. (2023)	EU	Technical potential under different supply scenarios	74-169
Roe et al. (2021)	EU	Technical potential	102
Roe et al. (2021)	EU	Cost-effective potential, at costs of less than USD 100 per tCO_2	79
Lefebvre et al. (2023)	EU	Technical potential from residual feedstocks	197

While the lower range of these estimates are based mainly on biochar produced from crop residues, more optimistic estimates are likely to involve trade-offs with other removal or mitigation activities, particularly with BECCS or forest management given the use of forest residues, but also biogas or biomethane (from manure and wastewater) (Tisserant et al., 2023). Underscoring these trade-offs, (Lehtilä et al., 2023) find more limited potential for biochar when considered within a wider portfolio of removal methods, with estimates of 0-70 $MtCO_2e$ per year over three scenarios. To avoid overlaps in the use of residual feedstocks and land with other removal methods, they assume a "land and calorie neutral approach" to biochar feedstock production, meaning that that increased crop yields due to biochar production could potentially free up land that could be used to produce the associated feedstock.

The IPCC (IPCC, 2022k) provided a global cost range of around EUR 10-310 per tCO_2e for the cost of biochar. Fuss et al. (2018) noted that while high biochar prices were a barrier to their current deployment, suggested a lower range of USD 30-120 per tCO_2e as 'first rough estimates' of biochar prices, while noting that cost estimates were uncertain given the lack of large-scale deployment. Market transaction data from CDR.FYI cited by Bednar et. al (Bednar et al., 2023b) show a mean price of USD 176 per tCO_2e between 2019 and 2023 among early-stage biochar projects in voluntary markets and an average weighted price of USD 193 per tCO_2e over a full range of USD 97-600 per tCO_2e.

European estimates from the literature are limited, although point to significant variability depending on the feedstock used. One earlier study from the UK estimated the costs to range from approximately GBP -144-208 per tCO_2e, depending on the feedstock used (Shackley et al., 2011). However within this range, only a relatively small volume of total biochar potentials were available at negative costs (mainly from household waste, sewage due to avoided disposal/landfill costs), from other residues and biomass sources ranged between 19 and 208 GBP/tCO_2e. The average cost they found was GBP 57 per tCO_2e. In a more recent European case study by Fawzy et al. (2022), the cost of biochar removals was also found to be dependent on the local market cost of feedstock, and estimated a range of around 175-258 EUR/tCO_2e in a Spanish case study based on feedstock prices of 30–70 EUR/tCO_2e, respectively. Corrected for currency exchange and price levels, these estimates suggest an approximate range of 30-200 EUR/ tCO_2.

Table 54: Cost estimates and conversions for biochar

Study	Region (details)	Original value	EUR_{2015} estimate
Fuss et al. (2018)	Global	30-120 USD_{2015}	27-108
Shackley et al. (Shackley et al., 2011)	UK	57 (-144-208) GBP_{2011}*	84 (-213-305)
Fawzy et al. (2022)	Spain	175-258 EUR_{2022}*	151-223
Bednar et al. (2023b)	Market transaction data, mean price	176 $USD_{2019-2023}$*	138
Bednar et al. (2023b)	Market transaction data, weighted average price	193 $USD_{2019-2023}$*	152

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

Ocean fertilisation

The IPCC (2022) estimated the global potential of iron fertilisation at 1-3 $GtCO_2$/year by 2050, and the potential of macronutrients fertilisation at 5.5 $GtCO_2$/year by 2050. Lebling et al. (Lebling et al., 2022) estimated the global potential of ocean fertilisation within 0.1-3.7 $GtCO_2$/year. Lubchenco (2023) estimated the global potential of iron fertilisation at 0.2 $GtCO_2$/year by 2030, 0.9 $GtCO_2$/year by 2050 and 1.8 $GtCO_2$/year in the longer term. The Royal Society (2018) estimated the global potential of ocean fertilisation at <3.7 $GtCO_2$/year. Schäfer et al. (Schäfer et al., 2015) estimated the global potential of ocean fertilisation at 500-3,000 $GtCO_2$/year.

