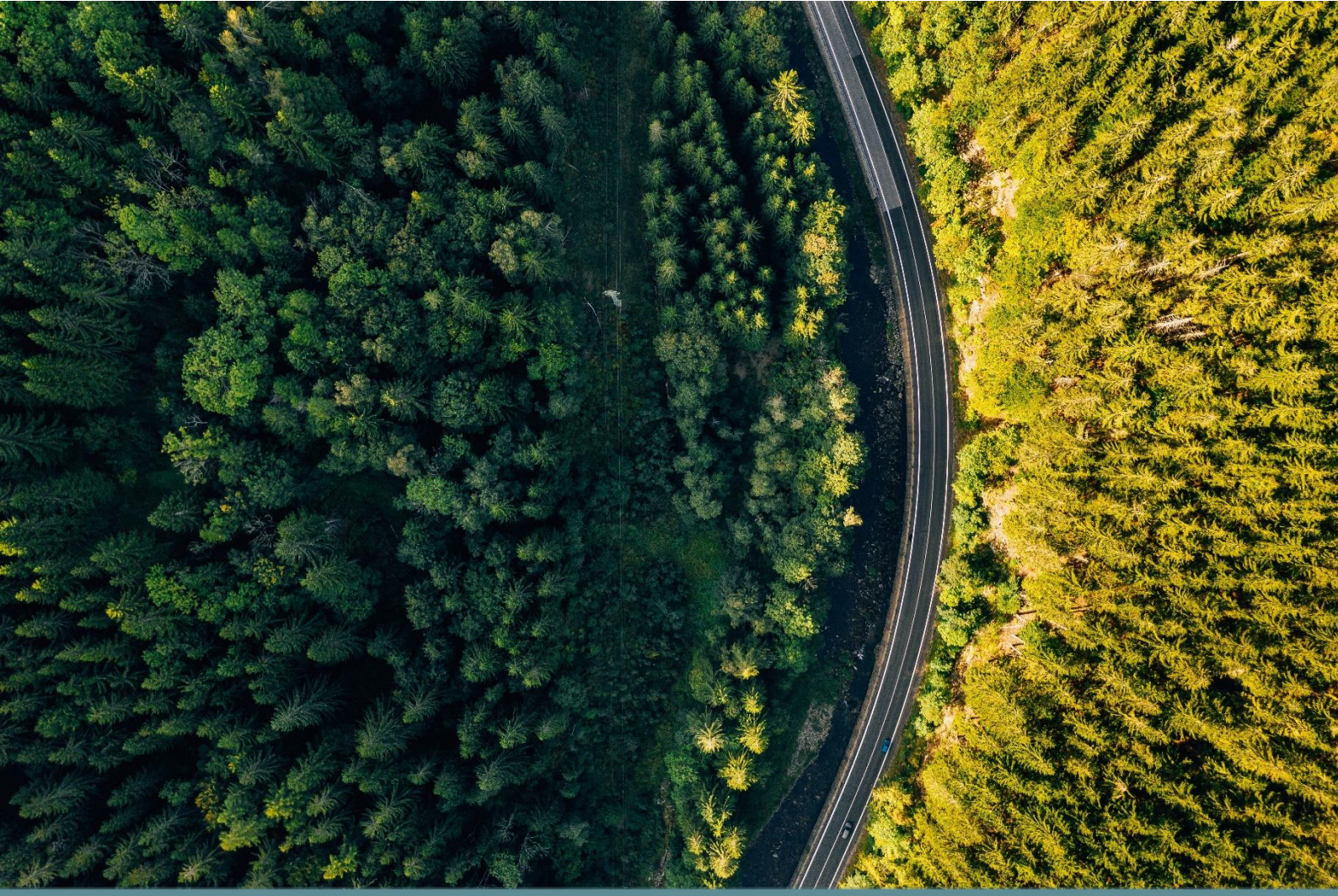

Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050

European Scientific Advisory Board on Climate Change

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List of abbreviations

AR6	sixth assessment report
BECCS	bioenergy with carbon capture and storage
CBAM	carbon border adjustment mechanism
CCS	carbon capture and storage
CCU	carbon capture and utilisation
CCUS	carbon capture utilisation and storage
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DACCS	direct air carbon capture and storage
EJ	exajoule
EU	European Union
EU-27	27 Member States of the EU
GDP	gross domestic product
Gt CO_2	gigatonnes (billion tonnes) carbon dioxide
Gt CO_2e	gigatonnes (billion tonnes) carbon dioxide equivalent
IPCC	Intergovernmental Panel on Climate Change
LULUCF	land use, land use change and forestry
Mt CO_2	megatonnes (million tonnes) carbon dioxide
Mt CO_2e	megatonnes (million tonnes) carbon dioxide equivalent
NDC	nationally determined contribution
NZIA	Net Zero Industry Act
SDG	sustainable development goal
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WG	IPCC Working Group

About the European Scientific Advisory Board on Climate Change

The European Scientific Advisory Board on Climate Change (the Advisory Board) 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.

The members of the Advisory Board are:

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Recommendations

The EU is committed to achieving climate neutrality by 2050 at the latest. To meet this objective, the European Climate Law requires the EU to adopt an intermediate greenhouse gas target for 2040. It mandates the European Commission to propose such a target, accompanied by a projected indicative EU greenhouse gas budget for the 2030-2050 period. These should be based on the best available and most relevant scientific evidence, and take into account the advice of the European Scientific Advisory Board on Climate Change.

The Advisory Board recommends keeping the EU's greenhouse gas emissions budget within a limit of 11 to 14 Gt CO_2e between 2030 and 2050. Staying within this budget requires emission reductions of 90–95% by 2040, relative to 1990. This range considers multiple dimensions of fairness and feasibility of the emission reductions. (Section 5.2)

- To derive these recommendations, the Advisory Board identified the latest available scientific evidence on scenario pathways for achieving climate neutrality in the EU that are in line with limiting global warming to 1.5°C with no or limited overshoot.
- It also considered what constitutes a fair EU contribution to global climate action, and some of the feasibility dimensions that could constrain the transition to a climate neutral EU.
- The target and budget figures in the headline refer to net domestic greenhouse gas emissions, including emissions from intra-EU aviation and maritime transport.

Pursuing the more ambitious end of the 2040 target range improves the fairness of the EU's contribution. Ambitious domestic emission reductions need to be complemented by measures outside the EU to achieve a fair contribution to climate change mitigation. (Section 5.2)

- The Advisory Board assessed the fairness of the EU's contribution under different ethical principles. Under some of these principles, the EU has already exhausted its fair share of the global emissions budget.
- Because none of the assessed pathways towards climate neutrality fully align with the fair share estimates, additional measures need to be pursued to account for this shortfall.
- Ambitious domestic emission reductions include pursuing the more demanding end of the recommended target range as well as achieving net negative emissions beyond 2050.
- Support, cooperation and partnerships outside the EU can address the shortfall between the EU's fair share and the recommended feasible budget.

The EU 2030 target of at least 55% reduction compared to 1990 enables reaching the recommended 2040 target range and climate neutrality by 2050. (Section 4.4)

- The EU has agreed to reduce net greenhouse gas emissions to at least 55% below 1990 levels by 2030. Subsequent climate action from this starting point can achieve the recommended 2040 target and keep post-2030 emissions within the recommended budget.
- Additional efforts to increase the ambition beyond 55% (up to 70% or more by 2030) would considerably decrease the EU's cumulative emissions until 2050, and thus increase the fairness of the EU's contribution to global mitigation.

The recommended 2040 target requires rapid, inclusive and well-managed transitions to address environmental risks and technology scale-up challenges. (Section 4.4)

- Feasibility analysis of environmental risks and scale-up challenges shows that transition policies need to pay specific attention to the short-term scale-up of solar, wind and hydrogen technologies, the sustainability of bioenergy supply and the attainable level of carbon removals.
- These policies also need to manage the pace at which service sectors change in order to reduce demand.
- A well-managed and inclusive transition requires policy implementation that accounts for local context, engages stakeholders, and ensures equity and justice.

Achievement of climate neutrality within the EU is to be supported through investments in innovation and wider capacity development. (Section 7.8)

- Investing in technological, social and governance innovation and wider capacity building can expand the range of feasible mitigation outcomes, which includes further emission reductions and a reduced need for carbon removals.
- The Advisory Board recommends taking a deliberate adaptive approach to harness and accelerate the dynamics of the energy transition.

The required transitions can be achieved by distinct combinations of demand management and technology deployment. (Chapter 6, Sections 7.1-7.7) Pathways with lower energy and natural resource use advance the Sustainable Development Goals and energy security and lower other risks compared to pathways that prioritise supply-side technological solutions. (Section 7.9)

- Reduced use of fossil fuels and natural resources in the pathways considered improves EU citizen's health and wellbeing, enhances air quality, reduces water stress, and enhances nature protection.
- Pathways that reduce energy demand offer greater opportunities to improve energy security through reduced fossil fuel imports, in some cases eliminating the need for imported natural gas.
- The realisation of these opportunities is contingent on local implementation.
- Pathways that reduce energy use reduce risks associated with the upscaling of supply-side options that have comparatively higher transition risks such as nuclear power, carbon capture, utilisation and storage (CCUS) and bioenergy.

There are different pathways to achieve climate neutrality. Decisive choices between various policy options therefore have to be made. Common features shown in the assessed scenarios could helpfully guide further policy developments. (Sections 7.1-7.7)

Common features of the assessed scenarios include the following.

- Near-to-complete decarbonisation of the EU power sector by 2040, with phase out of electricity generation from coal by 2030, of unabated gas-fired generation by 2040, the large-scale deployment of wind, solar and hydro energy and the substantial decrease in net fossil fuel imports.
- Considerable decrease in final energy consumption by 2040, partially but not exclusively due to the switch to more efficient electrified technologies, in particular in the transport sector.
- Prioritising of emission reductions, while at the same time scaling up carbon removals from both the land sector and novel technologies. Rapid scale-up of carbon removals is required in all scenarios; yet its deployment presents risks and challenges, which have to be managed.

In accordance with its mandate and its work programme, the Advisory Board will analyse in 2023 the consistency of EU measures with EU's climate objectives. It will also assess options for the enhancement of carbon removals in the EU, including for their governance.

Summary

The European Climate Law requires the EU to adopt a 2040 climate target, taking into account the advice from the European Scientific Advisory Board on Climate Change (Section 1.1)

The Paris Agreement sets out the goal of avoiding climate change by holding global warming to well below 2°C and pursuing efforts to limit it to 1.5°C, relative to pre-industrial levels (UNFCCC 2015, Article 2.1(a)). In its sixth assessment report (AR6), the Intergovernmental Panel on Climate Change (IPCC) highlights the existence of technological, political and economic solutions to achieve rapid and widespread emission reductions.

With the adoption of the European Climate Law in 2021, the EU made a legal commitment to achieve the goal of reducing its emissions to net zero by 2050 at the latest and aiming to achieve negative emissions thereafter, in pursuit of the long-term temperature goal set out in the Paris Agreement. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 emission levels (EU, 2021).

The EU recently adopted a key reform of its climate and energy legislation through a series of measures it had proposed in 2021 as part of the 'Fit for 55' package. With full implementation at the EU and national levels, these measures should enable the EU to achieve its emission reduction target of at least 55% by 2030, compared to 1990 ([1]).

For the period between 2030 and 2050, the European Climate Law requires the EU to establish a 2040 milestone target to drive the transition to a climate-neutral economy and mandates the European Commission to propose this intermediate 2040 target in the first half of 2024. This proposal will take into account inputs and evidence from scientific sources. This includes the advice of the European Scientific Advisory Board on Climate Change (hereafter Advisory Board), established to serve as a point of reference for the EU on scientific knowledge relating to climate change.

In January 2023, the Advisory Board published initial advice in which it recommended a systematic and transparent approach, guided by EU values, to determine the EU 2040 climate target and accompanying greenhouse gas budget (Advisory Board, 2023). Specifically, the Advisory Board recommended that the European Commission's analysis consider the following five key areas:

1. the scientific and legal context;
2. physical limits to global emissions (the global carbon budget) and the EU's 'fair share';
3. transformation scenarios for the EU to achieve net-zero greenhouse gas emissions by 2050;
4. the implications of different pathways in terms of side effects, co-benefits, resilience and feasibility;
5. the use of value judgements, especially when addressing tensions between different issues and principles.

With this report, the Advisory Board aims to support the European Climate Law's objectives by providing EU institutions with its own estimate of an EU greenhouse gas emissions budget for 2030-2050 and a 2040 target that is underpinned by science, consistent with the Paris Agreement's long-term

([1]) Legislation agreed in 2022 and adopted in 2023 would, if fully implemented, reduce EU net emissions to 57% below 1990 levels (EC, 2022b).

temperature objective and the EU's 2050 climate neutrality target, and in line with EU values and principles.

The Advisory Board recommends keeping the EU's cumulative greenhouse gas emissions below 11-14 Gt CO_2e between 2030 and 2050, and reducing EU greenhouse gas emissions by 90-95 % by 2040, relative to 1990 (Chapter 4, Section 5.1)

To deliver a contribution to achieving the temperature goal of the Paris Agreement that is both fair and consistent with the physical science of climate change, the Advisory Board recommends that the EU consider:

- emission pathways consistent at the global level with limiting warming to 1.5°C;
- estimates of its fair share of the remaining global carbon budget consistent with limiting global warming to 1.5°C.

The most ambitious category of pathways assessed by the IPCC are consistent with an at least 50% chance of limiting warming to 1.5°C by the end of the century (with no or limited overshoot). The remaining global carbon budget, consistent with limiting warming 1.5°C, is between 300 Gt CO_2 (83% chance) and 500 Gt CO_2 (50% chance) from the start of 2020 (± 220 Gt CO_2, depending on the changes in emissions of other greenhouse gases, such as methane and nitrous oxide emissions from agriculture).

Estimating the EU's fair share of this remaining budget has legal, ethical and practical dimensions. Dividing a 500 Gt CO_2 budget according to different approaches to equity shows that, from the start of 2020, the EU's share of the budget based on an equal per capita allocation of emissions would amount to 20-25 Gt CO_2. Dividing the same budget using approaches informed by other ethical principles (such as ability to pay or historical emissions) produces estimates of the EU share, which in some cases suggest that the EU has already used its fair share of the global carbon budget.

The Advisory Board collected and analysed over 1,000 EU emission pathways, and identified among them 36 scenarios that:

- are consistent with limiting global warming to 1.5°C with no or limited overshoot;
- are consistent with the EU's emission reduction objectives for 2030 and 2050;
- did not display characteristics exceeding one or more thresholds that would raise geophysical or sociocultural feasibility concerns, such as geological storage capacity or the rate of decline in final energy demand.

The Advisory Board further assessed these scenarios in terms of associated environmental risks (in relation to a high reliance on carbon capture, utilisation and storage (CCUS), carbon removals from land or bioenergy) and the challenges of short-term technological scale-up (for solar, wind and hydrogen energy). The analysis found that reductions in EU domestic emissions of at least 88% and up to 92% can be achieved, taking environmental risks and technology scale-up challenges into account. These correspond to an EU greenhouse gas budget of 16–14 Gt CO_2 equivalents (CO_2e) for 2030-2050. It also found that **reductions of up to 95%** can be achieved without exceeding any of the environmental risk levels identified, if technological scale-up challenges can be overcome, in particular related to the rapid scale-up of renewable energy. Such reductions could further reduce the 2030-2050 greenhouse gas budget to 11 Gt CO_2e.

The acceptable level for the EU's post-2030 greenhouse gas budget must also be informed by considerations such as political and societal ambition for climate action, questions of fairness and international effort sharing, and the economic and social case for climate action.

As the most ambitious reductions result in cumulative emissions that are higher than the most lenient equity-based fair share estimate (based on equal global per capita emissions), the Advisory Board considers that the EU should be looking to address this shortfall as part of its commitment to the Paris Agreement temperature goal. Taking fairness into account, the Advisory Board therefore considers that the minimum reduction for 2040 should be **90% below 1990 levels**, with a corresponding greenhouse gas budget under 14 Gt CO_2e for 2030-2050.

Consequently, **the Advisory Board recommends a 2040 target of a reduction in emissions in the range of 90–95% compared to 1990, corresponding to a budget of 11–14 Gt CO_2e in 2030-2050**.

A fair contribution to climate change mitigation requires ambitious reductions in domestic emissions, complemented by measures outside the EU (Chapter 3, Section 5.2)

To deliver a contribution to achieving the Paris Agreement that is both fair and consistent with the physical science of climate change, the Advisory Board recommends that ambitious reductions in domestic emissions be complemented by measures outside the EU (see Figure 1 and Figure 2). The EU must therefore ensure that it does the following.

1. **Aim for the highest level of ambition in domestic emission reductions and carbon dioxide removals**, while accounting for feasibility constraints, environmental risks and technological deployment challenges. The Advisory Board notes the importance of the EU communicating how it considers its contribution to be fair and ambitious, when submitting its post-2030 target as a nationally determined contribution under the Paris Agreement.
2. **Contribute to direct emission reductions outside the EU**, in the light of the shortfall identified between the feasible pathways and fair share estimates.
3. **Pursue sustainable net negative emissions after 2050**, as required under the European Climate Law, which would help manage temporary temperature overshoots, and support the international balancing of greenhouse gas emissions.

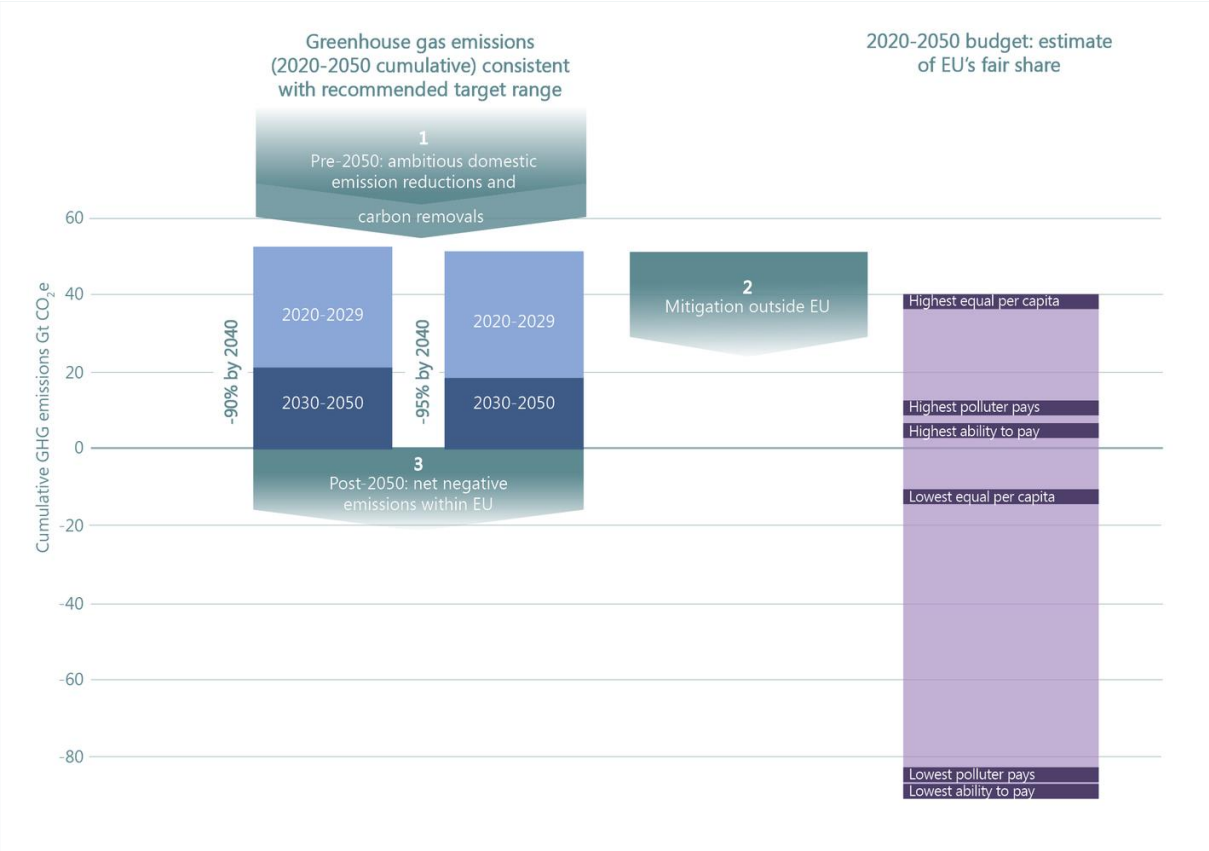
The EU 2030 target of at least a 55% reduction in greenhouse gas emissions compared to 1990 enables it to reach the recommended 2040 target range and climate neutrality by 2050 (Section 4.4.3)

The EU has agreed to reduce net greenhouse gas emissions to at least 55% below 1990 levels by 2030. Subsequent climate action from this starting point could achieve the recommended 2040 target and keep post-2030 emissions within the recommended budget.

While they are consistent with achieving climate neutrality by 2050, the pathways analysed by the Advisory Board imply a broad range of emission reductions by 2030, with some scenarios achieving 2030 reductions close to current EU targets (meaning reductions of 56-60% below 1990), and some others achieving reductions above 70% by 2030. The scenarios with short-term constraints on emission trends that do not exceed the environmental risk levels have 2030 emission reductions below 60%. Scenarios with the greatest short-term level of ambition achieve emission reductions above 60% and the lowest greenhouse gas budgets. Additional efforts to increase the level of ambition beyond 55%, including

through enhanced carbon removal, would considerably decrease the EU's cumulative emissions until 2050, and thus increase the fairness of the EU's contribution to global climate change mitigation efforts.

Figure 1 Reconciling feasible and fair EU contributions to global climate change mitigation



Notes:

The figure shows the period 2020-2050 rather than 2030-2050 only, because 2020 is the start year of the remaining global carbon budget published in the IPCC AR6, Working Group I contribution.

The cumulative emissions for 2030-2050 presented on this figure (dark blue bars) differ from the greenhouse gas emissions budget of 11-14 Gt recommended by the Advisory Board, because their scope was adjusted to allow a comparison with fair share estimates. These adjustments consist in the inclusion of emissions from all extra-EU aviation and maritime transport, and of an adjustment regarding emissions and removals from land. The latter reflects the difference in the way these emissions are accounted between greenhouse gas inventories and in the IPCC global carbon budget. Greenhouse gas inventories consider the entire land sink to be anthropogenic, whereas the IPCC AR6 (and science more generally) considers the indirect fraction to be natural (and excludes it from the total anthropogenic sink used to estimate the remaining global budget).

The fair share estimate presented in this figure consists of equity-based EU shares of the remaining global carbon budget, to which proxy non-CO_2 emissions for the period 2020-2050 are added. These proxy emissions are taken from the pathway that achieves 95% greenhouse gas emissions reduction while remaining within the environmental risk levels identified in this report.

Source: Advisory Board (2023).

The recommended 2040 emission reductions can be achieved through several pathways. Despite their differences, they show a high degree of convergence on a range of issues (Chapters 6 and 7)

The analysis of the feasibility of different scenarios and their compatibility with environmental risks and technological scale-up challenges shows that there is a general distinction between pathways that prioritise the rapid scaling up of non-fossil renewable energy technologies and those that mostly rely on land and/or CCUS technology to remove CO_2 from the atmosphere.

To further illustrate the different societal choices and strategies that the EU could make to achieve ambitious reductions in domestic emissions by 2040 and net zero emissions by 2050, the Advisory Board selected three 'iconic pathways' from the 36 scenarios analysed. The three pathways have different key characteristics (see Figure 2).

1. The **Demand-side focus pathway** is one of the illustrative mitigation pathways assessed in the IPCC AR6 ([2]) and combines ambitious climate policies with global achievement of the UN sustainable development goals. It has a focus on less resource-intensive lifestyles and features the lowest final energy demand by 2040 of the three iconic pathways.
2. The **High renewable energy pathway** is a more recent scenario that includes a focus on the level of emission reduction that is plausible in the short term. It is also characterised by a relatively high renewable energy deployment – i.e. of the three iconic pathways, it has the highest share of non-biomass renewable electricity in 2040.
3. The **Mixed options pathway** has the lowest net cumulative emissions of the three iconic pathways in 2030-2050. It features greater deployment of carbon removals from the land sink and an increase in the contribution of nuclear power compared with the other iconic pathways.

The Advisory Board compared the key characteristics of the scenarios analysed and identified key elements of the transition common to most climate neutrality pathways, as presented below.

Decarbonisation of the power sector

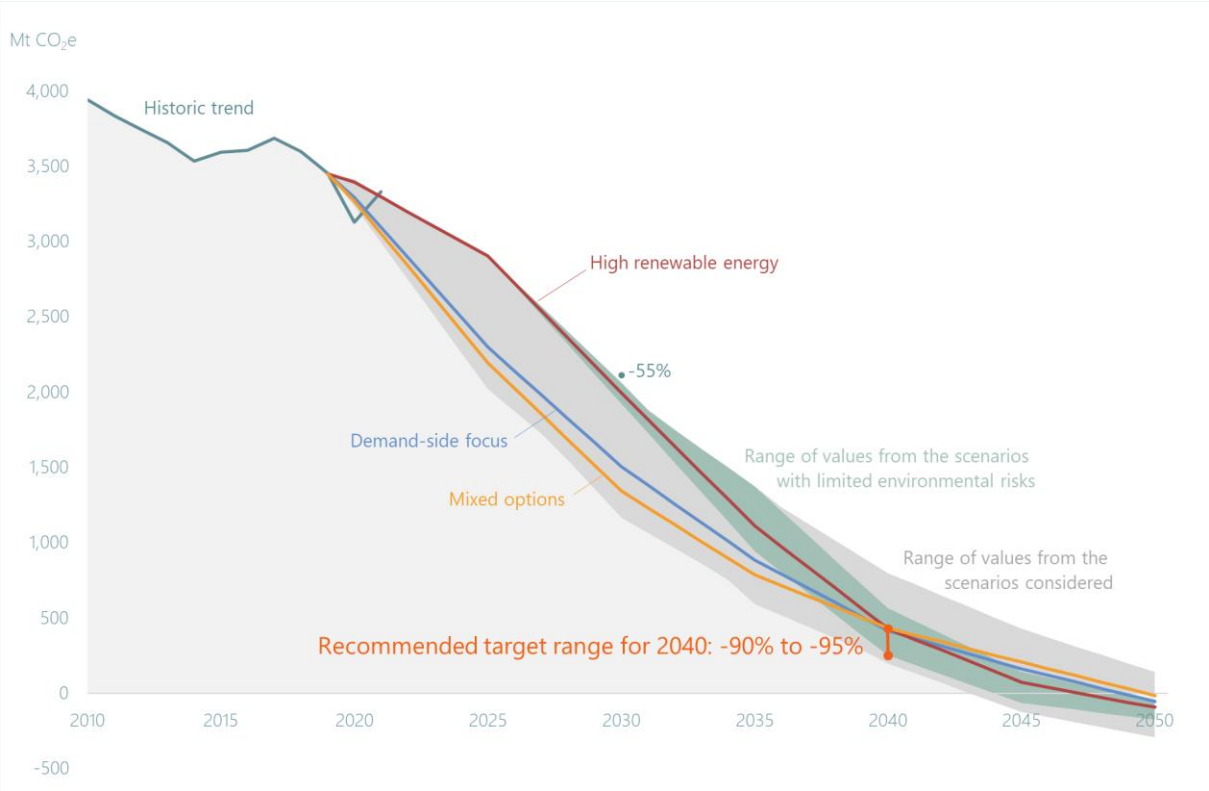
- The power sector reaches near-to-zero emissions by 2040.
- Under all pathways, the power mix will predominantly be based on renewable energy sources, in particular wind, solar and hydro (70-90% of the mix in 2040). Power generation is almost completely free from unabated gas-fired generation by 2040, and from coal by 2030. Some pathways rely heavily on carbon capture utilisation and storage (CCUS). In the scenarios with a lower share of renewable energy, the share of nuclear reaches up to 20% of the final energy use in 2040.
- The share of electricity in final energy demand is approximately twice its current level.

Scale-up of other, non-fossil energy carriers

- All scenarios, even those with a very high electrification rate, require alternative non-fossil energy carriers for applications that are hard to electrify, for example in industry and transport.
- The demand for bioenergy varies considerably among the different pathways. In some scenarios, demand increases by over 50% by 2040, whereas other scenarios see a more modest increase, or even no increase above today's levels.
- The use of hydrogen is scaled up in almost all pathways, with production of 5-10 Mt by 2030[3].

([2]) The illustrative mitigation pathways are used in the IPCC reports to contrast different scenarios for mitigating climate change.
([3]) In the scenarios analysed, hydrogen is mainly produced in the EU rather than imported.

Figure 2 Recommended range of 2040 greenhouse gas emission reductions compared to 1990, and iconic pathways illustrating possible strategies to achieve climate neutrality by 2050



Notes:

The emission reductions are relative to 1990 levels.

The range of values from the scenarios considered represent the range of values derived from 36 scenarios consistent with the Paris Agreement objective of limiting warming to 1.5°C and with the EU's climate neutrality objective by 2050, after removing scenarios raising high feasibility concerns.

The range of values from the scenarios with limited environmental risks represents the range of values derived from 7 scenarios that do not exceed any of the environmental risk levels identified, corresponding to emission reductions of 88-95% by 2040. All these scenarios but one feature emission reduction by 2040 of at least 90% below 1990. In light of this and taking into account the need to make a fair contribution to global climate change mitigation, the Advisory Board recommends emission reductions of 90-95% by 2040 compared to 1990.

The three pathways presented (Demand-side focus, High renewable energy and Mixed options) illustrate possible strategies to achieve the recommended emission reductions by 2040 and climate neutrality by 2050. The Demand-side focus pathway focuses on less resource-intensive lifestyles. The High renewable energy pathway is characterised by high deployment of non-biomass renewable energy and takes into account constraints to accelerating emission reductions in the short term. The Mixed options pathway deploys other options, including expansion of the land sink and increased deployment of nuclear power.

Source: Advisory Board (2023).

Reduction of total energy demand

- Under all pathways, total final energy use decreases considerably by 2040 (a 20-40% reduction from today), supported by a higher electrification rate.
- The decrease is largest in the transport sector (30-60%), followed by industry (20-45%) and residential and tertiary sectors (15-35%).

Reduction of non-CO_2 emissions

- All pathways assume considerable reductions in non-CO_2 greenhouse emissions, although the rate of reduction varies (20-60 % below today's levels).
- Some pathways display up to 50% reduction in livestock demand (this data is not available for all pathways).
- Trends in nitrogen fertiliser use are mixed: while some pathways show reductions of nearly 35%, others show an increase in nitrogen fertiliser use of up to 50%, mostly accompanied by large increases in agricultural and energy crop production.
- All pathways foresee large reductions in methane emissions of both waste (45-60%, linked to reduced landfilling) and energy use (70-90%, due to reduced fossil fuel use).

Carbon removals

- Some estimates from the scientific literature place potential carbon removals from the LULUCF sectors at between 100 and 400 Mt CO_2. Several scenarios within the recommended target range maintain the sink below 400 Mt CO_2. However, some scenarios rely on a land sink which exceeds this level by 2040, which raises feasibility concerns due to future climate impacts.
- Carbon removals through bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS) also varies considerably: between 50 and 200 Mt CO_2 in 2040 in scenarios where deployment remains within identified risk levels.

Energy security

- Net oil imports decrease 50-100% by 2040 (compared to today) under the different pathways, with net gas imports decreasing between 35% and 100%.
- Although the pathways do not provide direct results on increase in demand for critical materials, the large-scale deployment of both renewable energy and electrification technologies under all pathways suggest that the demand for critical raw materials would increase considerably.

1. Introduction

1.1 Context: international and EU climate policy objectives

The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, 2023) recently reminded the world that human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with the average global surface temperature reaching 1.1°C above 1850-1900 levels in 2011-2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals.

The IPCC further underlines that every increment of global warming will intensify multiple and concurrent hazards, while deep, rapid and sustained reductions in greenhouse gas emissions would lead to a discernible slowdown in global warming within around two decades.

The Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (the 'Paris Agreement'), sets out a global framework to avoid dangerous climate change by limiting global warming to well below 2°C and pursuing efforts to limit it to 1.5°C, relative to pre-industrial levels (UNFCCC 2015, Article 2.1(a)). To achieve this temperature goal, global greenhouse gas emissions should peak as soon as possible and reduce rapidly thereafter, in order to achieve net zero emissions, i.e. a balance between anthropogenic emissions by sources and removals by sinks in the second half of the century (UNFCCC 2015, Article 4.1).

With the adoption of the European Climate Law in 2021, the EU made a legal commitment to achieve the goal of reducing its emissions to net zero by 2050 at the latest and aiming to achieve negative emissions thereafter, in pursuit of the long-term temperature goal set out in the Paris Agreement. The law also sets the intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 emission levels (EU, 2021).

Since the European Climate Law entered into force in July 2021, EU legislation has been substantially revised and updated to align EU policies with the EU's target to reduce emissions by at least 55% by 2030, as set out in the European Climate Law, notably through the adoption of several elements of the 'Fit for 55' package. These include the revisions of the EU emissions trading system (EU ETS) Directive (EU, 2023a), of the Effort Sharing Regulation (EU, 2023c), and of the Regulation on land use, land-use change and forestry (LULUCF) (EU, 2023b), as well as the inclusion of maritime transport activities in the EU ETS (EU, 2023d) ([4]). With full implementation at EU and national levels, these measures should ensure the achievement of the EU's 55% target by 2030.

While the European Climate Law limits the contribution of net removals by natural sinks to the EU 2030 target to 225 Mt CO_2 equivalents (CO_2e), the revised LULUCF Regulation adopts a higher target of 310 Mt CO_2e for the land sink. Achieving this target would allow the EU to reduce its net domestic greenhouse gas emissions in 2030 by 57% below 1990 levels (EC, 2022b), thereby de facto strengthening its ambition to reduce emissions by 2030.

The energy crisis following Russia's invasion of Ukraine prompted the EU to envisage further measures having a direct effect on EU greenhouse gas emissions, including new objectives to reduce the EU's

([4]) At the time of writing, other elements of the Fit for 55 package were still under discussion by EU legislators (e.g. revision of the Renewable Energy Directive and Energy Taxation Directive).

dependency on Russian fossil fuels, saving energy and accelerating the deployment of renewable energy. As a result, the ambition of the headline targets of both the Renewable Energy Directive and the Energy Efficiency Directive were increased during negotiations beyond the original Fit for 55 proposals. Achieving these more ambitious objectives should help deliver reductions beyond the 55% reduction target.

In addition, under the Net Zero Industry Act (NZIA), the European Commission proposed in 2023 to scale up the manufacturing of clean technologies in the EU through an aggregate manufacturing capacity objective for 2030 and a simplified regulatory framework for manufacturing key products and technologies, including batteries, wind turbines, heat pumps, solar photovoltaics, electrolysers and carbon capture, utilisation and storage (CCUS).

For the period between 2030 and 2050, the European Climate Law requires the EU to establish a 2040 milestone target to drive the transition to a climate-neutral economy (EU, 2021). The European Climate Law mandates the European Commission to propose this intermediate 2040 target in the first half of 2024. This proposal will take into account various data and knowledge from scientific sources, including the latest reports from the European Scientific Advisory Board on Climate Change.

1.2 Objective of the report

In January 2023, the Advisory Board published its initial advice in which it recommended that the European Commission follow an approach that is systematic, transparent and guided by EU values when preparing its EU 2040 climate target proposal and accompanying greenhouse gas budget (Advisory Board, 2023). Specifically, the Advisory Board recommended that the European Commission's analysis consider the following five key areas:

1. the scientific and legal context;
2. physical limits to global emissions and the EU's 'fair share';
3. transformation scenarios for the EU to achieve net zero greenhouse gas emissions by 2050;
4. the implications of different pathways in terms of side effects, co-benefits, resilience and feasibility;
5. the use of value judgements, especially when addressing tensions between different issues and principles.

With this report, the Advisory Board aims to support the achievement of the European Climate Law's objective by providing EU institutions with its own estimate of an EU greenhouse gas emissions budget for 2030-2050 and a 2040 target that are underpinned by science, consistent with the Paris Agreement's long-term temperature objective and the EU's 2050 climate neutrality target, and in line with the EU values and principles featured in its initial advice.

In doing so, the Advisory Board aims to fulfil its role of serving 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. The aim here is also to frame future political discussions on an EU 2040 target, taking a robust approach in line with the latest available scientific evidence.

1.3 Outline

The advice presented in this report presents findings and recommendations based on the Advisory Board's own analysis, consistent with the method outlined in its the initial input published in January 2023.

In addition to setting out the context in which this advice is provided, this introductory chapter provides further clarifications on the approach taken and underlying assumptions made by the Advisory Board to develop this advice. Chapter 2 presents the scientific findings on the remaining global carbon budget consistent with achieving the long-term goal of the Paris Agreement. Chapter 3 explores various ethical perspectives to define the EU's fair share of this remaining global carbon budget. Chapter 4 presents the outcome of the identification and assessment of greenhouse gas emission scenarios that would enable the EU to achieve climate neutrality by 2050, in the framework of the Paris Agreement temperature goals. The analysis narrows down a range of feasible climate-neutral emission pathways for the EU. It also addresses the implications of different pathways in terms of feasibility and the challenges associated with the transformations implied. The feasible pathways emerging from this analysis are assessed in Chapter 5 against possible EU fair shares, leading to the Advisory Board's recommendations on the EU's 2040 target and associated 2030-2050 greenhouse gas budget.

Chapter 6 presents a subset of 'iconic pathways', selected to illustrate political and societal options to achieve Europe's necessary transformation climate neutrality. Lastly, Chapter 7 explores in detail the implications of the different scenarios in terms of sectoral transformations, economic aspects, and synergies and trade-offs with the sustainable development goals.

1.4 Further clarification on the Advisory Board's approach

Providing advice supporting the determination of the EU 2040 target and of an indicative greenhouse gas budget for 2030-2050 requires clarification of the Advisory Board's understanding of EU climate objectives under the European Climate Law and of EU commitments under the Paris Agreement. These are explained in this chapter.

1.4.1 Aligning the EU 2040 target with the 1.5°C objective

The Paris Agreement commits its signatories to keeping global warming well below 2°C and pursuing efforts to limit the increase to 1.5°C relative to pre-industrial levels. In its initial advice, the Advisory Board recommended that the EU 2040 target and greenhouse gas budget be consistent with pursuing efforts to limit global warming to 1.5°C, recognising the reiteration of this goal in the outcomes of the UN climate change conferences in Glasgow (2021) and Sharm El-Sheikh (2022) (UNFCCC, 2022a) (UNFCCC, 2022b). This assessment considers how the EU can contribute to this goal.

1.4.2 Reconciling time frames of EU objectives with the Paris Agreement process

The Paris Agreement decision on 'common time frames' encourages each Party to communicate successive nationally determined contributions (NDCs) to the global temperature goal that cover a period of five years, communicated five years in advance (UNFCCC, 2021). Under such a time frame, the EU is therefore expected to communicate an NDC in 2025, with a target for 2035.

This leaves the possibility for the EU to communicate targets for both 2035 and 2040 in 2025, with the 2035 target seen as a waypoint towards the 2040 target. The European Commission could therefore consider including a 2035 target in its proposal for a 2040 target.

1.4.3 Reconciling scenarios with latest trends and developments

Most of the scenarios considered for analysis in this report pre-date the latest EU policy developments described in Section 1.1. To address this issue, the Advisory Board consulted newer scenarios accounting for the most recent trends in EU greenhouse gas emission, which include near-term constraints on steep decarbonisation in the EU. In addition, the report's analysis of feasibility includes comparison of the scenarios' technology scale-up rates against some of the REPowerEU targets.

1.4.4 Key definitions and assumptions used in this report

The greenhouse gas reductions and 2030-2050 budgets discussed in this report are derived using the following assumptions. These assumptions are made for analytical purposes and are not necessarily legal or policy interpretations on the part of the Advisory Board.

Net emissions (emissions and removals from LULUCF). The emissions pathways analysed in this report, and the budgets and targets derived from them, refer to EU net emissions of all greenhouse gases (emissions after deduction of removals). This is defined on the same basis as national greenhouse gas inventories. Greenhouse gas emissions are aggregated as tonnes of CO_2 equivalent using the values for 100-year global warming potential from the IPCC Fourth Assessment Report, to enable comparison with the latest EU greenhouse gas inventory available at the time ([5]).

Carbon capture, utilisation and storage, and carbon removals. These technologies are accounted for in emission reductions or removals. CCUS, when applied to industrial processes or fossil energy sources that capture carbon directly from the emission source, is not considered to contribute to removals. Carbon removals refer to anthropogenic activities removing CO_2 from the atmosphere by enhancing terrestrial biological sinks ('the land sink') ([6]) and technologies such as bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). See Section 7.7 for further discussion of this topic.