The IPCC (2022) estimated the cost of iron fertilisation at 2 USD/tCO_2, macronutrient fertilisation at 20 USD/tCO_2 and nitrate fertilisation at 457 USD/tCO_2, indicating that the macronutrients' cost might be underestimated due to a possible overestimation of sequestration rates. Median costs were reported at of 230 USD/tCO_2. Lebling et al. (2022) estimated the cost of ocean fertilisation at 8-80 USD/tCO_2 with material costs between 4-48 USD/tCO_2, with iron being less costly and phosphorous the most expensive. Emerson et al. (Emerson et al., 2023) estimated the cost of ocean fertilisation at 23 [7-475] USD/tCO_2 for distribution by airplane, 83 [23-1735] USD/tCO_2 including monitoring and verification costs, and 33 [9-1,502] USD/tCO_2 for distribution by ship, 94 [25-4,481] USD/tCO_2 including monitoring and verification costs.

Ocean alkalinity enhancement

The IPCC (2022) estimated the global potential of ocean alkalinity enhancement at 1-100 $GtCO_2$/year by 2050. The Royal Society (2018) estimated the global potential of ocean alkalinisation at 3,500 $GtCO_2$/year by 2100 (cumulative potential). Cooley et al. (2022) estimated the global potential of this method at 7.3 $GtCO_2$/year, based on an assumed distribution by ship in ocean basins deeper than 200 meters and with less than 50% of sea ice cover. Lebling et al. (2022)(Lebling et al., 2022) estimated the global potential of this method at 0.1-1 $GtCO_2$/year. Lubchenco et al. (2023) estimated the global potential of this method at 0-1 $GtCO_2$/year, based on a yearly growth of 7-10% capacity per year, and with a null lower bound based on the international law challenge. Kwiatkowski et al. (Kwiatkowski et al., 2023) estimated the global potential of this method at 10.8-15.3 $GtCO_2$/year in the long term.

The IPCC (2022) estimated the costs of ocean alkalinity enhancement at 40-260 USD/tCO_2, with the cost of adding reactive calcium or magnesium oxide/hydroxides estimated at 6-240 USD/tCO_2, the cost of electrochemical processes at 3-160 USD/tCO_2, and the cost of addition of alkaline elements at 20-50 USD/tCO_2. The Royal Society (2018) estimated the cost of producing lime and distributing it in the ocean at 72-159 USD/tCO_2 Cooley et al. (2022) estimated the costs of ocean alkalinisation at 100-150 USD/tCO_2. Lebling et al. (Lebling et al., 2022) also estimated the costs of ocean alkalinisation at 100-150 USD/tCO_2.

Enhanced weathering

The IPCC (2022) (Bindoff et al., 2019) estimated that the already deployed enhanced weathering on coast land and ocean accounts for 0.25 GtCO_2/year. Regarding future potential, the IPCC (2022) estimated the global removal potential from enhanced weathering at 2-4 GtCO_2/year. Beerling et al. (Beerling et al., 2020) estimated the potential of enhanced weathering at 57, 103 or 206 MtCO_2/year by 2050, if deployed on 10%, 17-25% or 38-57% (respectively) of cropland in five of the largest EU countries (France, Germany, Italy, Spain and Poland). As part of the NEGEM project, Lehtilä et al. (Lehtilä et al., 2023) draw on these estimates to model the EU potentials of enhanced weathering within a broader portfolio of removal methods. Their results suggest the EU-31 potential of enhanced weathering in a similar range, at about 100-200 MtCO_2/year by 2050 across three scenarios, although it should be noted that they rely on inputs from Beerling et al. (2020). While concluding that enhanced weathering shows moderate removals potential, they caution that this depends on a better understanding of its future environmental and practical implications, and also highlight uncertainties in the extent to which these estimates would overlap with other removal practices in the land sector.