Emissions from international aviation and maritime transport. The emissions pathways in this report include emissions from international aviation and maritime transport between EU destinations ('intra-EU' travel), but do not include travel between the EU and a non-EU country ('extra-EU' travel). This is to ensure comparability with previous EU target assessments. However, emissions including extra-EU travel are also estimated, and the implications for the post-2030 budget and target are discussed in Section 5.2.

Greenhouse gas emissions budget. The budget is defined as the total cumulative anthropogenic greenhouse gas emissions. Its relationship with the global carbon budget is discussed in Section 2. References to the indicative 2030-2050 greenhouse gas budget in this report include net emissions for 2030 and 2050.

Europe region. Almost all numbers mentioned in this report refer to the EU (i.e. the current 27 Member States (EU-27)). However, the report occasionally refers to a wider European region ([7]) to provide additional insights where scenario data are not available at EU-27 resolution.

([5]) The publication of the 2023 EU inventory submission in April 2023 (which uses the global warming potential values from the IPCC Fifth Assessment Report) came too late for inclusion in this analysis.

([6]) The land sink removals referred to in this report include estimated indirect effects for comparability with net LULUCF emissions reported in national greenhouse gas inventories.

([7]) This is the 'R10' region used in IPCC assessments, which includes Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, Türkiye and the United Kingdom as well as the EU-27 and a number of smaller states.

2. The global carbon budget in line with limiting global warming to 1.5°C

As noted in the Advisory Board's initial advice, proposals for an EU 2040 climate target and accompanying greenhouse gas budget must start with a robust scientific understanding of the limits consistent with EU climate objectives and global temperature goals.

In its AR6, the IPCC provides estimated values for the remaining global carbon budget ([8]), which corresponds to the quantity of CO_2 emissions that can be released to the atmosphere from the start of 2020 while keeping global warming to 1.5°C. The exact value of the budget depends on several factors, including the accepted chance of keeping warming within this limit, and the assumed path of non-CO_2 greenhouse gas emissions (that also contribute to warming but are not typically expressed as a budget).

Table 1 Estimates of remaining global carbon budget from 2020

Likelihood of limiting global warming to 1.5°C (%)	**83**	**67**	**50**	**33**	**17**
Remaining global carbon budget (Gt CO_2)	300	400	500	650	900
Variation in carbon budget due to non-CO_2 emissions in 1.5°C-compatible pathways			± 220		

Source: Table SPM.2 in IPCC (2021).

In this report, two different approaches are used in combination to ensure consistency with the physical science of climate change as assessed in the IPCC AR6.

For the **scenario analysis** (presented in Chapters 4 and 7), all of the scenarios that are analysed in detail are **consistent at global level with an at least 50% chance of limiting warming to 1.5°C by the end of the century with no or limited overshoot** (the 'C1' category of the IPCC (IPCC, 2022b)). This is the lowest temperature category used for classifying the most ambitious climate mitigation pathways in the literature (IPCC, 2022j). This consistency between physical climate science and modelled socioeconomic pathways is ensured using techniques similar to those of the IPCC assessment, including use of a reduced complexity climate model to check the climatic impacts of the scenarios' emissions outcomes. The process is documented in greater detail in Byers et al. (2023). It means that each scenario featured is scientifically consistent with a global pathway to a 1.5°C world, from which we can assess the EU's contribution. However, **no explicit judgement is made about whether these scenarios' allocation of emission reductions between the EU and the rest of the world should be considered fair**.

Conversely, in the fair share analysis (presented in Chapter 2), different fairness principles are used to estimate EU carbon budgets **but without explicit consideration of whether and how the EU can respect these limits on its domestic emissions**. The fair shares are based on a remaining global carbon budget of 500 Gt CO_2 from the start of 2020 (see Table 1).

([8]) Updated estimates of the remaining carbon budget point towards even smaller values (Forster, P.M., et al., 2023). These would further reduce the fair shares estimated for the EU.

Regarding the **relationship between CO_2 and other greenhouse gases**, the IPCC physical science assessment makes the following clear:

- stabilising global temperature requires reaching at least net zero CO_2 emissions at a global level;
- limiting global warming to a specific level (such as 1.5°C) requires limiting cumulative CO_2 emissions to within a carbon budget.

However, emissions of other greenhouse gases, such as methane and nitrous oxide from agriculture, are also key drivers of global warming. Strong reductions in these emissions are a key component of the 1.5°C remaining carbon budget and scenarios assessed by the IPCC.

The European Climate Law reflects this reality, as well as long-standing conventions in climate policy, by requesting an **indicative EU greenhouse gas budget** covering all major greenhouse gases and expressed in tonnes of CO_2 equivalent (t CO_2e) ([9]). The term 'budget' in this context refers to the cumulative net emissions of all greenhouse gases regulated under EU law that are expected to be emitted in 2030-2050 without putting at risk the EU's commitments under the Paris Agreement ([10]). In this report, the recommended greenhouse gas budget for 2030-2050 refers to cumulative EU emissions over this period in the scenarios assessed. The adequacy of this budget with regard to the EU's individual and collective commitments under the Paris Agreement is examined through the scenario analysis and fair share estimation as described above.

It is not possible to compare an EU greenhouse gas budget with the Paris Agreement global temperature goal using physical climate science alone, since it requires assumptions about the EU's share of the global mitigation effort. Nonetheless, both the socioeconomic and equity-based analyses in this report are underpinned by the IPCC AR6 physical climate science assessment, thereby ensuring consistency with the best available science as far as possible.

([9]) In EU climate policy, and for reporting under the Paris Agreement, t CO_2e is measured using a metric known as 100-year global warming potential. Scientifically speaking, other metrics could be used. Their pros and cons are discussed at length in the scientific literature, including Box TS.2 in (IPCC, 2022k).

([10]) The phrase 'without putting at risk the EU's commitments under the Paris Agreement' comes from the definition of the greenhouse gas budget in the European Climate Law (Article 4(4)). It is not specified whether it refers to the EU's individual commitments or the collective commitment to the Paris Agreement goal. Regarding individual commitments, the EU has communicated its 2030 target to the UNFCCC as an NDC and its climate neutrality objective as a long-term strategy (UNFCCC, 2023b) (UNFCCC, 2023a).

3. Different perspectives on the EU's fair share of emissions

Climate change is a global problem, since the greenhouse gases emitted by human activity are well mixed in the Earth's atmosphere and cause temperatures to increase all over the world. Responding to climate change is a global challenge, with over 190 countries committed to the collective Paris Agreement goal of holding the global temperature increase to well below 2°C and pursuing efforts to limit it to 1.5°C.

Estimates of the EU's fair contribution to this goal have legal, ethical and practical dimensions. This chapter discusses these dimensions in turn.

Chapter 5 compares the equity-based fair share estimates discussed in this chapter against feasible pathways to climate neutrality identified through scenario analysis.

3.1 From a legal perspective

The EU and its Member States have agreed to act jointly in their pursuit of the Paris Agreement temperature goal and have submitted a NDC (EU, 2020). Like all Parties to the Paris Agreement, the EU has committed to the principle that its NDC will 'reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances', and to the requirement that each Party communicate how it considers its NDC to be fair and ambitious (UNFCCC, 2018).

The EU has also made commitments to climate action under domestic law (as discussed in the Advisory Board's initial advice (Advisory Board, 2023)). Several principles cited in the European Climate Law, such as the *polluter pays*, *precautionary* and *do no significant harm* principles, could be considered to apply both domestically and as guiding influences on the EU's contribution to global goals. The European Climate Law also contains more explicit guidance on the European Commission's 2040 target proposal, including 'the need to ensure a just and socially fair transition for all, energy affordability and security of supply, competitiveness of the EU economy, cost effectiveness and international developments and efforts undertaken to achieve the long-term objectives of the Paris Agreement and the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC)'.

Consequently, when deciding on its climate targets beyond 2030, the EU needs to communicate how it has considered its responsibility for climate change or climate action, its capability to act and its national circumstances. As a party to a treaty in its own right, the EU has a legal responsibility to pursue the achievement of the Paris Agreement temperature goal, and it shares this with over 190 countries, each with different responsibilities, capacities and national circumstances. The EU is also entitled to expect that all major emitters will prepare and implement their own NDCs based on the same Paris Agreement goal and requirements. However, there is no guarantee that the NDCs will be sufficient, collectively, to achieve the Paris temperature goal.

3.2 From an ethical perspective: equity-based estimates

While it is ultimately up to governments to come to a mutual understanding of what constitutes a fair share under the terms of an international agreement, a substantial body of scientific literature (including successive IPCC assessment reports) has considered the issue. Several papers have categorised and calculated national 'fair shares' starting from different ethical and legal principles.

Although the European Climate Law, and this report, covers all major greenhouse gases, this section (and the equity literature more generally) focuses primarily on CO_2 emissions as expressed by a carbon budget. This is primarily because:

1) CO_2 emissions are the main driver of global warming (although emissions of greenhouse gases such as methane and nitrous oxide also have a significant effect);
2) CO_2 is a long-lived gas that accumulates in the Earth's atmosphere and remains for centuries, meaning that cumulative and present-day CO_2 emissions provide a good indicator of past and present contributions to global warming, respectively.

Table 2 gives an example of fair share allocations applied to a global carbon budget (based on van den Berg et al. (2020)). A comprehensive review of this literature has been conducted by Pelz et al. (2023).

Table 2 An example of matching effort-sharing approaches to equity principles applied to a global carbon budget

Approach	Equity principle	Description
Grandfathering	Sovereignty	Allocations of carbon budgets based on current emission shares
Immediate per capita convergence	Equality	Allocation of national carbon budgets based entirely on population shares (which can be present day or projected cumulative population)
Per capita convergence	Sovereignty /equality	Allocation of national carbon budgets based on both current emission shares and population shares (i.e. a combination of grandfathering and immediate per capita convergence)
Equal cumulative per capita emissions	Equality /responsibility	Allocation of national carbon budgets based on cumulative emissions per capita in a certain period that is equal across countries. Can incorporate historical cumulative emissions (responsibility)
Ability to pay	Capability/need	Baseline national carbon budget (e.g. based on equal per capita) is modified so that those able to pay (e.g. countries with higher gross domestic product per capita) have a lower budget
Greenhouse development rights	Responsibility/capability/need	Carbon budget is reduced (compared to baseline) for countries with high historical responsibility and high capacity
Cost-optimal	Cost-effectiveness	Emissions are reduced where this is most cost-effective (e.g. marginal mitigation cost is equalised across countries - as assessed by models or marginal abatement cost curves)

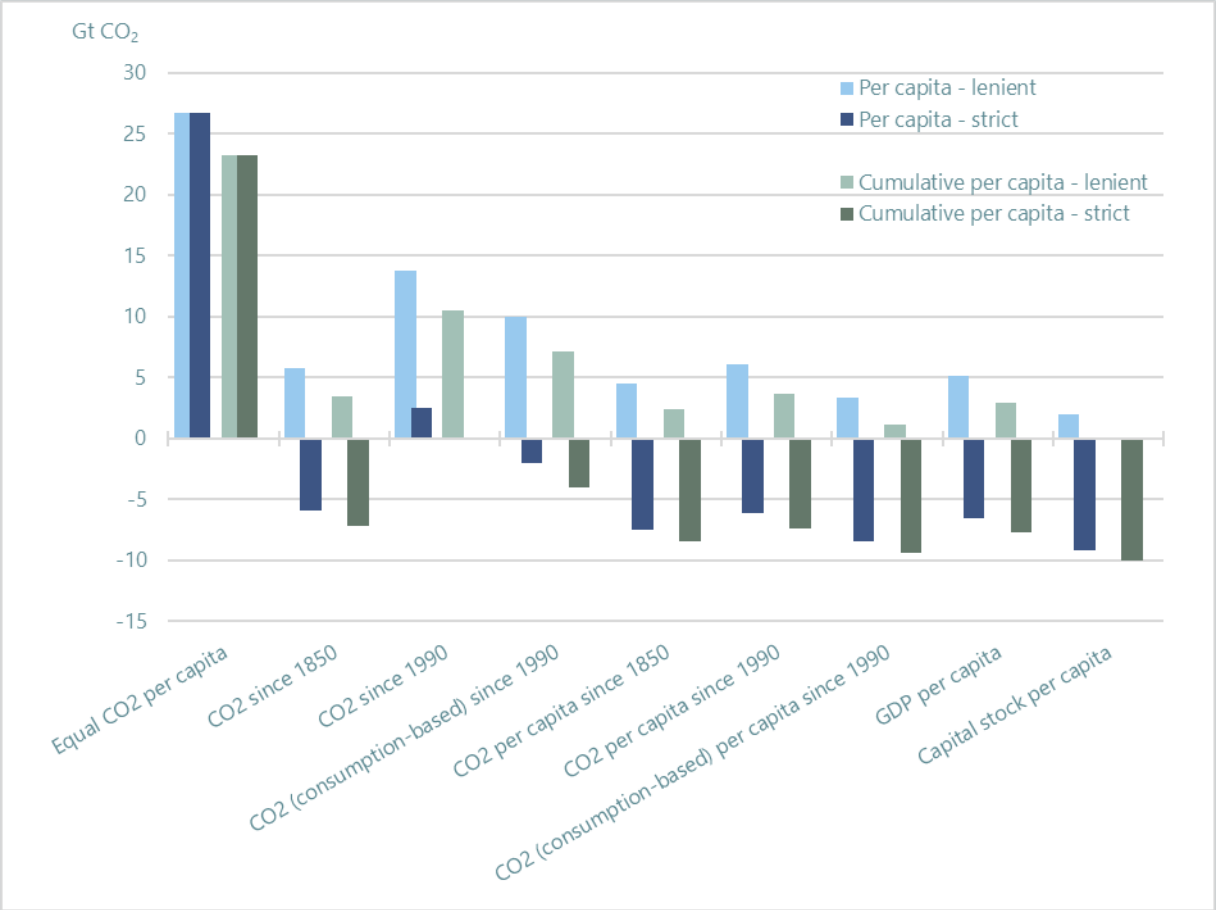
Source: modified from Table 1 in Van den Berg et al. (2020).

The approaches listed in Table 2 are neither complete (a far larger number of both principles and approaches are possible) nor universally acknowledged as means of estimating fair shares. For example, Rajamani *et al.* (2021), Dooley *et al.* (2021) and others argue that grandfathering and cost-effectiveness should not be considered a 'standard of equity', since they are not underpinned by equitable principles,

and grandfathering in particular maintains current patterns of uneven distribution of emissions. While not necessarily a fairness principle in its own right, cost-effectiveness can be a relevant consideration when choosing between different mitigation options and locations. It is also pointed out in the IPCC AR6 (IPCC, 2022g) that cost optimal global mitigation estimates allocate regional investments to occur where they will be most cost-effective in limiting global warming, but typically do not provide any indication of who would finance the investments.

Figure 3 shows estimates from Pelz et al. (2023) of the EU-27's remaining carbon budget share, informed by several different approaches (excluding cost-optimal and grandfathering – see paragraph above). These estimates found that, from the start of 2020, the highest budgets (20-27 Gt CO_2, or seven to nine times the EU's CO_2 emissions in 2021 ([11])) were associated with equal per capita allocation of emissions. Approaches based on the polluter pays principle (which is cited as a guiding principle in the European Climate Law) lead to lower budget estimates, such as those using historical emissions since 1850 or 1990. Several of these estimates are already negative. The most stringent budget estimates were found when the carbon budget was adjusted to reflect the ability to pay principle (interpreted as capital stock per capita).

Figure 3 EU fair share carbon budget estimates from 2020, according to different principles and allocation methods



([11]) Refers to CO_2 emissions from fossil fuel combustion and industrial processes.

Notes:

Lighter and darker bars demonstrate the difference that lenient and strict calculation parameters can make when estimating a fair share carbon budget. The starting point is the equal global per capita carbon budget (leftmost bars). Where the fair share budget takes account of the EU's historical responsibility, or greater capability to take climate action, this budget is reduced. The extent of the reduction in budget depends on the 'adjustment function' applied. The darker blue and green bars represent a relatively harsh adjustment function (1/x). The lighter blue and green bars represent a relatively lenient function (1/√x). The choice of adjustment function is ultimately a value judgement and is not limited to the two forms shown in this figure.

The carbon budgets in this figure were allocated in the year 2015 (chosen because it is the year of the Paris Agreement). The EU-27 budget has been reduced to account for CO_2 emissions (from fossil fuels and industry) between 2015 and 2019.

Alternative allocation years are possible. Pelz et al. also allocate the same budgets in 1990 (chosen because it is the year of the IPCC First Assessment Report). This results in a less lenient allocation. The lowest estimate is a fair share of -99 Gt CO_2 from the start of 2020, estimated on the basis of ability to pay (capital stock per capita in 1990). GDP per capita and capital stock per capita are based on data for the year 2014.

Source: Pelz et al. (2023).

The fair share carbon budget estimates considered in this section cover CO_2 emissions only. Chapter 5 of this report compares these equity-based fair share estimates against the EU decarbonisation pathways assessed in other sections, including the addition of proxy non-CO_2 emissions to the fair share carbon budget estimates to enable a like-for-like comparison.

3.3 From a practical perspective

3.3.1 Historical emissions

Since the EU is one of the earliest industrialising regions in the world, fair share estimates based on historical emissions tend to attribute a greater share of the burden to the EU, particularly when the historical responsibility is considered to begin a long time ago (e.g. 1850). As Table 3 shows, the EU-27 share of global CO_2 emissions has declined over time. Today, the EU-27 accounts for around 8% of global greenhouse gas emissions and account for around 5.6% of the global population (EDGAR, 2021) (World Bank, 2023). The declining trend in both shares is likely to continue as EU emissions fall in absolute terms and population remains broadly stable or begins to fall.

Table 3 Cumulative CO_2 emissions and shares of total global emissions of today's largest emitting economies since 1850

	Economy							
	EU-27		**United States**		**China**		**India**	
Period	Gt CO_2	Global share (%)	Gt CO_2	Global share (%)	Gt CO_2	Global share (%)	Gt CO_2	Global share (%)
1850-2021	292	17%	422	24%	249	14%	57	3%
1990-2021	110	12%	178	19%	208	22%	47	5%
2015-2021	21	8%	36	14%	73	29%	17	7%

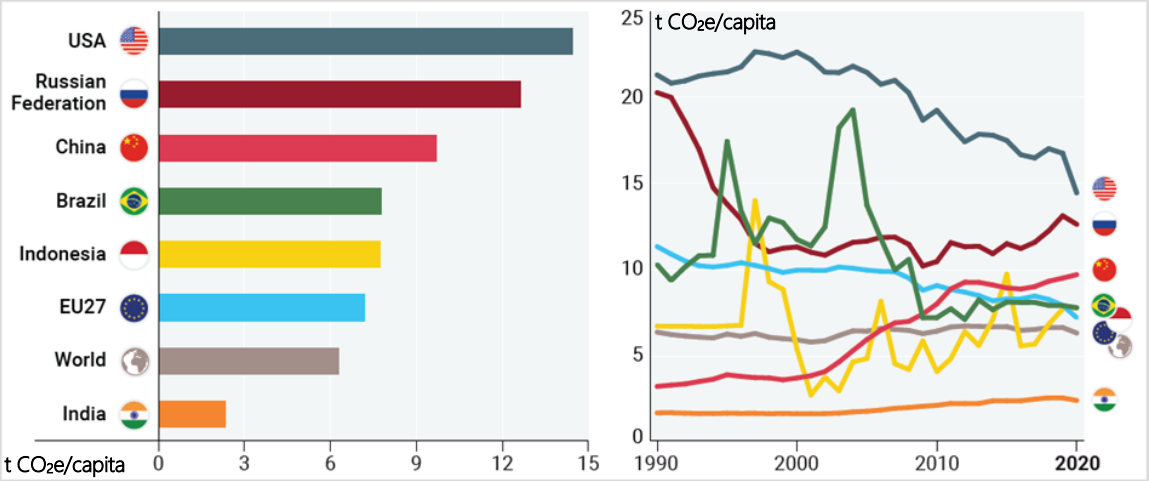
Source: Global Carbon Project (Friedlingstein et al., 2022).

3.3.2 Per capita emissions

On a per capita basis, EU-27 greenhouse gas emissions (including LULUCF) are above the global average, but below the level of several high- and middle-income economies, as Figure 4 shows. If only emissions from fossil fuels and industry are considered (i.e. excluding LULUCF), EU per capita emissions climb above those of Brazil and Indonesia, but remain below those of the United States, China and Russia (EDGAR, 2021). Although a reduction in LULUCF emissions is an important part of climate action (e.g. combatting deforestation), Pelz *et al.* (2023) and other cross-country studies focusing on equity often exclude them, since:

- attributing changes in LULUCF emissions to human activity is complicated;
- differences across countries are in large part due to different geographical circumstances (e.g. whether a country has a large forest endowment relative to its population size).

Figure 4 Per capita greenhouse gas emissions of the EU-27 and major emitting countries in 2020, and trend since 1990, including inventory-based LULUCF



Source: UNEP Emissions Gap Report (UNEP, 2022).

3.3.3 Consumption-based emissions

EU-27 emissions calculated on a consumption basis are typically higher than those calculated on a territorial basis. However, EU-27 CO_2 emissions since 1990 have declined to a similar extent on both measures, as Figure 5 (top panel) shows. Consumption-based estimates include emissions embodied in imports (e.g. upstream emissions from fossil fuel extraction and manufacturing) and deduct emissions associated with exports.

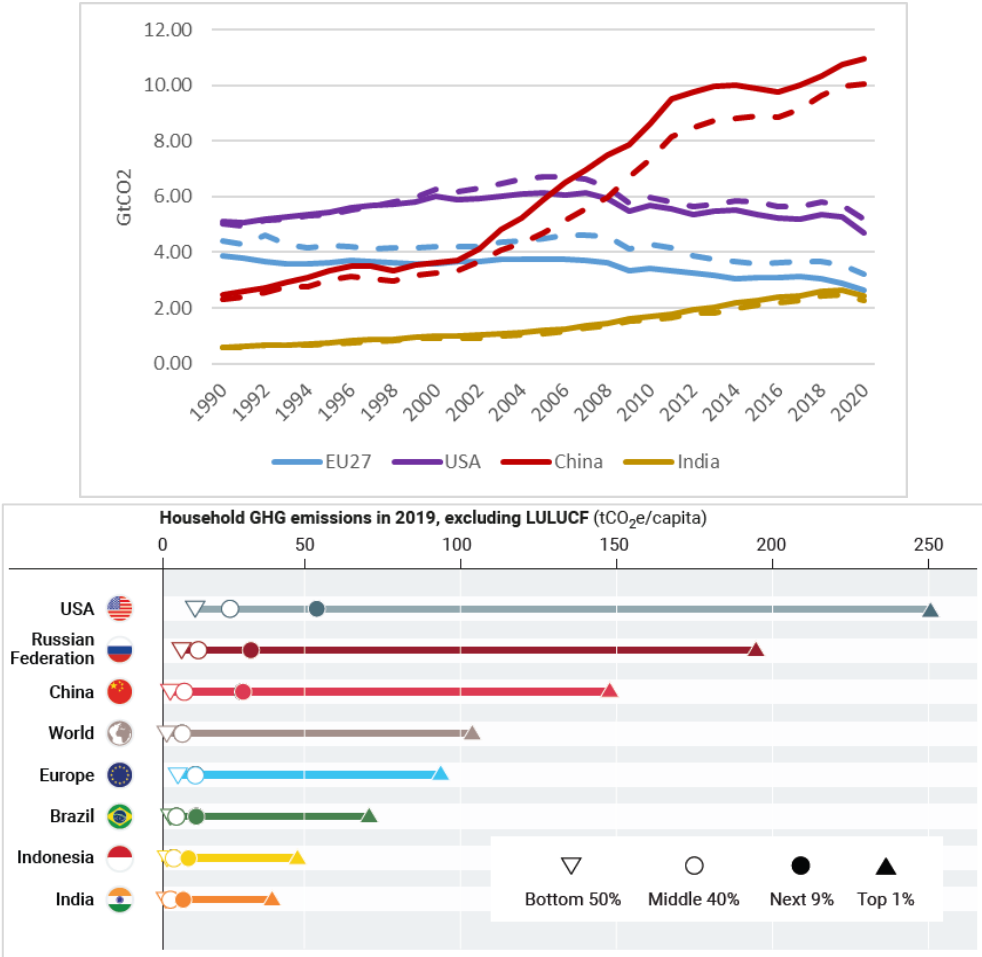
Recent literature has begun to combine consumption-based emissions with analysis of inequality, both within and between countries, highlighting that equity in climate action is not only a cross-country phenomenon – as Figure 5 (bottom panel) demonstrates. The IPCC AR6 Synthesis Report shows that the 10% of households with the highest per capita emissions accounts for 34–45% of global consumption-based household GHG emissions, while the bottom 50% accounts for 13–15%. Zheng et al. (2023) find that across multiple developed and developing countries, the carbon footprint of the highest income group has risen faster (or fallen more slowly) compared to the lowest income group ([12]).

([12]) Refers to change in consumption-based per capita emissions from 2005 to 2015, from households in the top and bottom 20% of income in each country.

The choice between territorial and consumption-based emissions for fair share estimates is not straightforward. Territorial emissions are used for official accounting and reporting (including EU and international targets). This is partly due to sovereignty (the emissions for which a country can be held responsible) and measurement issues (allocating part of another country's emissions to the EU is technically complex). In addition, consumption-based estimates can penalise countries that are active in reducing emissions in sectors involved in international trade. This is because a country would see part of its mitigation effort allocated to its export partners, while it would be penalised for a lack of similar effort from its import partners.

A number of authors have proposed alternative methods for attributing trade-related emissions (e.g. (Jakob et al., 2021) (Baumert et al., 2022)). This type of analysis may become increasingly relevant as the EU begins to implement trade-related climate policies, such as the carbon border adjustment mechanism (Beaufils et al., 2023) (Grubb et al., 2022).

Figure 5 1990-2020 trends in consumption-based CO_2 emissions and territorial emissions, and 2019 levels of consumption-based greenhouse gas emissions per capita, in major emitting countries



Note: in the top panel, solid lines represent territorial CO_2 emissions. Dashed lines represent consumption-based emissions of major emitting countries since 1990.

Sources: Global Carbon Project (Friedlingstein et al., 2022) (top). UNEP Emissions Gap Report (UNEP, 2022) (bottom).

4. Feasible climate-neutral pathways for the EU and their implications

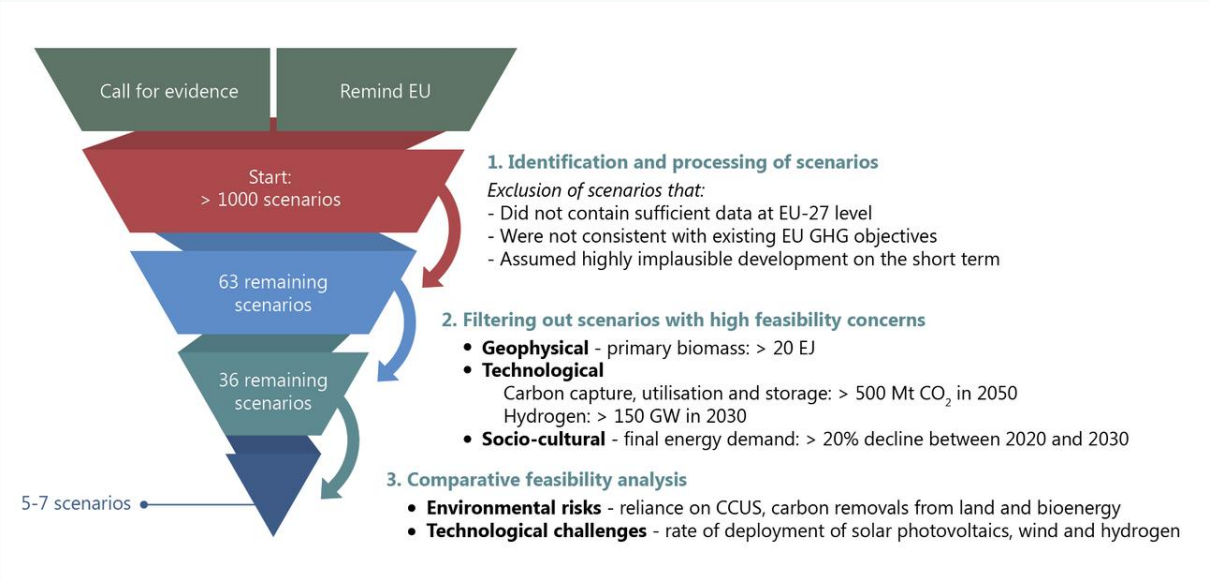
4.1 Introduction to the feasibility assessment

In the academic literature, including IPCC reports, the term 'feasibility' refers to an assessment of whether the scale of transformation implied in mitigation scenarios is within or outside the range of what could be considered feasible in the real world. To identify feasible emission reduction pathways for the EU, the Advisory Board conducted an assessment of several climate change mitigation scenarios, consisting of the following steps:

1. identification and processing of scenarios – where a set of scenarios consistent with EU climate policy objectives and limiting global warming to the 1.5°C goal was selected;
2. filtering out scenarios with high feasibility concerns – where scenarios considered highly implausible were excluded from detailed consideration;
3. comparative feasibility analysis – exploring the effect of feasibility concerns on the greenhouse gas reductions the EU can achieve by 2040, and on cumulative emissions for 2030-2050.

A visual overview of these steps is shown in Figure 6, followed by a more detailed description of each step in the following sections (Sections 4.2-4.4). The chapter concludes by summarising the overall messages on feasible mitigation pathways for the EU (Section 4.4.3). In the next chapter, the feasibility analysis is combined with the equity-based fair share analysis. Section 5.3 ends Chapter 5 by considering the implications of making different assumptions about the inclusion of international aviation and maritime transport emissions in EU targets in order to ensure that the report's recommendations are relevant to and comparable with existing and forthcoming EU mitigation assessments.

Figure 6 Overview of the methodology used to identify feasible emission reduction pathways



Source: Advisory Board (2023).

This report thus uses a three-stage approach to analysing feasibility:

1) **processing of scenarios**, including the exclusion of scenarios that assumed highly implausible short-term developments (e.g. scale-up of specific technologies between 2020 and 2030) (discussed in Section 4.2)
2) **filtering of scenarios** to exclude those with a high level of concern over feasibility in the longer term because of their exceedance of high feasibility concern thresholds (discussed in Section 4.3);
3) **comparison of feasibility risks and challenges**, which is used to narrow the target and budget range by comparing the remaining climate neutrality scenarios in a systematic way (discussed in Section 4.4).

The approach of using different feasibility levels occurs elsewhere in the literature. For example, Warszawski et al. (2021) distinguish between reasonable, challenging and speculative options for achieving 1.5°C scenarios, and Brutschin et al. (2021) use low, medium and high levels of concern. Warszawski et al. (2021) conclude that a challenging deployment of at least some options is needed in any 1.5°C-consistent scenario.

The analysis in this chapter was conducted by the Advisory Board with the assistance of external researchers with expertise in managing the scenario database and processing the scenarios. They also proposed feasibility criteria, building on the findings of Brutschin *et al.* (2021) and other authors. Both of these exercises are documented in Byers *et al.* (2023). The Advisory Board made use of this material to conduct its own analysis of scenarios described in this chapter, which includes making use of the feasibility indicators and thresholds proposed in Byers *et al.* (2023).

4.2 Step 1: identification and processing of scenarios

4.2.1 Collecting scenario data

In October 2022, the Advisory Board issued a public call inviting the wider research community to submit emissions scenario data to support its task of providing advice on targets and indicative budgets for EU greenhouse gas emissions in 2030-2050. Over 1,000 scenarios from global-, regional- and national-level models were submitted, including some scenarios from the IPCC AR6 scenarios database, modelling inter-comparison projects and scenarios submitted individually by modelling teams ([13]).

The analysis of the initial set of submissions showed that several of the 1.5°C-consistent pathways reaching climate neutrality in 2050 and achieving deep emission reductions in 2040 featured immediate, sustained emission reductions from 2020 that may not be plausible in the short term and considerably exceed the current 2030 target of reducing EU emissions by 55% in 2030 relative to 1990 levels (or 57% including the enhanced LULUCF target, as discussed in Section 1.1). Recent significant global developments could have potential impacts on global and EU emission trajectories, including the COVID-19 pandemic and the 2022 energy crisis caused by Russia's invasion of Ukraine. The Advisory Board therefore decided to look for additional, more recent, scenarios that account for the impacts of these developments and have a trajectory that is more closely aligned with the current 55% reduction by 2030 objective. New scenarios from recent research using version 3.2 of the Remind-EU (Remind 3.2) model were submitted and included in the database and analysis (these are described in Byers et al.

([13]) This database is available online (https://data.ece.iiasa.ac.at/eu-climate-advisory-board/) and is hosted by the International Institute for Applied Systems Analysis.

(2023)). These scenarios explore high-ambition decarbonisation pathways for the EU constrained in the near term by recent developments, as well as inertia in policy processes and technology development.

4.2.2 Processing scenarios

All scenarios in the database were checked for data quality and vetted for plausibility. Scenarios were rescaled to EU-27 resolution where necessary and assessed for consistency (at global level) with limiting global warming to 1.5°C with no or only a low overshoot. Lastly, scenarios were checked for consistency with the EU 2030 target and 2050 objective.

Scenarios were excluded that:

- were considered to be highly implausible in the short term when compared against historical data and near-term projections;
- did not contain sufficient regional information to derive results at EU-27 level;
- were not consistent with EU and global climate goals.

This scenario processing is summarised in Table 4. It was performed with support from the International Institute for Applied Systems Analysis (Byers et al., 2023).

Table 4 Summary of scenario processing

Step	Purpose	Number of scenarios after step
Scenarios considered		1,124
Quality control and data processing	Checks for: • file format • structure of the dataset • submitted variables and units • model and scenario names • time horizon • regional designation	1,062
Vetting	• Baseline checks (against energy and emissions data for 2019) • Near-term plausibility checks (for scenarios that are highly implausible, e.g. regarding the scale-up of key technologies over 2020-2030)	492
Consistency with 1.5°C at global level	• Identification of scenarios consistent with the 1.5°C (> 50% chance, 'C1') category of IPCC AR6 ([a])	86
Rescaling and harmonisation	• Where possible, rescaling of scenarios not reporting for the EU-27 region (e.g. models reporting a well-defined 'western Europe' region were rescaled to cover the EU-27) • Harmonisation of all scenarios, i.e. setting historical emissions to the same levels up to and including the year 2019.	
Consistency with EU targets	• Consistency with achieving a reduction of at least 55% by 2030 compared to 1990 and climate neutrality by 2050	63

Note:

([a]) See, for example, Table SPM.2 in IPCC (2022i) for details of these categories.

Source: Advisory Board (2023).

Regarding consistency with EU climate goals, the 63 scenarios that passed the process described in Table 4 had the following characteristics:

- **by 2030** net greenhouse gas emissions of between 56% and 78% below 1990 levels (including emissions from intra-EU aviation and maritime transport);
- **by 2050** net greenhouse gas emissions (including intra-EU bunkers) of between -1,478 Mt CO_2e and +186Mt CO_2e in 2050; 48 of these scenarios had net emissions below zero.

4.3 Step 2: filtering out scenarios with high feasibility concerns

In this analysis, the 63 scenarios that were consistent with the EU climate goals and limiting global warming to 1.5°C were filtered and compared against thresholds for high feasibility concerns derived from other lines of evidence.

All scenarios present different sets of feasibility issues, since each one provides a different vision of the economic and societal transformation needed to achieve climate neutrality and limit global warming to 1.5°C. Assessing these issues in a systematic way therefore requires a multidimensional framework. The mitigation scenarios were evaluated against the following dimensions of feasibility:

1. geophysical
2. technological
3. sociocultural.

For each of these dimensions, at least one indicator and high concern threshold was identified. Scenarios exceeding these thresholds (e.g. where global bioenergy demand exceeds 240 EJ per year) were considered infeasible and excluded from further assessment. The indicators and thresholds are listed in Table 5 (see Annex 1 for more detailed tables describing the feasibility indicators and their rationale).

Filtering the scenarios on this basis resulted in identifying a smaller set of 36 'filtered' scenarios.

Table 5 Feasibility indicators and 'high' thresholds used for scenario filtering

Level	Dimension	Indicator	Threshold	Source
Global	Geophysical: sustainability	Primary bioenergy use	240 EJ/year	Based on the estimates in Creutzig et al. (2015) and Frank et al. (2021)
	Technological: geological storage capacity	CO_2 sequestration	8.6 Gt CO_2/year	Based on calculations from Luderer et al. (2022), assuming 0.1% of regional technical potential and Grant et al. (2022)
EU-27	Geophysical: sustainability	Primary energy from biomass	20 EJ/year in 2050	Based on the literature overview from other reports and assessments. (JRC, 2019) (Material Economics, 2021)
	Technological: deployment potential	Carbon capture utilisation and storage	500 Mt CO_2/year	Based on Holz et al. (2021) and the impact assessment of Commission communication on sustainable carbon cycles (EC, 2021a) The impact of lower deployment levels is considered in the next section
	Technological	Hydrogen production capacity	150 GW in 2030	Odenweller et al. (2022) give an estimate of 50 GW for green hydrogen based on historical growth rates for wind and solar power The REPowerEU target is equivalent to 100 GW (EC, 2022c).

				An upper bound of 50% more than that (150 GW) is considered
	Sociocultural	Final energy demand decline	20% decline between 2020 and 2030	Based on the global threshold derived in Brutschin et al. (2021)

Note: the thresholds and rationale are from Byers *et al.* (2023). The table reproduces the underlying source and rationale from that study.

Source: Advisory Board (2023).

4.4 Step 3: comparative feasibility analysis

The exclusion of scenarios with a high feasibility concern left 36 'filtered' scenarios with a wide range of emission reduction outcomes post 2030.

These scenarios were compared in a second round of feasibility analysis that explored how the scenarios perform against stricter feasibility criteria, with a particular focus on the implications for EU emission reductions in the post-2030 period.

The additional criteria cover environmental risks and technology scale-up challenges.

- The assessment of **environmental risks** considered the extent to which scenarios count on large-scale uses of:
  - carbon capture, utilisation and storage (CCUS) from fossil fuels, bioenergy and industry combined (including direct air capture),
  - carbon removals from the land sink,
  - bioenergy.
- The assessment of **technological deployment challenges** considered the implications of conservative estimates for the deployment potential of:
  - solar energy (photovoltaic),
  - wind energy,
  - hydrogen technologies.

The deployment levels used to examine these risks and challenges are shown in Table 6. Although each level is based on the literature, there is no 'true' level at which deployment becomes a risk or challenge. Each deployment issue is qualitatively different and needs to be considered on its own merits. 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 **socio-economic dimension of feasibility** is not included in this section's quantitative analysis because of the difficulty in identifying relevant risk and challenge levels that can be compared with scenario results. The socioeconomic aspects of the transition to climate neutrality are discussed further in Section 7.8 on economic implications and costs and in Section 7.9 on synergies and trade-offs with sustainable development.

Table 6 Environmental risks and technological deployment challenges

Technology	Risk/challenge level	Source
Environmental risks		
CCUS (from fossil fuels, bioenergy, industry or direct air capture)	425 Mt CO_2 annually by 2050. This represents the highest annual capture level in the study consulted	Holz et al. (2021)
Carbon removals from the land sink	A net sink of 400 Mt CO_2 per year by 2050 This is lower than several estimates in the literature ([a]), but is still higher than the current level of removals (210 Mt CO_2) and the 2030 objective (310 Mt CO_2). Furthermore, the LULUCF sink has been declining for around a decade, and it may be further impacted by climate change as well as human activity	Pilli et al. (2022)
Bioenergy	9 EJ of annual primary bioenergy use by 2050	Material Economics (2021)
Technological deployment challenges		
Solar photovoltaics	Installed capacity of 900 GW by 2030, assuming a 20% annual growth rate (historical growth rates of 25% would imply a level of 1245 GW) The implications of reaching (or missing) the 600 GW target in the European Commission's REPowerEU plan are also examined.	Byers et al. (2023) EC, 2022b
Wind power	Installed capacity of 623 GW by 2030, assuming a 15% annual growth rate (historical growth rates of 20% would imply a level of 875 GW) The implications of reaching (or missing) the 510 GW target in the European Commission's REPowerEU plan are also examined.	Byers et al. (2023) EC, 2022b
Hydrogen	Installed capacity of 50 GW by 2030 The implications of reaching (or missing) the 10 Mt of hydrogen (assumed equivalent to 100 GW) target in the European Commission's REPowerEU plan are also examined.	Odenweller et al. (2022) ([b])([c]) EC, 2022b

Notes:

([a]) For example, Nabuurs *et al.* (2017) and Böttcher and Hennenberg (2021)

([b]) For comparison with model results, this threshold is converted to 0.63 EJ of hydrogen production, which assumes a 5,000 hour annual load factor and 70% efficiency.