The removal potential of enhanced weathering depends on the rate of application, mineral types, and assumptions over land use. Raek et al. estimate that the application of 10 t of basalt on croplands per year can result in sequestration rates of ~1 tCO_2 per hectare per year across Europe, which they describe as a 'conservative' application rate compared to other studies Baek et. al. (Baek et al., 2023). Beerling et al. (Beerling et al., 2020) suggest rates of ~3.4 tCO_2 per hectare per year, up to a 'theoretical maximum' of 16.2 tCO_2 per hectare per year. However, much lower estimates from the UK of less than 1 tCO_2 per hectare per year suggest significant uncertainty, and the possibility that capture rates will vary depending on the sites and the mineral materials (Buckingham and Henderson, 2024).

Regarding costs, Fuss et al. (2018) estimated the cost of enhanced weathering, depending on the rocks being used, with 60 USD/tCO_2 for dunite and 200 USD/tCO_2 for basalt application. They note that costs are closely related to the chosen technology for rock grinding, as well as material source, transport and distribution requirements. Beerling et al. (2020) also estimated the average cost of enhanced weathering at 158-193 USD/ tCO_2 in the five EU countries. The UNEP Emissions Gap Report Chapter 7 (UNEP, 2023) estimated the cost of enhanced weathering at USD 100-500 per tCO_2. Market transaction data cited by Bednar et al. (Bednar et al., 2023b) show a mean price of USD 392 per tCO_2 between 2019 and 2023 across enhanced rock weathering projects in voluntary markets, with average weighted price of USD 332 per tCO_2, indicating that the cost of early-stage projects are significantly higher than estimates in the literature.

Table 55: Cost estimates and conversion for enhanced weathering

Study	Region (details)	Original value	EUR_{2015} estimate
Fuss et al. (2018)	Global, cost estimates based on different technologies	60-200 USD_{2015}	54-180
Beerling et al. (2020)	Europe, cost estimates in five EU countries	158-193 USD_{2019}	134-164
UNEP (2023)	Global	100-500 USD_{2023}*	80-400
Bednar et al. (2023b)	Global, market transaction data between 2019-2023 from CDR.FYI (average price)	392 $USD_{2019-23}$*	310
Bednar et al. (2023b)	Global, market transaction data between 2019-2023 from CDR.FYI (average weighted price)	332 $USD_{2019-23}$*	262

*Indicates that the original year of cost estimates was not indicated in the study, and conversion was made on the basis of the study year.

Bioenergy with carbon capture and storage (BECCS)

Among the scenarios used to prepare the Advisory Board's advice on a 2040 objective, most deployed BECCS as the most common permanent removal method. The Board scenarios according to different filtering criteria (for more details see chapter for of (Advisory Board, 2023). In the Advisory Board's scenarios that were within the environmental risk thresholds for CCUS technologies and primary bioenergy use, described in section 1.4 previously, BECCS deployment reaches 147-248 $MtCO_2$/year by 2050, which corresponds to scenarios with 5-7.5 EJ/year of primary energy from biomass. In the 5-7 scenarios that were aligned with the Advisory Board' 90-95% range for 2040, BECCS deployment was 232-248 $MtCO_2$/year in 2050, corresponding to scenarios that used approximately 7.5 EJ/year of primary energy from biomass.

Other modelling results from the EU show a wider range. Over the four scenario variants used in the European Commission's (2024i) impact assessment for the 2040 target communication, the level of BECCS in 2050 ranges is between 39-61 $MtCO_2$/year, although higher levels are noted in some complementary models analysed. The lowest level corresponds to the LIFE scenario variant, while in scenario S3, this is 57 $MtCO_2$/year. The overall levels of BECCS deployment are constrained by a similar restriction in the level of gross available energy from biomass (9 EJ), additional restrictions imposed on forest biomass and import levels, with additional differences due to a higher level of biogenic carbon capture and utilisation compared to scenarios analysed by the Advisory Board.

Sultani et al. (2024) consider the potential *demand* for two main permanent removal methods (BECCS and DACCS) to counterbalance residual emissions within the EU ETS system, highlighting the dynamic relationship between these two permanent removal methods. On average, they estimate overall demand for removals to stabilise at around 60-70 $MtCO_2$ per year by 2050. Initially in their reference scenario, this demand is mostly met by BECCS, with around 40 $MtCO_2$/year by 2050. They assume a decrease in DACCS costs globally beginning in the late 2040s, which would result in BECCS installations being gradually crowded out once they reach their end-of-life. However, in other cost scenarios where DACCS costs do not decline (due to low global deployment), BECCS deployment stabilises at approximately 60-70 $MtCO_2$/year by 2050.

European potential for BECCS were also modelled as part of the NEGEM project, which assessed the future removal potential of a broader portfolio of methods in EU-31 countries (including the UK, Norway, Switzerland, Iceland). Potentials were assessed in three scenarios, with the primary constraint being the assumed level of biomass available:

- The storyline and parameters of the '1.5-Env' scenario ('Nature Conservation and biodiversity') are designed around limiting resource use and avoiding overshoot of planetary boundaries. BECCS is mainly limited to existing installations and biogenic point sources, with modern bioenergy crops and residues as the main feedstock. The use of bioenergy crops (although it is not clear whether this also includes residues etc.) is 1.5 EJ per year by 2050, and removals from BECCS are 250 $MtCO_2$ per year
- The '1.5 Tec' scenario ('Advanced technology and global markets') assumes *"optimistic technological development, and moderate limitations for land use and planetary boundaries"*. BECCS is limited to field and forestry residues, and capture from biogenic point sources. The level of bioenergy crops is 2.4 EJ/year, and removals from BECCS are 330 $MtCO_2$/year.
- The '1.5 Sec' ('Security and self-sufficiency') scenario assumes – among others – a 25% shift to the EAT-Lancet diet, releasing former pasture land for removals and nature restoration. This allows the highest level of removals from BECCS across the three scenarios, with 360 $MtCO_2$ per year by 2050, corresponding to 3.8 EJ per year of bioenergy crops each year.

Rosa et al. (2021a) also assessed the technical potential from applying BECCS to *existing* point-source installations and potential residual feedstocks only. They estimate technical potential of 202 (171-233) $MtCO_2$/year, comprised of 131 (115-147) $MtCO_2$/year by retrofitting BECCS technologies onto existing point sources; and a further potential of 71 (56-86) $MtCO_2$/year from BECCS applied to potential distributed sources, including crop residues, food waste and manure. Among point-sources, the highest potential comes from existing pulp and paper facilities (62 $MtCO_2$/year), followed by incinerators (36 $MtCO_2$/year), bioenergy facilities (31 $MtCO_2$/year), and wastewater (2 $MtCO_2$/year). While this suggests a similar potential of up to 200 $MtCO_2$/year from BECCS from existing facilities and residues, the authors emphasise the practical challenge in realising this potential due to an 'unfavourable sink-source distribution', noting a need to develop an EU-wide CO_2 transport network and a network of distributed storage sites. A separate study from Rosa and Mazotti (2022) also examined the technical potential of BECCS from bio-hydrogen production from the same distributed feedstocks, finding a technical removal potential of 133 (109-157) $MtCO_2$/year.