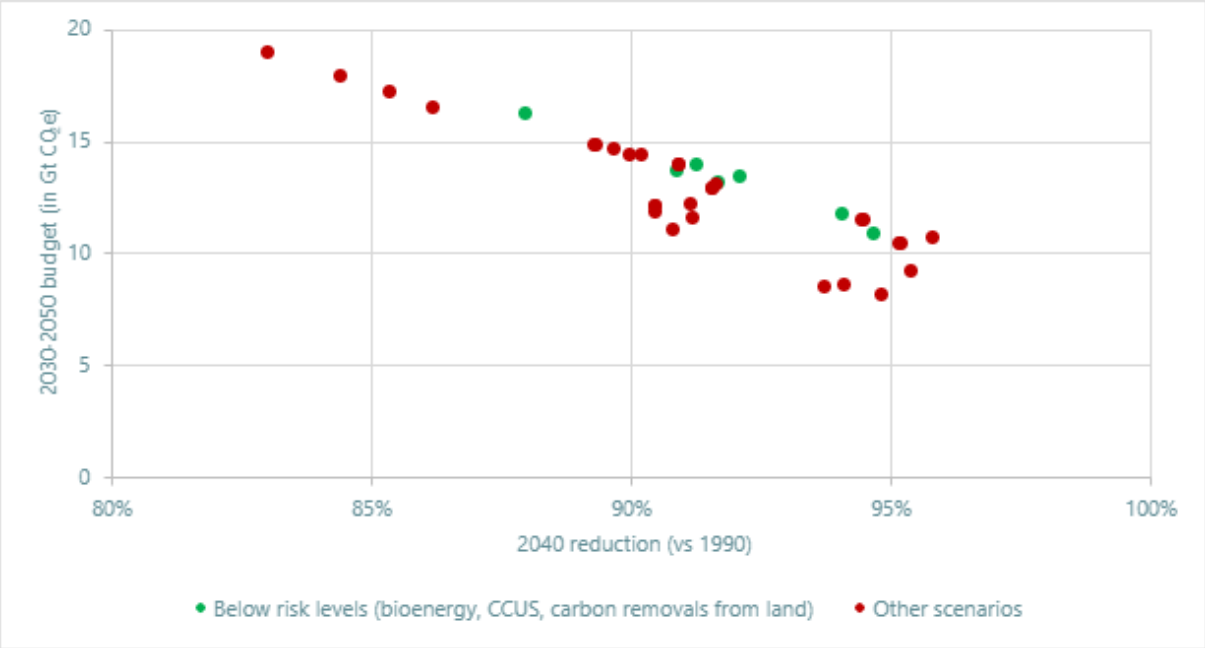
([c]) This is explained in brief in a note by the European Parliament Think Tank (EP, 2022).

Source: Advisory Board (2023)

4.4.1 Environmental risks

Seven of the filtered scenarios maintain deployment of **CCUS**, **bioenergy** and expansion of the **land sink** below the risk levels identified. They achieve emission reductions by 2040 of 88%-95% below 1990 levels, with all but one reducing emissions by more than 90%. All scenarios with a 2030-2050 budget below 10 Gt CO_2e or 2040 emissions above 95% exceed one or more of the risk levels.

Figure 7 Implications of CCUS deployment, bioenergy deployment and size of land sink on post-2030 emissions



Source: Advisory Board (2023)

Table 7 summarises how the deployment of these mitigation options varies among the scenarios. In general, scenarios with the highest use of bioenergy also have the highest levels of CCUS (e.g. through greater deployment of BECCS). However, this is not always the case, with some scenarios deploying more CCS without bioenergy (e.g. fossil CCS or DACCS), or using relatively more biomass in other applications (e.g. in transport). Scenarios with the lowest bioenergy use have the highest land sink.

Table 7 Deployment of CCUS and bioenergy, and expansion of the land sink in filtered scenarios, compared to identified environmental risk levels

Environmental risk	**Deployment in 2050** across filtered scenarios	**Risk level**	**Number of scenarios exceeding risk level ([a])** (out of 36)
CCUS	127-490 Mt CO_2 captured per year	425 Mt CO_2	19
Bioenergy	5-13 EJ per year	9 EJ	22
Carbon removals from the land sink	272-674 Mt CO_2	400 Mt CO_2	7

Note:

([a]) Some scenarios exceed more than one risk level. Seven scenarios exceed none.

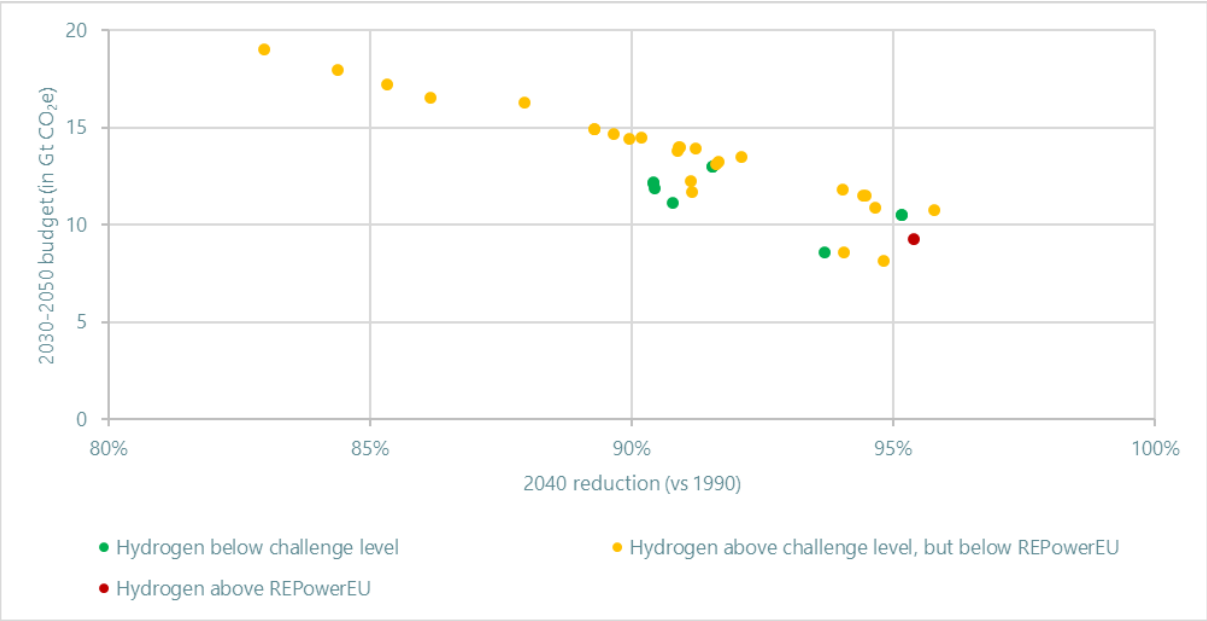
Source: European Scientific Advisory Board on Climate Change, 2023

The seven scenarios that avoid all the environmental risk levels identified come from a set of scenarios from the Remind 3.2 model, in which a limit of 7.5 EJ is placed on bioenergy deployment.

4.4.2 Technological deployment challenges

All but nine scenarios count on producing more **hydrogen** than the challenge level of 50 GW by 2030 (as shown in Figure 8). Most scenarios (26 – the yellow dots in Figure 8) deploy more than this but only one deploys more than 100 GW (equivalent to the 10 Mt REPowerEU target). Hydrogen production expands beyond 2030 in all filtered scenarios, and by 2040 the amount of hydrogen produced is equivalent to between 5% and 24% of final energy demand, indicating that scaling up production in the short and medium term could be an important element of a strategy to deliver climate neutrality.

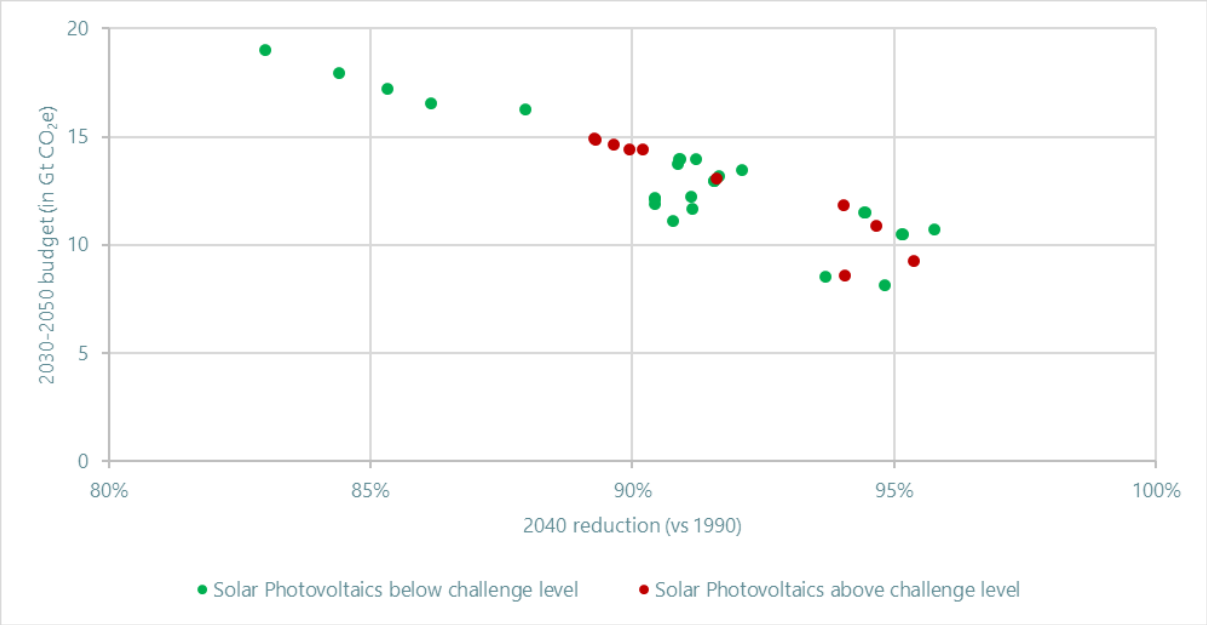
Figure 8 Implications of hydrogen deployment challenge level and REPowerEU target on 2030-2050 emission reductions



Source: Advisory Board (2023)

All scenarios except one maintain **wind** deployment within the identified challenge level (the other exceeds it by 18 GW). Ten scenarios exceed the challenge level for **solar PV** deployment, as Figure 9 shows.

Figure 9 Implications of solar photovoltaic (PV) deployment challenge level on 2030-2050 emission reductions



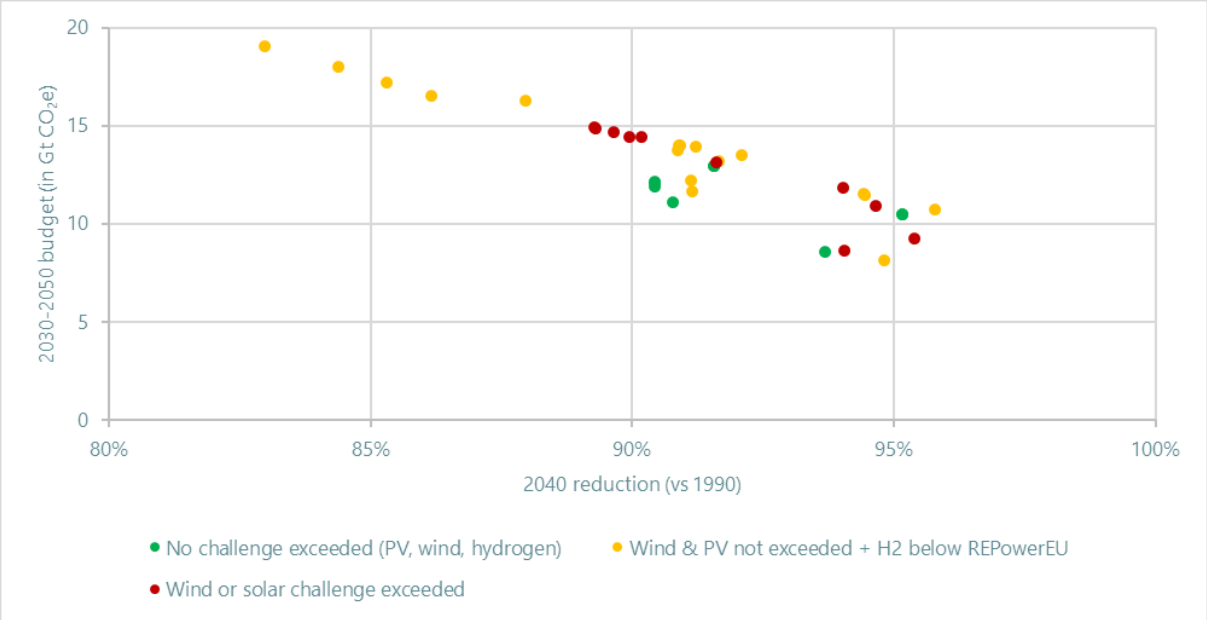
Note: some scenarios report wind and solar generation, but not capacity. In these cases, capacity has been estimated using the same load factor as the other scenarios.

Source: Advisory Board (2023)

Compared with the European Commission's REPowerEU scenario (EC, 2022a), the scenarios assessed in this report tend to have greater deployment of solar photovoltaics and lower deployment of wind energy. All but six scenarios deploy more solar photovoltaics by 2030 than the 600 GW REPowerEU target, but only six scenarios deploy more wind by 2030 than the 510 GW estimate of the REPowerEU scenario (EC, 2022a).

The **combined effect of the technological deployment challenges** is shown in Figure 10. Nine scenarios do not exceed any of the identified challenge levels for solar photovoltaics, wind power or hydrogen, while achieving 2040 emission reductions of 90–95%. A larger number of scenarios remain within the challenge level for wind and solar photovoltaics, and within the 100 GW hydrogen target of REPowerEU (but above the 5 GW challenge level). Ten scenarios exceeding the challenge level for solar photovoltaics or wind power. Nine of these exceed only the 900 GW challenge level for solar PV, eight by less than 50W and one by over 300 GW. Only scenario exceeds the challenge level for wind (by 18 GW).

Figure 10 Implications of solar photovoltaic (PV), wind and hydrogen (H_2) production challenge levels on 2030-2050 emission reductions



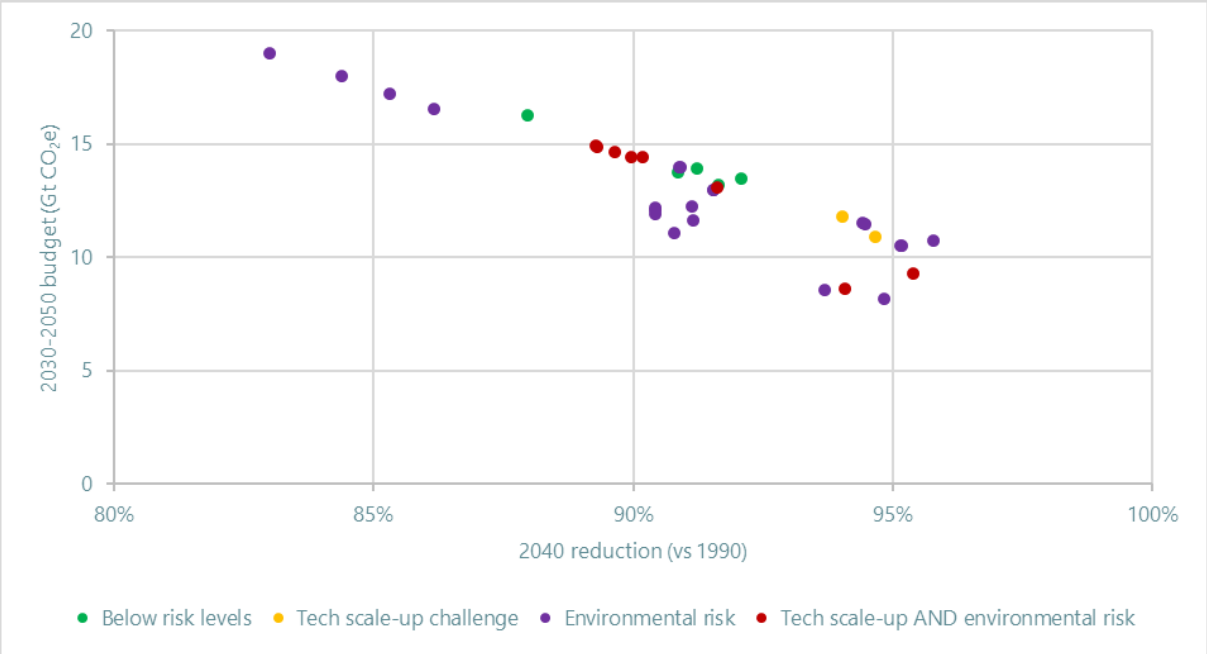
Note: PV, photovoltaics.

Source: Advisory Board (2023)

Considering the combined **environmental risks and technological deployment challenges**, Figure 11 shows four groups of scenarios.

- **No risk or challenge level exceeded (green)**. Five 'moderate' scenarios, achieving 2040 emission reductions of 88%-92%, remain within both the environmental risk and technological deployment challenge bounds (although only when the hydrogen challenge is relaxed to the 10 Mt of the REPowerEU target).
- **Technological scale-up challenge (yellow)**. Two scenarios achieve emission reductions of 94-95% by 2040. They avoid greater reliance on the environmental risk options but rely on the rapid scaling up of solar photovoltaics which (slightly) exceeds the challenge level. In these two scenarios, the installed capacity of solar power exceeds the 900 GW challenge level by less than 50 GW, and remains below the 1,245 GW that would be achieved if the historical growth rate were continued (+25% annually).
- **Environmental risk (purple)**. Twenty-one scenarios have greater reliance on CCUS, bioenergy or enhancing the land sink. They avoid the higher levels of scale-up for solar photovoltaic, wind power and hydrogen.
- **Combined technological scale-up challenge and environmental risk (red).** Eight scenarios deploy CCUS, bioenergy or land sink expansion beyond the identified risk levels, while also deploying solar photovoltaic, wind power or hydrogen above the challenge levels identified.

Figure 11 Implications of environmental precautions and technological deployment challenges



Note: for the technological scale-up challenges, this figure uses the 10 Mt hydrogen target based on REPowerEU.

Source: Advisory Board (2023)

4.4.3 Implications for EU climate targets before 2040

Table 8 and Figure 12 summarise the emission reduction profile over the period 2020-2050 for scenarios that achieve an 88–95% reduction by 2040 below 1990 levels. They distinguish between scenarios that achieve 2030 reductions close to current EU targets (meaning 56-60%) and more ambitious scenarios (above a 60% reduction by 2030). This indicates the following.

- **Climate neutrality is achieved in both types of scenarios.** This confirms that it is possible to achieve climate neutrality from a 2030 starting point of achieving the 55% target and the goals of the Fit for 55 package.
- **The lowest greenhouse gas budgets are achieved only in the scenarios with greatest short-term ambition.** The smallest budget (of 32 Gt CO_2e over the period 2020-2050) is lower, by more than 20%, than the smallest budget in the scenarios where short-term reductions are more constrained.

In addition, **the scenarios with emission reductions by 2030 below 60% include all those that include short-term constraints, and those that remain within identified environmental risk levels.** Some scenarios assume inertia in investment and policy development up to 2030 (as discussed in Section 4.2.1), and seven scenarios deploy CCUS, bioenergy and land sink enhancement remain within identified environmental risk levels (discussed in the previous section (4.4.1)). The scenarios that have either feature (or both) have 2030 emission reductions within the 56-60% range.

Scenarios with emission reductions well beyond 55% considerably decrease the EU's cumulative emissions until 2050, and thus they increase the fairness of the EU's contribution to global mitigation of climate change.