Table 56: Estimates of future removal potential from BECCS, 2050

Author	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Advisory Board (2023b)	EU-27	Economic (below identified environmental risk thresholds)	147-248
Advisory Board (2023b)	EU-27	Economic (within 90-95% advice range)	232-248
European Commission (2024i)	EU-27	Economic (range over 4 scenarios)	39-61
Sultani et al. (2024)	EU-27	Economic (within EU ETS)	40-70
Rosa et al. (2021a)	EU-27	Technical (from existing point sources & residues)	202 (171-233)
Rosa and Mazotti (2022)	EU-27	Technical (bio-hydrogen production)	133 (109-157)
Lehtilä al. (2023)	EU-31	Cost-effective potential, across three storyline scenarios	250-360
Roe et al. (2021)	EU-27	Technical potential	91
Roe et al. (2021)	EU-27	Cost-effective potential, at costs of less than USD 100 per tCO_2	4

Fuss et al. (2018) estimated global BECCS costs at USD 30-120 per tCO_2, with a full global cost range of USD 30-400 per tCO_2. Market transaction data cited by Bednar et al. (Bednar et al., 2023b) show a mean price of USD 300 per tCO_2 between 2019 and 2023 among early-stage BECCS projects in voluntary market transactions. Abegg et al. (2024) included current BECCS cost estimates of EUR 172 per tCO_2, and explored potential cost reductions towards 2050 based on an expert elicitation study. Average 'best-guess' es360+timates from these surveys indicated potential BECCS costs of EUR 205 per tCO_2 by 2030 (154-266 as the average of the minimum and maximum ranges provided by authors), EUR 183 per tCO_2 (132-266) by 2040, and EUR 153 per tCO_2 (102-246) by 2050 (Abegg et al., 2024).

Table 57: Cost estimates and conversions for BECCS

Study	Region (details)	Original value	EUR_{2015} estimate
Fuss et al. (2018)	Global, likely range	30-120 USD_{2015}	27-108
Fuss et al. (2018)	Global, full range	30-400 USD_{2015}	27-360
Bednar et al. (2023b)	Global, current market costs from CDR.FYI	300 $USD_{2019-2023}$*	246
Abegg et al. (2024)	2020 Reference cost	172 EUR_{2020}	160

*2021 taken for the purposes of conversion

Direct Air Carbon Capture with Carbon Storage

Among the Advisory Board's scenarios used to support its advice on the EU's 2040 climate target (Advisory Board, 2023), not all included estimates for DACCS. Among those that did, the overall level of DACCS deployment was 0-120 $MtCO_2$/year by 2050, although not evenly distributed across this range, with one cluster of scenarios showed 2050 potentials of around 30-40 $MtCO_2$/year, and one scenario with a value of 120 $MtCO_2$/year. In the scenarios where overall CCUS deployment did not exceed the environmental risk threshold used for comparative feasibility analysis, removals from DACCS were 0-22 $MtCO_2$ (Advisory Board, 2023).

The European Commission's scenarios for the 2040 target impacts assessment showed potentials at between 52-59 $MtCO_2$/year by 2050 in scenarios S1, S2 and S3. DACCS does not feature at all until 2040 and only in some scenarios, with permanent removal needs otherwise coming from BECCS. The demand-oriented LIFE scenario shows minimal DACCS deployment in all time periods due to an overall lower need for removals.

Sultani et al. (Sultani et al., 2024) consider the potential *demand* for permanent removal methods (BECCS and DACCS) to counterbalance residual emissions within the EU ETS system. On average, they estimate overall demand for removals to stabilise at around 60-70 $MtCO_2$ per year by 2050, with around 20 $MtCO_2$ per year of this capacity modelled to come from DACCS initially in their reference scenario. Although removals from DACCS do not begin to feature until the late 2040s, after 2050, their central assumption is that DACCS gradually becomes cost-competitive and crowds out BECCS. However, under two alternative cost scenarios for DACCS, they highlight the potential for widely diverging outcomes: in one where global DACCS costs do not decrease significantly, DACCS does not appear at all in the results in 2050, and all removal needs are met by BECCS; while in another where the opposite occurs, DACCS deployment reaches around 50 $MtCO_2$ per year by 2050.