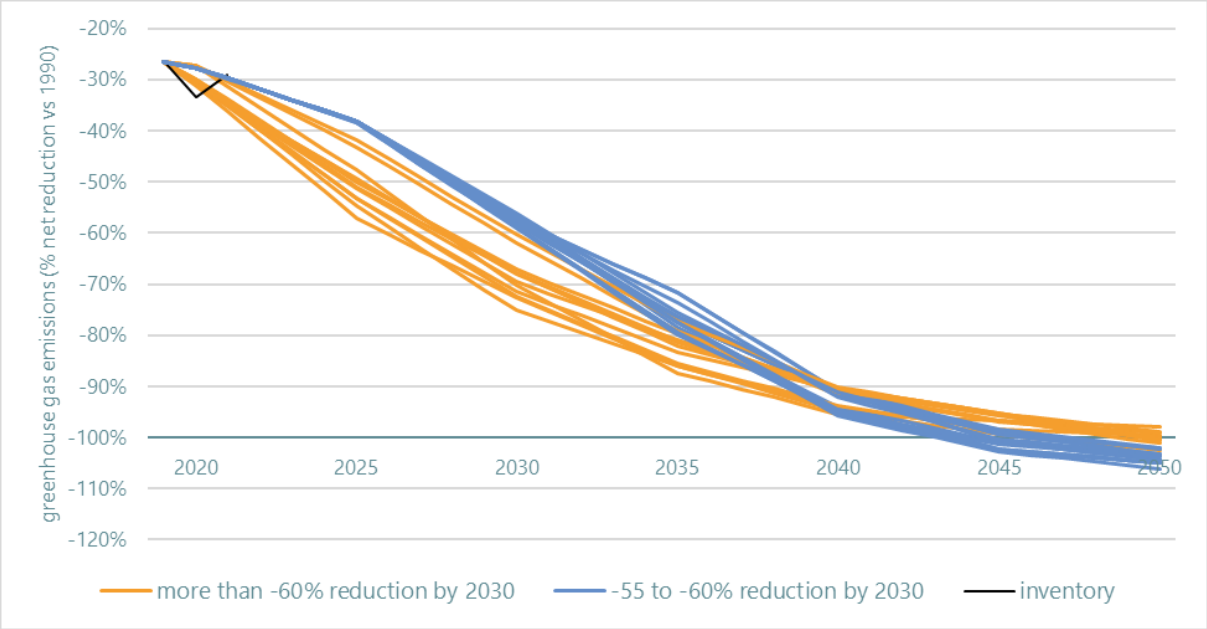
Table 8 Emissions profile over time for scenarios with 88–95% reductions by 2040

Greenhouse gas emission reduction by 2030 (% below 1990)	Greenhouse gas emission reduction below 1990 levels (%)				Cumulative greenhouse gas emissions (Gt CO_2e)		
	2030	2035	2040	2050	2020-2029	2030-2050	2020-2050
56-60%	56-60%	71-80%	88-95%	99-105%	29-30	10-16	41-44
Above 60%	60-75%	77-87%	90-95%	99-104%	24-29	8-15	32-44

Note: the scenarios with 2030 reductions of 56-60% include all 7 scenarios that remain within environmental risk levels identified in the feasibility analysis.

Source: Advisory Board (2023).

Figure 12 Emissions profile over time for scenarios with 88–95% emission reductions by 2040



Source: Advisory Board (2023).

4.5 Conclusions on feasible pathways: narrowing the target and budget range for post-2030

This analysis has highlighted potential feasibility risks and challenges in most of the 1.5°C-consistent decarbonisation scenarios examined. While these risks and challenges vary between scenarios, the analysis identified:

- pathways that are most reliant on bioenergy and/or carbon removals (from land or CCS);
- pathways that have more balanced deployment of these options and greater scale-up of non-biomass renewable energy technologies.

Chapter 7 discusses how pathways that are more successful in promoting sustainable lifestyles and lowering energy demand can reduce some of these challenges.

The risks identified in this analysis allow us to draw the following conclusions about the potential ranges for the EU's 2040 emission reduction target and accompanying greenhouse gas budget.

- The four scenarios with over 95% emission reduction by 2040 fall into the high environmental risk category.
- The five scenarios that stay within the environmental risk and high technology scale-up challenge levels identified achieve 2040 reductions of 88-92% below 1990. However, scenarios achieving up to 95% reduction remain within environmental risk levels. If the technological deployment challenges of scaling-up renewable energy could be overcome (in particular hydrogen and of solar photovoltaic, according to the scenarios assessed in this section), the potential reduction range would expand to an upper level of 95% while remaining beneath the environmental risk levels. All but one of the scenarios that remain within the environmental risk levels have 2040 emission reductions of at least 90% compared to 1990 levels.
- The four scenarios with the lowest 2040 ambition fall into the high environmental risk category. This does not mean that lowering climate ambition per se increases the risks analysed in this section, but it does demonstrate that there are 'lose–lose' scenarios that have higher challenges and risks without the benefits of lower emissions.

The societal acceptability of a target level is contingent on considerations broader than those explored in this feasibility analysis, including but not limited to, its economic implications (discussed in Section 7.8) and synergies and trade-offs with sustainable development (discussed in Section 7.9). The determination of a minimum acceptable level of ambition requires consideration of other factors, such as political and societal commitment to climate action, questions of fairness and international effort sharing.

Assessing the robustness of the results, the Advisory Board notes that 2040 emissions are reduced by over 90% compared to 1990 levels in six of the seven scenarios that stay within the environmental risk boundaries identified (and in four of the five scenarios that stay within both the levels of environmental risk identified and the high technology scale-up challenge).

Based on the preceding analysis, the Advisory Board considers that a suitable range of feasible scenarios for consideration would imply the following:

- an emission reduction target directly derived from the feasibility risks and challenges would lie between 88% and 92% (corresponding to a budget of between 13 and 16 Gt CO_2e);
- a target above 90% is possible, and an upper bound of 95% could be achieved if the challenges of deploying renewable energy can be overcome. In these cases, greenhouse gas budgets for 2030–2050 would range from 11 to 14 Gt CO_2e.

Table 9 Implied EU greenhouse gas emission budgets for 2030-2050 and 2040 emission reductions for different ranges of scenarios

Range of scenarios	Number of scenarios	Implied range for an EU budget for 2030-2050 ([a]) (Gt CO_2e)	Implied range for an EU reduction target for 2040 (% reduction vs. 1990)
All scenarios assessed	36	8-19	83-96%
• within environmental risk levels (less reliance on CCS, LULUCF, bioenergy)	7	11-16	88-95% ([b])
• within environmental risk levels **and** technological deployment challenge levels (less rapid scale-up of non-biomass renewables)	5	13-16	88-92% ([c])

Notes:

([a]) Data including intra-EU bunkers only.

([b]) Only one scenario features emission reductions of less than 90%, the remaining six scenarios are above 90%.

([c]) Only one scenario features emission reductions of less than 90%, the remaining four scenarios are above 90%.

Source: Advisory Board (2023).

5. Towards a feasible, fair and science-based climate target and greenhouse gas budget for the EU

5.1 Comparing feasible emission reduction pathways with equity-based fair share estimates

This section compares the equity-based fair share estimates (introduced in Chapter 3 of this report) against the pathways examined in the feasibility analysis in Chapter 4.

To **ensure a like-for-like comparison** between the fair share estimates and emission reduction scenarios, several adjustments need to be made. These are listed in Table 10.

Table 10 Differences in scope between fair share estimates and climate neutrality scenarios

Issue	Treatment in fair share estimates (Chapter 3)	Treatment in climate-neutral pathways (Chapter 4)	Adjustment to ensure comparability
Timing	From January 2020: the start of the remaining global carbon budget in IPCC AR6	Analysis in Chapter 4 focuses on post-2030 period, but results are available from 2020	Whole 2020-2050 period is considered
Non-CO_2 emissions	Not explicitly considered, since fair shares are based on allocation of the remaining global carbon budget	Scenarios consider all relevant greenhouse gases	Non-CO_2 emissions from the most ambitious scenario are added to the fair share carbon budget estimates
Aviation and maritime emissions	All international aviation and maritime emissions are included	For most of this report, only intra-EU aviation and maritime emissions are included. However, results including all emissions are available	All emissions are included in the fair share comparison
Land sink: inclusion of the fraction of the sink caused by 'indirect effects' of human-induced environmental change ([a])	Not included: this sink is not included in the remaining global carbon budget, and fair shares derived from it	Included: this sink is included in national greenhouse gas inventories. It is therefore included in the scenario analysis to allow like-for-like comparison between the scenarios and EU official emissions and targets	An estimate of the indirect fraction of the land sink is added back onto the scenario emissions. This is 250 Mt CO_2 per year, based on Grassi et al. (2023)

Note:

([a]) This difference relates to the fact that aggregate global net emissions from inventories count emissions and removals from land in a different way from the IPCC global carbon budget. Greenhouse gas inventories consider the entire land sink to be anthropogenic, whereas the IPCC AR6 (and science more generally) considers the indirect fraction to be natural (and excludes it from the total *anthropogenic* sink used to

estimate the remaining global budget). It would therefore not be appropriate to ignore this scope difference when comparing official inventories and targets for the global carbon budget. See, for example, Cross-Chapter Box 3 in IPCC (2022i) and Grassi et al. (2023).

Source: Advisory Board (2023).

Shortfall between feasible reductions and fair share estimates

When the scenario with a 95% reduction by 2040 (from Chapter 4) is compared against the fair share estimates, a shortfall is identified, as Table 11 shows. There is no objectively true value for this shortfall, since any fair share estimate represents a value judgement, and a number of simplifying assumptions were made in estimating it. Nevertheless, none of the 36 'filtered' scenarios examined in Chapter 4 were found to overlap with the range of equity-based fair share estimates.

Table 11 Comparison between emission reduction pathways and equity-based fair shares: cumulative greenhouse gas emissions

	95% emission reduction pathway ([a])	Equity-based fair shares	
		Highest estimate	Lowest estimate
Period	*Gt CO_2e*	*Gt CO_2e*	*Gt CO_2e*
2030-2050			
Cumulative net greenhouse gas emissions (including intra-EU aviation and maritime)	11	N/A	N/A
2020-2050			
• Net CO_2 emissions: GHG inventory basis (including all aviation and maritime)	30	27	-99
• Inventory scope adjustment (land sink) ([b])	8	N/A	N/A
• Non-CO_2 emissions ([c])	14	14	14
Total greenhouse gas emissions	**52**	**40**	**-85**

Notes:

([a]) Figures in this column refer to the scenario achieving a 95% emission reduction by 2030 without exceeding environmental risk levels identified in Chapter 4.

([b]) An adjustment made to the emission reduction pathway due to differences in treatment of the land sink. See Table 10 for details.

([c]) The fair share estimates are assumed to have the same non-CO_2 emissions profile as the most ambitious scenario emerging from the feasibility analysis in Chapter 4.

Source: Advisory Board (2023).

Feasibility

The Advisory Board's analysis found that domestic reductions of at least 88% and up to 92% can be achieved, taking environmental risks and technology scale-up challenges into account. These correspond to an EU greenhouse gas budget of 13-16 Gt CO_2e for 2030-2050.

It also found that reductions of up to 95% could be achieved within the environmental risk levels identified, if challenges in the deployment of renewable energy can be overcome, further reducing the greenhouse gas budget to 11 Gt CO_2e. All but one of these scenarios reduced emissions by at least 90% (corresponding to a budget of up to 14 Gt CO_2e).

Fairness

The lowest feasible budget estimates from the scenarios assessed in this report are still higher than the equal per capita emissions allocations and other fair share estimates based on principles such as 'polluter pays' and 'ability to pay'. Whichever ethical principle is considered, there is a gap between the feasibility estimates and fair share estimates. This indicates that the EU should be looking to address this shortfall as part of its commitment to the Paris Agreement temperature goal. Taking the quantification of an EU fair share into account, the Advisory Board considers that the minimum reduction for 2040 should be 90% below the 1990 level, with a corresponding greenhouse gas budget of under 14 Gt CO_2e for 2030-2050.

Setting a minimum target and budget at this level should be feasible, since four out of the five scenarios that stay within the environmental risk levels and technology scale-up challenges identified have lower greenhouse gas emissions than this over 2030-2050.

Table 12 Post-2030 greenhouse gas emissions from feasibility and fair share perspectives

	2040 reduction	2030-2050 budget
Range informed by feasibility Noting that achieving the more ambitious end of this range implies challenging levels of energy technology scale-up.	88-95%	11-16 Gt CO_2e
Minimum ambition informed by fair share estimates Noting that emissions in the climate neutrality pathways exceed equity-based fair share estimates	At least 90%	Up to 14 Gt CO_2e

Source: Advisory Board (2023).

5.2 Recommendations for a 2040 target and accompanying greenhouse gas budget for 2030-2050

In light of the evidence summarised in the previous section, **the Advisory Board recommends a 2040 emission reduction range of 90–95% compared to 1990, corresponding to a greenhouse gas budget of 11-14 Gt CO_2e over the period 2030-2050.**

Pursuing the more ambitious end of this range improves the fairness of the EU's contribution. Ambitious domestic emission reductions need to be complemented by measures outside the EU in order to achieve a fair contribution to climate change mitigation.

To deliver a contribution to the achievement of the Paris Agreement that is both fair and consistent with the physical science of climate change, the EU must therefore do the following.

1. **Aim for the highest ambition in domestic emission reductions and sustainable carbon removals**, while accounting for feasibility constraints, environmental risks and technological deployment challenges.
2. **Contribute to direct emission reductions outside the EU**. This action is necessary in the light of the shortfall identified between the feasible pathways and the fair share estimates. This report

does not provide advice on the options available for doing this, or on the adequacy of the EU's current international collaboration on climate action. As a first step, the Advisory Board notes the importance of the EU communicating how it considers its contribution to be fair and ambitious, when the post-2030 target is submitted as an NDC under the Paris Agreement.

3. **Pursue sustainable net-negative emissions after 2050**, as required under the European Climate Law, which would help manage temporary temperature overshoots and support the international balance of greenhouse gas emissions.

Figure 13 Comparison of feasible 1.5°C pathways with equity-based fair share estimates (2020-2050)

Notes:

The figure shows the period 2020-2050 rather than 2030-2050 only, because 2020 is the start year of the remaining global carbon budget published in the IPCC AR6, Working Group I contribution.

The cumulative emissions for 2030-2050 presented on this figure (dark blue bars) differ from the greenhouse gas emissions budget of 11-14 Gt recommended by the Advisory Board, because their scope was adjusted to allow a comparison with fair share estimates. These adjustments consist in the inclusion of emissions from all extra-EU aviation and maritime transport, and of an adjustment regarding emissions and removals from land. The latter reflects the difference in the way these emissions are accounted between greenhouse gas inventories and in the IPCC global carbon budget. Greenhouse gas inventories consider the entire land sink to be anthropogenic, whereas the IPCC AR6 (and science more generally) considers the indirect fraction to be natural (and excludes it from the total anthropogenic sink used to estimate the remaining global budget).

The fair share estimate presented in this figure consists of equity-based EU shares of the remaining global carbon budget, to which proxy non-CO_2 emissions for the period 2020-2050 are added. These proxy

emissions are taken from the pathway that achieves 95% greenhouse gas emissions reduction while remaining within the environmental risk levels identified in this report.

Source: Advisory Board (2023).

5.3 Implications of the inclusion of additional transport emissions from aviation and maritime transport

This report's recommendations for a 2040 target and accompanying budget include emissions from international aviation and maritime transport between EU destinations.

This decision was made for comparability with previous EU target assessments (e.g. EU's 2030 Climate Target Plan, (EC, 2020b)) and does not constitute a recommendation from the Advisory Board about which sectors should be covered by EU policies and targets. In the view of the Advisory Board, including all sectors is the preferred option from the point of view of fairness and environmental integrity, provided this does not result in a weaker overall target. Table 13 is therefore provided to ensure that the Advisory Board's recommendations can be used appropriately regardless of the state of play of political discussions on the scope of EU targets.

Each option (1-5) presented in Table 13 features the same underlying emissions. The difference is only a matter of which sectors are included. Adding each successive element of international transport has the effect of reducing the headline percentage reduction in emissions compared to 1990 and increasing the total greenhouse gas budget. The more comprehensive scope (i.e. option 5) has the lowest headline reduction and highest budget because these sectors are expected to decarbonise more slowly than the rest of the EU economy. The numbers presented in Table 13 assume that ambitious decarbonisation takes place in the aviation and maritime sectors, in keeping with each scenario's overall consistency with limiting global warming to 1.5°C. Failure to decarbonise these sectors would result in greater differences between the option ranges than those shown in Table 13. This effect, and the method used to estimate these sectors' emissions, is discussed in more depth in Annex C.

Table 13 Effects of international aviation and maritime emissions on the post-2030 EU emission reduction target and greenhouse gas budget recommendation

Option number	Option description	**2040 objective (% vs 1990)**	**2030-2050 budget (Gt CO_{2e})**
1	Excl. international transport	91.1-96.0%	9.5-13.4
2	1 + intra-EU aviation	90.7-95.5%	10.0-13.9
3	2 + intra-EU maritime	90.2-94.7%	10.9-14.4
4	3 + extra-EU maritime	89.3-94.1%	11.5-15.5
5	4 + extra-EU aviation	88.3-92.0%	13.7-16.5

Notes:

For the purpose of this analysis, emissions from international transport are calculated based on sales of bunker fuels.

Option 3 (inclusion of intra-EU aviation and maritime emissions) is the scope used by default in this report, but does not constitute a recommendation of the Advisory Board regarding the optimal scope of EU legislation

Source: Advisory Board (2023).

The European Climate Law and greenhouse gas emission reduction objectives therein apply to all anthropogenic greenhouse gas emissions by source that are regulated by EU law. To what extent the 2040 objective includes international aviation and maritime transport sectors thus depends on whether these sectors are regulated by EU law.

In terms of **present and future EU policies**, the situation regarding coverage of international aviation and shipping emissions is as follows.

- Under **legislation currently in force**, only emissions from **intra-EU aviation** are covered by a climate target. These emissions are regulated under the EU ETS. Extra-EU aviation emissions also fall under the scope of EU ETS but a derogation has in practice excluded them since 2012 ([14]).
- **Legislation entering into force in 2024** will bring **intra-EU and extra-EU maritime emissions** into the scope of the EU ETS (Council of the European Union and European Parliament, 2023).
- **Legislation to be proposed in 2026** *should* **cover extra-EU aviation**, through inclusion in EU ETS and/or under the International Civil Aviation Authority's carbon offsetting and reduction scheme (CORSIA). The European Parliament and Council's 2022 political agreement introduces a mandate whereby the European Commission is to monitor the implementation of CORSIA. If it is found that the scheme is not strong enough to meet the goal of climate-neutral aviation by 2050 ([15]), the Commission is required to introduce a proposal to apply the EU ETS to extra-EU flights from January 2027 (Council of the EU, 2022).

([14]) This is explained in brief in a note by the European Parliament Think Tank (EP, 2022).
([15]) The 'long term aspirational goal' of the International Civil Aviation Organization (ICAO) is for international aviation to achieve net-zero carbon emissions by 2050 in support of the Paris Agreement temperature goal.

6. Iconic pathways towards climate neutrality

To support the analysis of the possible implications of various feasible scenarios for policy makers, the Advisory Board decided to select amongst these a set of three iconic pathways that illustrate different societal choices and climate change mitigation strategies that the EU could follow to achieve climate neutrality, in the context of a global effort pursuing the goal of limiting global warming to 1.5°C.

Key distinctive features of the selected iconic pathways relate for example to characteristics (and therefore policy priorities) such as:

- the resource intensiveness of lifestyles,
- the level of final energy demand,
- the reliance on carbon removals,
- the level of deployment of renewable energy,
- the contribution of nuclear power,
- the overall level of cumulative emissions in the 2030-2050 period.

These iconic pathways are mainly used in the analysis of the implications of decarbonisation in line with the proposed budget and target for the transformation of the different economic sectors in the EU, presented in Chapter 7.

The iconic pathways, as well as the range of feasible pathways included in this analysis, might not represent all possible technological developments, and do not constitute predictions of future technological developments. The climate-neutral pathways are tools used to explore different ways to achieve emission reductions, however the potential for over-achievement or under-achievement of technological development should be accounted for with an adaptive approach.

The iconic pathways and their key features are described in Table 14 and represented on Figure 14.