As part of the NEGEM project, Abegg et al. (Abegg et al., 2024) used an expert solicitation method to estimate the potential scalability of DACCS in Europe under two stylised policy scenarios, with average best estimates of 39 $MtCO_2$/year in 2050 in a scenario based on stated policies only; and up to 353 $MtCO_2$/year in 2050 in a more ambitious scenario consistent with a net-zero ambition. In another output of the NEGEM project, the potential of DACCS was also assessed by Lehtilä al. (2023) as part of a broader removals portfolio for the EU-31 region. Their results show a higher level of DACCS deployment than other sources, at approximately 200-400 $MtCO_2$/year in EU-31 countries in three different scenarios, which similarly to other authors, only appears in the second half of the century. They highlight several factors behind the high deployment of DACCS, including constraints on BECCS, and assumptions of significant cost declines in some scenarios.

Table 58: Estimates of future removal potential from DACCS, 2050

Author	Scope	Estimate type	2050 or long-term estimate ($MtCO_2$ per year)
Advisory Board (2023b)	EU-27	Economic (below identified environmental risk thresholds)	0-22
European Commission (2024i)	EU-27	Economic (range over 4 scenarios)	0-59
Sultani et al. (2024)	EU-27	Economic, modelled deployment within the EU ETS	0-50
Abegg et al. (2024)	EU-27	Technical, based on expert opinion in two stylised policy scenario	39-353
Lehtilä al. (2023)	EU-31	Cost-effective potential, across three storyline scenarios	200-400

Cost is the most significant constraint to the potential of DACCS in these scenarios. Estimates of the current cost of DACCS are high, but subject to significant variability. Market transaction data cited by Bednar et al. (2023b) show a mean price of USD 1,120/tCO_2 between 2019 and 2023 across DACCS projects in voluntary markets, with average weighted price of USD 718/tCO_2. Overall, there was a wide range with reported current prices between USD 321-2,345/tCO_2 (Bednar et al., 2023b). While these average estimates are broadly consistent with other literature estimates of average costs of USD 500-1,000/tCO_2 for early-stage DACCS plants (Fuss et al., 2018), it also shows significant variability and outliers. However, like many other emerging technologies, the cost of DACCS is generally assumed (but not guaranteed) to decline with greater deployment due to experience and learning effects. Sievert et al. (Sievert et al., 2024) model potential cost trajectories for three DACCS technologies based on an experience curve. At a global cumulative deployment level of 1 Gt CO_2 per year, they estimate average costs falling to USD 341/tCO_2 (USD 226–544 at 90% confidence) for liquid solvent DACCS, USD 374/tCO_2 (USD 281–579) for solid sorbent DACCS, and USD 371/tCO_2 (USD 230–835) for calcium oxide ambient weathering DACCS; compared to early-stage cost estimates of USD600-2,000. Abegg et al. (Abegg et al., 2024) also carried out an expert elicitation survey that estimated similar cost trajectories for DACCS, albeit with significant variation and ranges between individual experts. DACCS costs were expected to decrease from a reference cost of EUR 600 per tCO_2 in 2020 to an average estimate of around EUR 300 per tCO_2 in 2050 among surveyed experts. However, these estimates are caveated by significant uncertainty and show an average min-max range of EUR 200-400 per tCO_2 by 2050. This also reflects uncertainty in the trends of key factors likely to drive cost reductions, such as future learning rates, energy availability and costs, and infrastructure development.

Study	Region (details)	Original value	EUR_{2015} estimate
Fuss et al. (2018)	Estimates for early-stage DACCS plants	500-1,000 USD_{2015}	450-900
Bednar et al. (2023b)	Global, market transaction data between 2019-2023 from CDR.FYI (average price)	1,120 $USD_{2019-23}$	930
Bednar et al. (2023b)	Global, market transaction data between 2019-2023 from CDR.FYI (average weighted price)	718 $USD_{2019-23}$	596
Abegg et al. (2024)	2020 reference cost	581 USD_{2020}	540