Table 14 Iconic pathways towards climate neutrality in the EU

Iconic pathway	Description	Prominent features amongst the three iconic scenarios
Demand-side focus pathway	• One of the illustrative mitigation pathways assessed in the IPCC AR6 ([16]) • Aims to combine ambitious climate policies with global achievement of the UN Sustainable Development Goals (Soergel et al., 2021)	• Less resource-intensive lifestyles • Lowest final energy demand in 2040 • Lowest reliance on carbon removals (from CCS and the land sink combined) by 2050
High renewable energy pathway	• Newer scenario reflecting the ambition level set by the European Climate Law targets for 2030 and 2050 • Includes a constraint reflecting the plausible level of emission	• Largest greenhouse gas budget • High renewable energy deployment • Highest deployment of non-biomass renewable energy

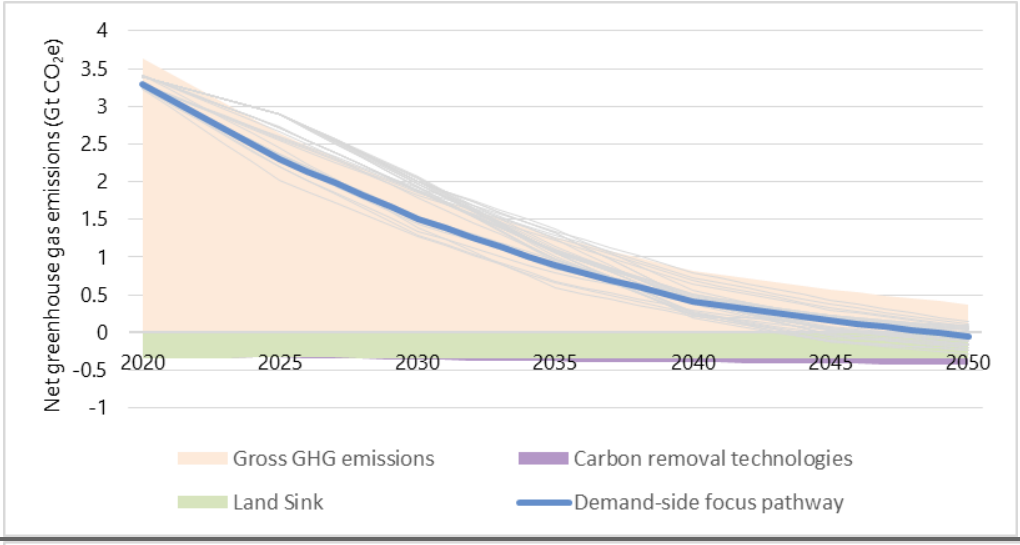
([16]) The illustrative mitigation pathways are pathways used in the IPCC reports to contrast different stories of mitigating climate change.

	reduction in the short-term (does not assume overachievement of the 2030 target)	• Highest rate of electrification by 2040
Mixed options pathway	• Developed as part of a global scenario set exploring how to limit warming to 1.5C with low overshoot (Riahi et al., 2021)	• Lowest cumulative emissions in the 2030-2050 period • Greatest deployment of CO_2 removals (with specific focus on sustainable land-based removals) • Increase in the contribution of nuclear power over time (as opposed to the two other iconic pathways)

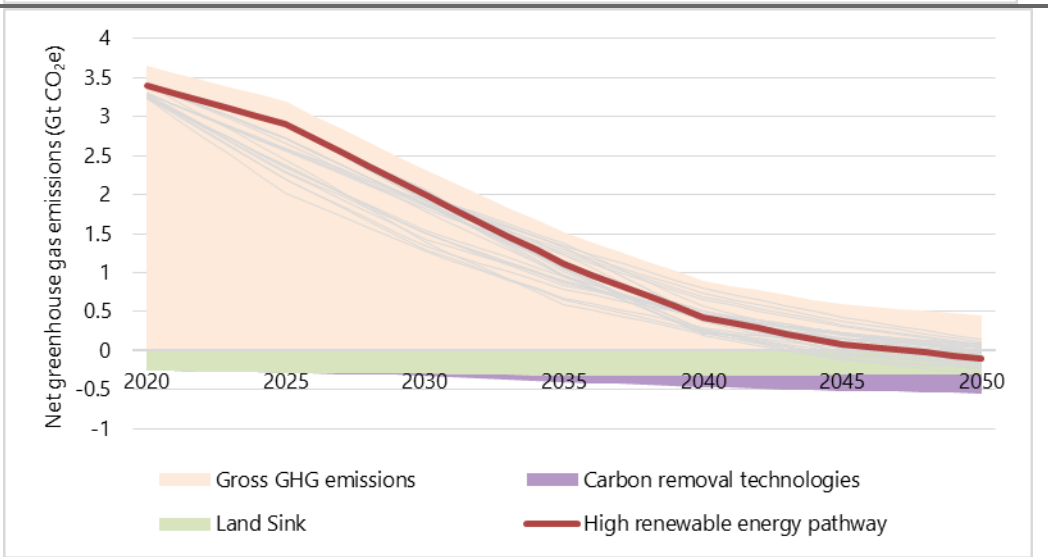
Source: Advisory Board (2023).

Figure 14 Emission reduction trajectory and key features of iconic pathways

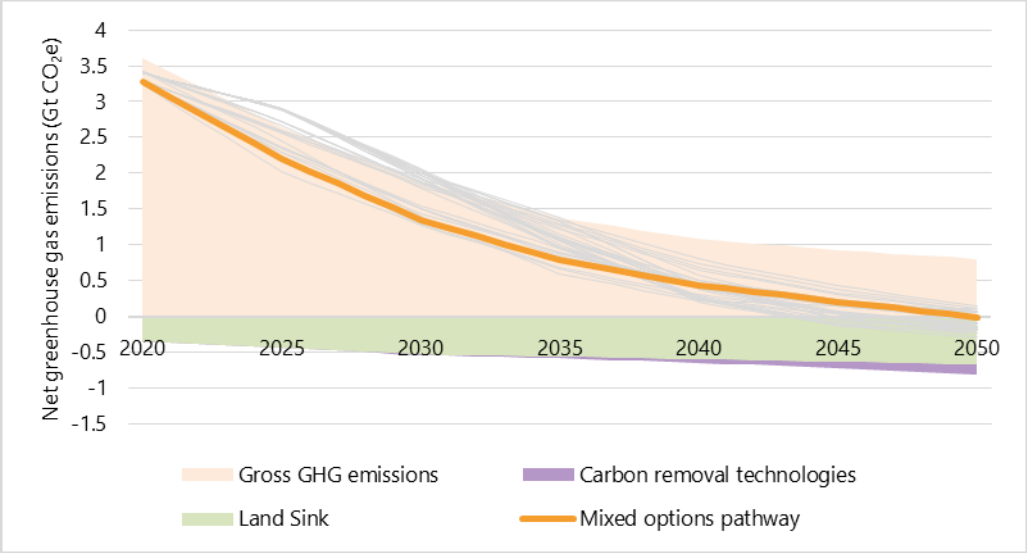
Demand-side focus pathway



High renewable energy pathway



Mixed options pathway



Source: Advisory Board (2023).

The three iconic pathways correspond to greenhouse gas budgets for 2030-2050 ranging from 11.1 to 13.8 Gt CO_2e (13.2 to 16.8 Gt CO_2e when bunker emissions are included). They also imply emission reductions by 2040 ranging from 90.8% to 91.2% below 1990 levels, i.e. within the range of reductions implied by the feasible emission pathways identified in Section 4.4.3. These results, together with implied values for other key parameters, are presented in Table 15.

Table 15 Greenhouse gas budgets for the period 2030-2050 and 2040 reductions from iconic pathways

	Iconic pathway		
	Demand-side focus	**High renewable energy**	**Mixed options**
Greenhouse gas budget 2030-2050 (Gt CO_2e)			
Intra-EU bunkers only	11.7	13.8	11.1
All bunkers	13.7	16.8	13.2
Greenhouse gas reduction below 1990, including intra-EU bunkers			
By 2040	-91.2%	-90.9%	-90.8%
By 2050	-101.1%	-102.0%	-100.3%
Other key parameters			
Final energy demand (% change in 2040 vs 2015)	-40%	-38%	-23%
Electrification (electricity share of final energy demand in 2040)	45%	50%	45%
Share of electricity production in 2040 (%)			
Non-biomass renewables	90%	87%	72%
Nuclear	3%	7%	23%
Natural gas (with and without CCS)	2%	2%	4%
Net imports			
Fossil fuels in 2040 (EJ)*	6.1	5.8	8.0
% change since 2015	-81%	-82%	-70%
Bioenergy consumption (primary) in 2040 (EJ)	10.3	7.1	5.3

	Iconic pathway		
	Demand-side focus	**High renewable energy**	**Mixed options**
Hydrogen production in 2040 (EJ)	1.7	1.6	3.5
Carbon capture, utilisation and storage (Mt CO_2 captured per year by 2050)			
Total	145	308	417
of which biomass *	*77*	*234*	*147*
Land sink (net LULUCF Mt CO_2 removed annually)*			
In 2040	351	323	601
In 2050	351	312	669

Source: Advisory Board (2023).

7. Scenario implications for the transformation of key sectors

The following sections examine key aspects of the pathways to climate neutrality one-by-one in order to identify the implications of following different paths towards this goal. They are based on results from the 36 filtered scenarios, with a particular focus on the iconic pathways to illustrate the different mitigation options available.

7.1 Summary

Key elements of the transition identified from this analysis include the following:

- **Energy efficiency, electrification and decarbonisation of the power sector are mutually reinforcing ways to lower emissions** to the recommended level by 2040 and a milestone towards climate neutrality. Final energy demand falls compared to today's levels across all scenarios and sectors, with an overall decline of 21-42% by 2040 compared to 2019. Electricity accounts for 42-57% of final energy demand by 2040, which is at least double the 2019 share ([17]).
- **Large-scale renewable energy deployment.** Renewable energy sources, especially solar and wind (excluding bioenergy) account for 69-90% of electricity generation, and over 85% in more than half of the scenarios.
- **Coal and gas are virtually phased out of power generation.** By 2030, coal accounts less than 1% of power generation in most scenarios, and at most 4% in remaining ones. By 2040 the picture is similar for natural gas, which accounts for at most 6% of generation and in many scenarios below 1%.
- **Scale-up of alternatives to fossil fuels where electrification is not possible.** Scenarios with a lower electrification rate make greatest use of alternative decarbonisation options. However, all scenarios require alternatives to electrification for some applications in industry and transport.
    - Use of **hydrogen** is rapidly scaled up compared to today, but also varies widely between the scenarios. It accounts for 5-24% of final energy demand by 2040 ([18]).
    - **Bioenergy** use also varies. While some scenarios see its use increase by over 50% by 2040 compared to 2019, others see more modest increases, or even no increase above today's levels. Biofuels support the decarbonisation of heavy-duty vehicles, aviation and the maritime sector.
- **Nuclear power** ranges from 2% to 23% of electricity generation depending on the scenario.
- **Reduced non-CO_2 emissions, including in agriculture**. Overall non-CO_2 emissions fall to 20-62% below 2019 levels, with the extent and nature of this transformation varying between scenarios. The scenarios that stress sustainable lifestyles see demand for livestock for food fall by around 50% and reductions in emissions of nitrous oxide (related to nitrogen fertiliser application) of over 30%.
- **Carbon removals at scale (both land-based and technological)**. Each scenario places a different emphasis on both the need for carbon removals and the extent to which its deployment is through technologies such as BECCS or enhancement of the sink. However, both sources are required, and both have important benefits and risks. In 2040, BECCS represents 46-207 Mt CO_2 and DACCS represents 0-7 Mt CO_2, in scenarios where deployment remains within identified risk levels. Recent analysis of future climate impacts suggests that the land sink would be limited to 100-400 Mt CO_2 (compared to today's level of 212 Mt CO_2). Several scenarios within the recommended target range

([17]) Eurostat, NRG_BAL_C (2023).
([18]) Based on comparison with final energy consumption by product from Eurostat (2023).

maintain the sink below 400 Mt CO_2. However, some scenarios rely on a land sink which exceeds this level by 2040, which raises feasibility concerns.

- **Enhanced energy security**. Net imports of oil by 2040 are 52-99% below those of 2019 by 2040, while net imports of natural gas are either eliminated entirely, or reduced by at least 35% below 2019 levels and combined with CCS and use of alternatives to fossil gas.

In addition, scenarios focussing on efficiency and sustainable consumer choices to reduce energy and natural resource uses can reduce trade-offs and bring multiple benefits:

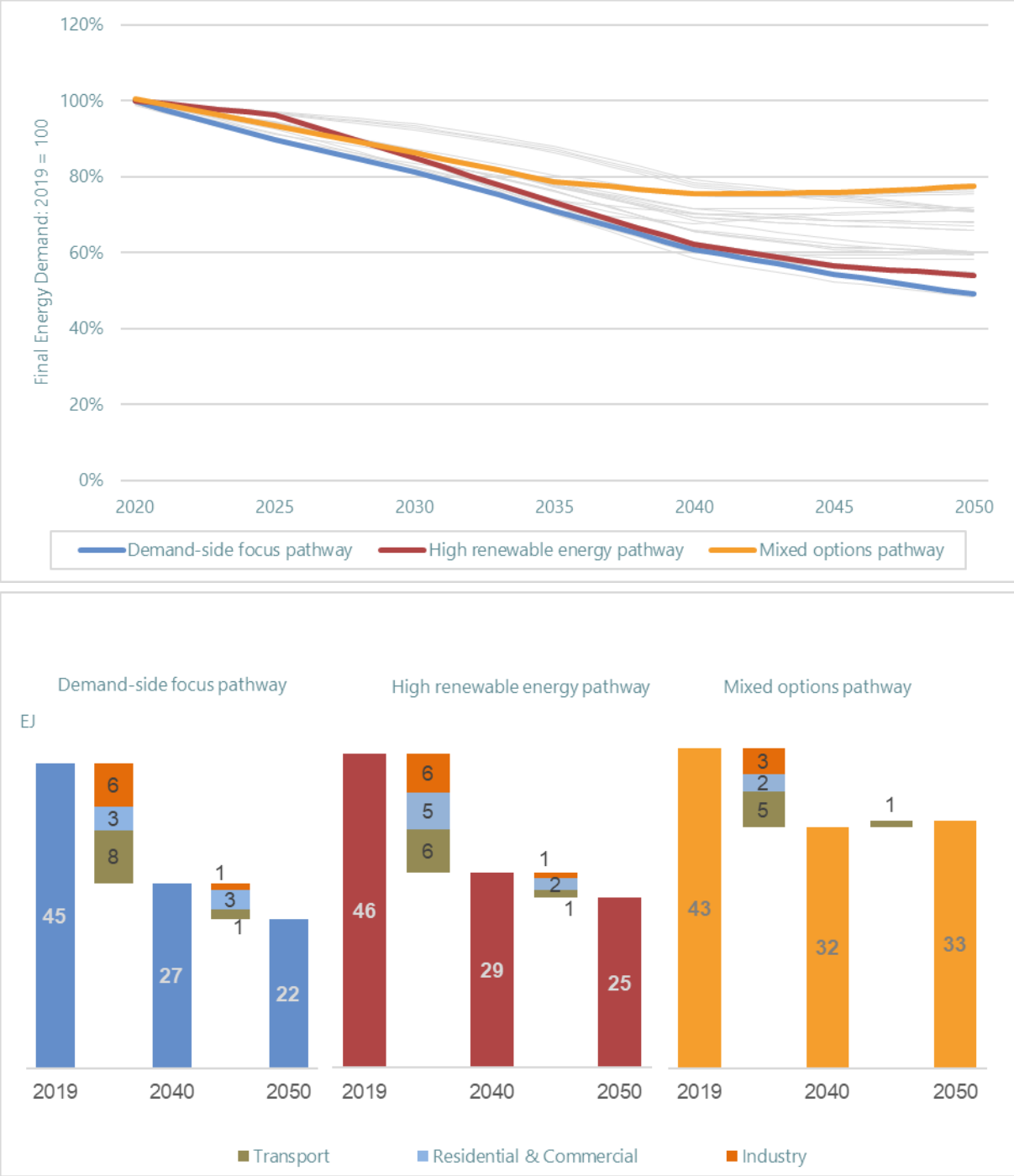
- ***Reduced reliance on technology scale-up***. While technology options such as renewable energy sources, hydrogen and CCS, need to be scaled up rapidly in all scenarios, the amounts of these technologies needed by 2040 and 2050 are much lower in scenarios with lower energy demand. For example, the Demand-side focus and High renewable energy pathways produce less than half the amount of hydrogen in 2050 than the Mixed options pathway.
- ***More potential benefits and fewer trade-offs***. Climate action can contribute to multiple improvements in health, well-being and environmental protection, and it can also produce trade-offs in these same areas that need to be addressed by policymakers. Screening of the iconic pathways shows that the Demand-side focus and High renewable energy pathways, stand a better chance of maximising the benefits, in particular related to health and affordability of energy, through their focus on energy efficiency and healthier diets. At the same time, by deploying less CCS and nuclear energy, these pathways reduce some of trade-offs related to water stress.

7.2 Energy

7.2.1 Final energy demand

The 36 filtered scenarios feature a **reduction in final energy demand of 21-42% by 2040 compared to 2019 levels**. Beyond 2040, a continued trend in demand reduction is present in most scenarios, and can also be seen in the Demand-side focus and High renewable energy pathways. This can be attributed to efficiency gains enabled by direct electrification, among other factors. Other scenarios feature a flattening or even reversing of trend from 2040 onwards, in particular those scenarios that foresee large amounts of energy needed for production of hydrogen, including the Mixed options pathway.

Figure 15 Change in final energy demand (filtered scenarios, EU)



Source: Advisory Board (2023).

7.2.2 Power sector: electrification, renewable energy and fossil fuel phase-out

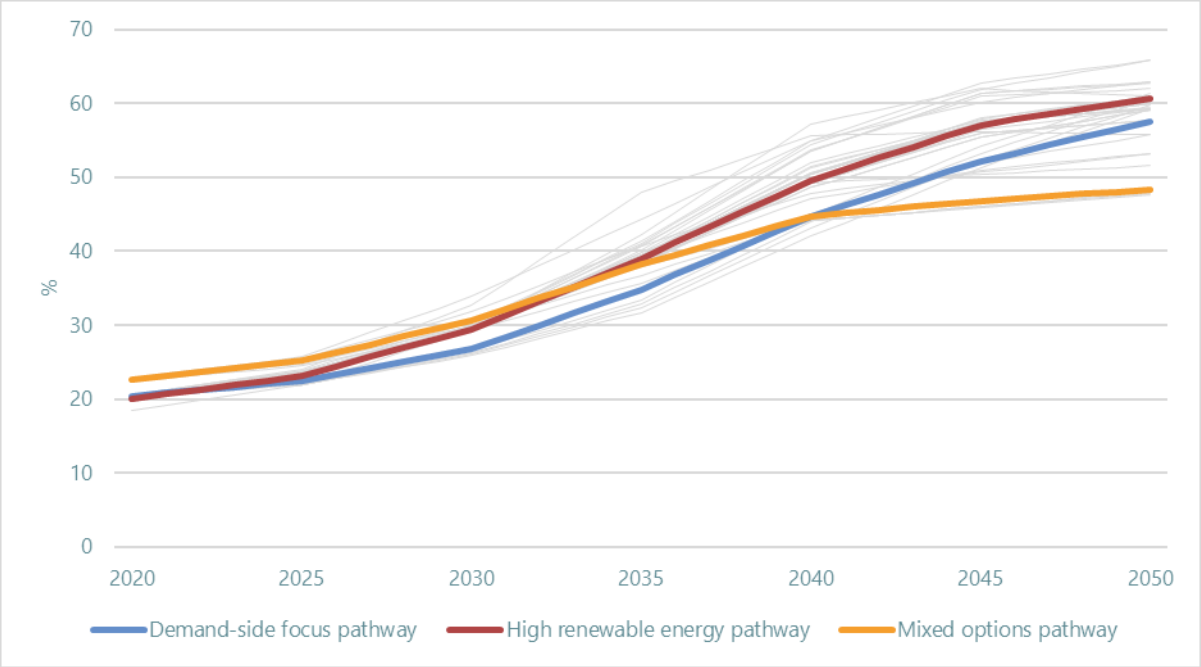
Electrification is a key feature of all assessed pathways. By 2040, **electricity accounts for at least 42% of final energy demand** in the 36 filtered scenarios, which is around double today's level ([19]) (see Figure

([19]) Based on comparison with final energy consumption by product from Eurostat (2023).

16). Electrification accelerates rapidly and remains an important feature of most scenarios over the whole period, but stalls after 2040 in the Mixed options pathway.

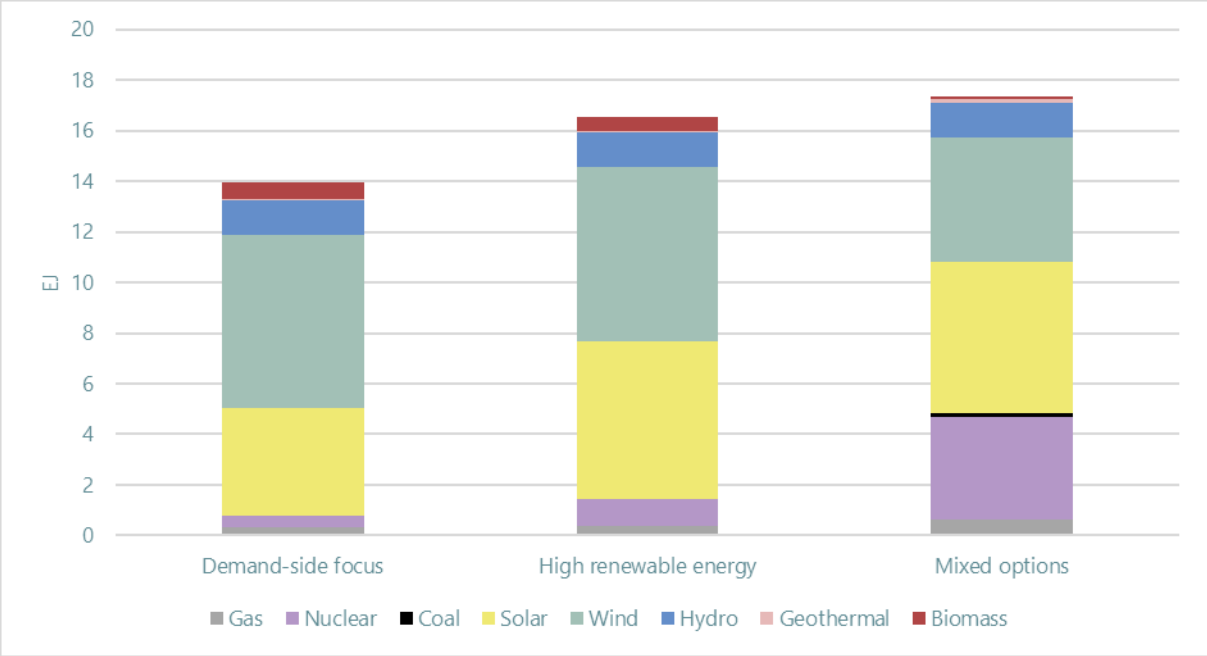
By 2040, non-biomass renewables, including **wind, solar and hydro power, provide 70-91% of electricity**. In most of the filtered scenarios (30 out of 36), the share is higher than 85%. **Nuclear power supplies between 3% and 23% of electricity** in the filtered scenarios.

Figure 16 Electrification share of final energy (filtered scenarios, EU)



Source: Advisory Board (2023).

Figure 17 Fuel and electricity generation in 2040 by source (iconic pathways, EU)



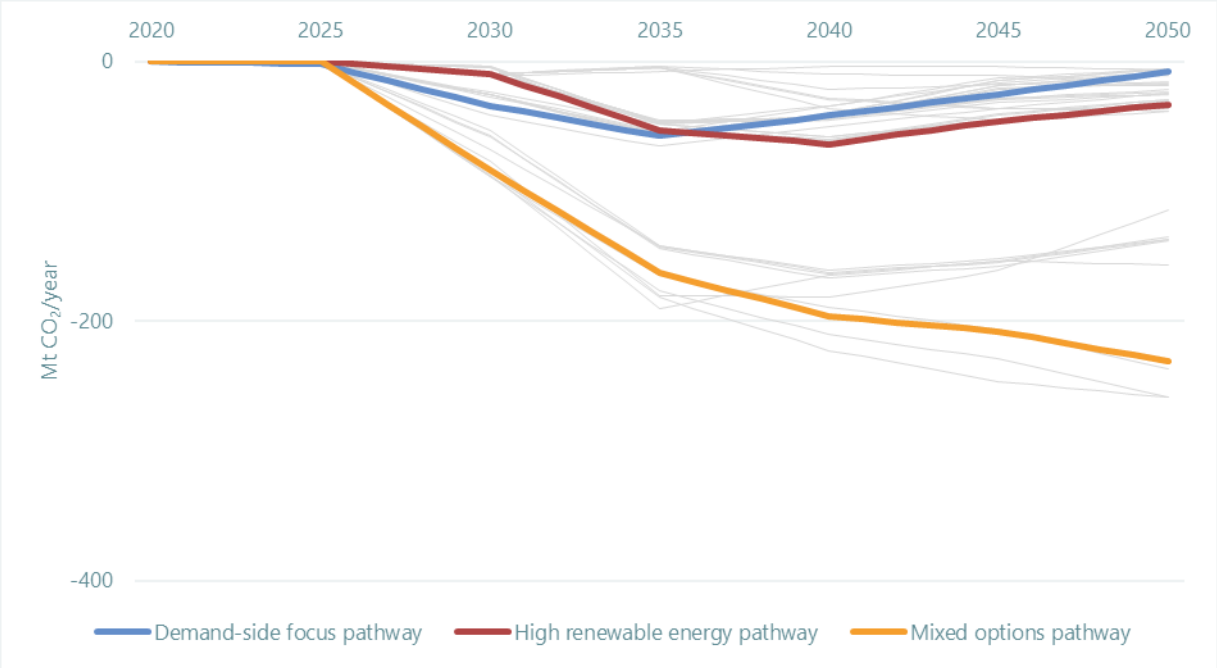
Source: Advisory Board (2023).

Most of the 36 filtered scenarios achieve a **near-total phase-out of fossil fuels from the power sector**, as shown in Figure 17, though some use of fossil gas in power stations remains in those scenarios that feature the greatest amount of Carbon Capture and Storage (CCS). **Coal accounts for less than 4% of electricity generation by 2030** in all 36 filtered scenarios, less than 3% in the iconic pathways, and less than 1% in 14 scenarios.

Fossil gas accounts for up 11% of electricity generation in 2030 in some of the 36 filtered scenarios, though in others it falls to 1% or below. **By 2040 the share of fossil gas is 6% or less** in all 36 scenarios, 2% to 4% in the iconic pathways, and less than 1% in 12 of the scenarios. Scenarios that use higher amounts of fossil gas tend have greater reliance on carbon removals.

All three iconic pathways feature a stark reduction in the share of fossil gas in electricity generation, albeit with different trajectories. In the Demand-side focus pathway, use of fossil gas falls steadily until 2035, after which it, remains at 0.3 EJ (just over 2% of generation) until 2050. In the High renewable energy pathway, fossil-gas-powered electricity declines continuously after 2025 to 0.1% by 2050. In the Mixed options pathway, its use drops sharply until 2030 but increases thereafter, accompanied by the deployment of CCS, which accounts for 30% of primary fossil gas consumption by 2040. The use of fossil CCS (rather than BECCS) is in part related to the pathway's prioritisation of carbon removals from land rather than bioenergy.

Figure 18 Fossil CCS (filtered scenarios, EU)



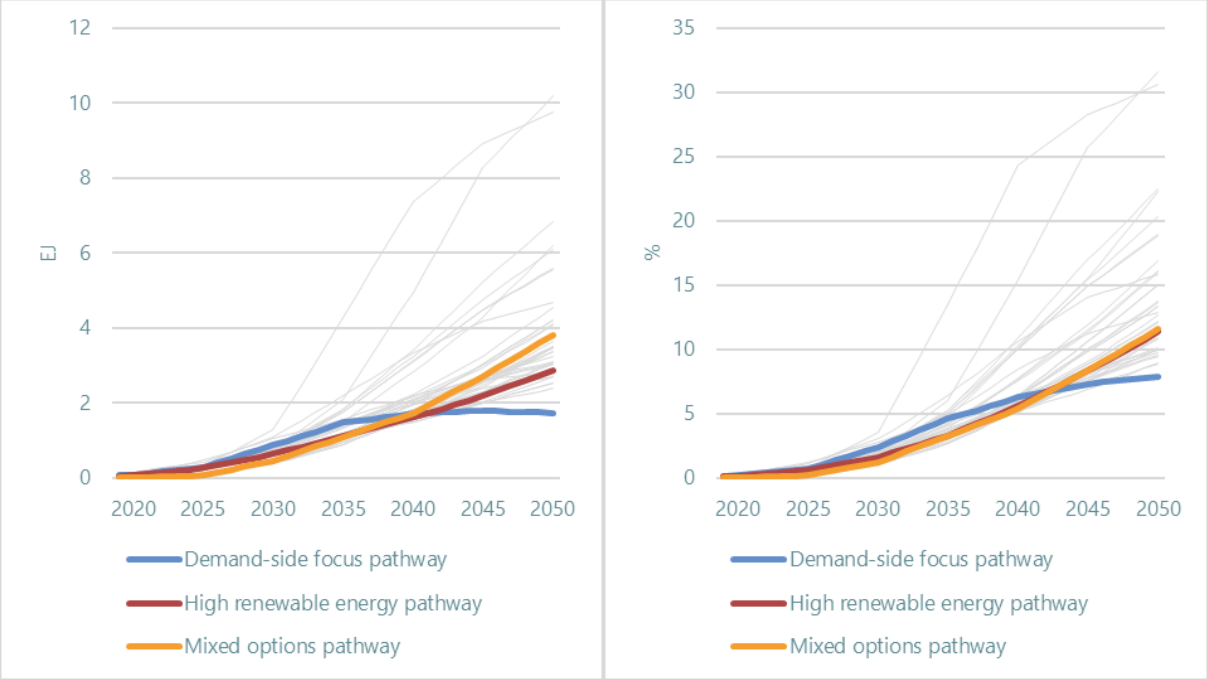
Source: Advisory Board (2023).

7.2.3 Hydrogen

Production and use of hydrogen expands quickly in all scenarios, but with considerable variation in overall use in the post-2030 period. In most scenarios (26), the domestic production of hydrogen ramps up to a level between 5 Mt and 10 Mt by 2030 (5 Mt corresponds to the challenge level identified in Table 6, and the 10 Mt corresponds to the REPowerEU target).

In the iconic pathways, the production of hydrogen reaches the same level of around 1.5 EJ by 2040, after which production levels diverge (see Figure 19Figure 19). The Mixed options pathway features a rapid growth up to 2050, by which point it produces more than twice as much hydrogen as the Demand-side focus pathway.

Figure 19 Hydrogen production in exajoules (left) and expressed as a percentage of final energy consumption (right) (filtered scenarios, EU)



Note: the figure to the right expresses the amount of hydrogen produced in the EU as a proportion of total final energy consumption. This does not mean that all hydrogen is used as 'final' energy. Some is used as secondary energy, e.g. as feedstock in the production of e-fuels.

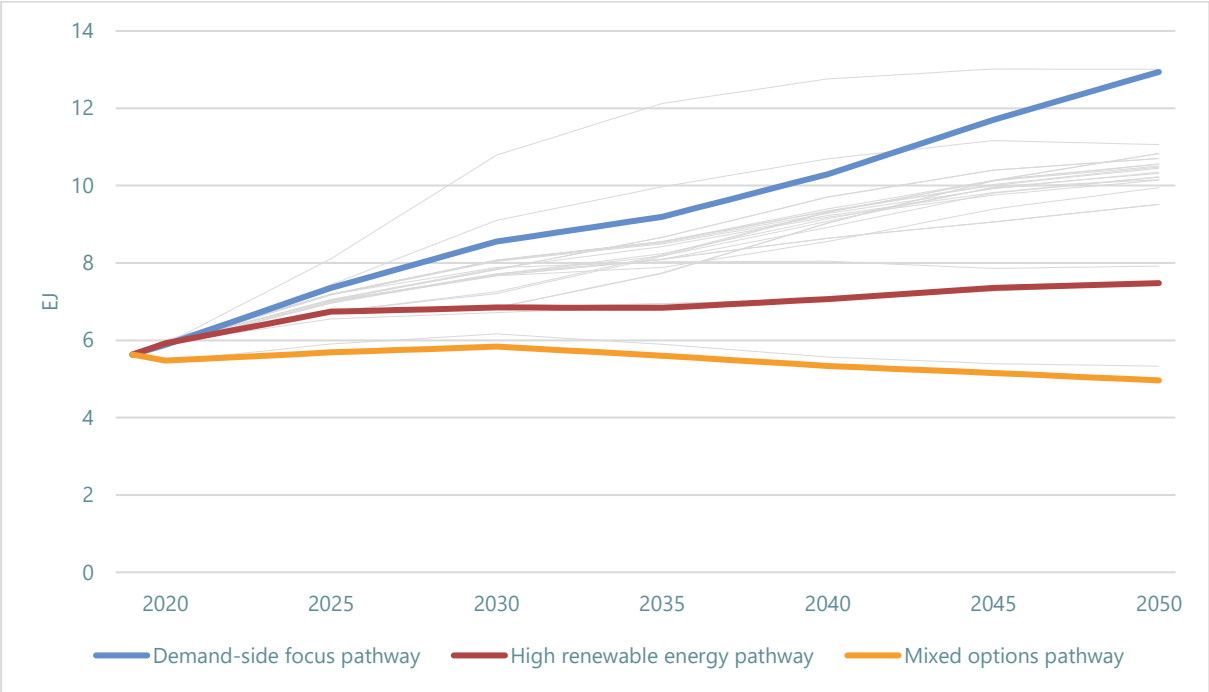
Source: Advisory Board (2023).

7.2.4 Bioenergy

Almost all the considered scenarios foresee an expansion of bioenergy, especially in the use of primary biomass compared to today's level of around 5 EJ ([20]). However, in some scenarios, the expansion is limited, with even a decreasing use of bioenergy in the Mixed options pathway. The maximum amount of biomass use across all the 36 filtered scenarios is 13 EJ per year in 2040 and 2050. Biomass use remains below the risk level of 9 EJ (used in Section 4.4 on feasibility analysis) in 14 of these scenarios (Table 6 and Figure 20Figure 20).

([20]) NRG_CB_RW (Eurostat, 2023).

Figure 20 Primary bioenergy use (filtered scenarios, EU)



Source: Advisory Board (2023).

The High renewable energy pathway limits biomass use to 7.5 EJ/year. Low bioenergy use is compensated by fast scale-up of non-biomass renewables and large-scale electrification of end-uses, in line with earlier studies (Luderer et al., 2022). This also results in low final energy demand, due to efficiency gains. The 'Mixed options' pathway uses the least primary biomass for energy production since the scenario prioritises enhancement of the sink as a land use option. The Demand-side focus pathway is exceptional among the filtered scenarios in that it has one of the highest levels of bioenergy use in 2050, combined with the lowest deployment of BECCS. The research publication behind this scenario explains that the assumed shifts to sustainable and healthy diets imply strong reductions in demand for meat and dairy products, which makes more land available for energy crops (Soergel et al., 2021).

Bioenergy can contribute to fossil phase-out, especially in those pathways that assume limited other options to replace certain fossil fuel uses (e.g. fuels for aviation and maritime transport, some industrial processes). It should be noted that the climate benefits of bioenergy use depend on its sustainable sourcing (e.g. biomass from limited added value, based on the cascading principle), and that it competes with other land uses, including nature conservation and food production.

7.2.5 Energy imports

The filtered scenarios improve the energy independence of the EU by reducing net imports of fossil fuels and, in some cases virtually eliminate them by 2050. In the filtered scenarios, net **primary fossil energy imports decrease by 65-93%** below 2019 levels by 2040. In most of the filtered scenarios, net **imports of fossil gas are largely eliminated** by 2040, and net **imports of fossil oil fall by 60-80%** compared to 2019 levels.

Imports of hydrogen have been identified as an option for the EU in the REPowerEU plan (EC, 2022c). This option does not feature in most of the scenarios, either because it is not part of the model, or because it is little used in the scenario. Therefore, this analysis cannot draw conclusions on the benefits and drawbacks of hydrogen trade, except to conclude that pathways to climate neutrality have been

identified that do not make use of it, and instead produce hydrogen domestically and/or deploy it at lower levels than might otherwise be the case if imports were available and used.

The use of non-fossil energy imports also poses practical challenges regarding monitoring, verification and certification of the supply chain to ensure the EU does not import energy carriers with high embodied emissions, such as hydrogen produced from unabated fossil fuels (White et al., 2021) or biomass associated with emissions from land use change (Junginger et al., 2019).

7.3 Transport

7.3.1 Final energy demand

Domestic transport represented 23% of total greenhouse gas emissions in the EU in 2019 (EEA, 2020a), and international transport represented 7% of emissions. The transport sector is a source of carbon dioxide emissions, is the largest contributor to nitrogen oxides emissions, and is also a source of nitrous oxide, carbon monoxide and ammonia emissions. These emissions are mainly caused by combustion engines.

As with the energy sector more generally, scenarios in the transport sector (excluding international aviation and maritime) show a trend of declining final energy demand combined with a decline in fossil energy use and increased electrification. By 2040, **final energy demand in the transport sector is 28-62% lower** than the 2019 level in the 36 filtered scenarios.

- The High renewable energy pathway is characterised by low energy demand, mostly a consequence of efficiency gains from high levels of electrification, and continuous declines in fossil fuel use (which falls to 49% of the sector's final energy by 2040 and 34% by 2050).
- The Demand-side focus pathway follows a similar path but with greater use of biofuels and slower growth of electrification beyond 2040.
- The Mixed options pathway has higher overall demand, which is met by both electricity and retaining a higher share of fossil fuels than the other iconic pathways. In this pathway, the use of biofuels in transport peaks before 2030, supporting the transition towards higher electrification.

Figure 21 Final energy demand in the transport sector: total and by energy carrier (filtered scenarios, EU)

Source: Advisory Board (2023).

7.3.2 Decarbonisation options in the transport sector

The scenario database contains little information about how the emission reductions are achieved. Many decarbonisation options exist, as pointed by the IPCC. The following sections summarise some of the decarbonisation options which could be leveraged in the transport sector to achieve the level of emission reductions displayed by the scenarios.

Passenger cars

Road transport represented 95% of the emissions from the transport sector in 2019 (EEA, 2020a), including 70% from light duty vehicles and 30% from heavy duty vehicles. The demand for personal transport can be reduced with behaviour shifts, for example shared rides, mode shift to active or public transport, increased teleworking, or dematerialisation (IPCC, 2022l, p. 10). Smaller, lighter passenger cars also reduce energy demand. The largest decarbonisation potential for light duty vehicles relies on battery-electric vehicles, powered by low-emissions electricity (Wolfram, P., et al., 2020), supported by cost effectiveness and sufficient charging infrastructure(Wolfram, P., et al., 2020).

Heavy duty vehicles

The fuel consumption from the transport of goods can be reduced with supply chain optimisation and the roll out of connected vehicles. The decarbonisation of heavy-duty vehicles can be supported by battery-electric lorries including electric road systems, sustainably sourced biofuels, and hydrogen supported by the required infrastructure, as well as fuel efficiency improvements. Biofuels can support the transition period towards possible future electrification; however, the production of biofuels is limited by land resources, competing with food production and ecosystems services (IPCC, 2022l, p. 10).

Rail and multi-modal transport

The decarbonisation of the transport sector can be achieved with a decrease in road and air transport and an increase in rail transport, other modes of public transportation and shared mobility services. This shift requires a change in behaviours, as well as the development of the rail network, including high speed rail, and can be supported by digitalisation, the development of Intelligent Transport Systems and multi-modal transport connections, and connected vehicles for shared services. According to the IPCC, urban design and integrated spatial planning through the co-location of higher residential and job densities, mixed land use and transit-oriented development could reduce greenhouse gas emissions between 23% and 26% by 2050 compared to the IPCC's business-as-usual scenario (IPCC Chapter 8, see also Javaid, A, et al. 2023).

Active transport

Moreover, emissions can be reduced by encouraging a rise in non-motorised, active transport, including walking and cycling. This relies on the development pedestrian and cycling pathways and can be encouraged by the development of electric bikes (IPCC, 2022l, p. 10).

Aviation

Aviation and maritime transport are a growing source of emissions both within the EU and globally. The efficiency of airplanes has seen a steady progress, which was more than offset by increased demand. The scope of radical efficiency increases is small. Innovation and scale-up are needed to commercialise low-carbon jet fuels such as advanced, sustainable biofuels or synthetic fuels produced from hydrogen or Bio-Energy with Carbon Capture and Storage (IPCC, 2022l, p. 10). The electrification of airport operations and possibly the electrification of short-haul trips can make further contributions (IPCC, 2022l, p. 10).

Maritime transport

Maritime transport emissions can also be mitigated with efficiency improvements, and with the deployment of bio-based fuels.

Emissions from aviation and shipping in domestic transport, intra-EU transport and international transport are counted separately in the current EU's emissions reporting system. See more explanations about how they are counted in our analysis in Section 5.3 on 'Inclusion of international transport emissions in EU climate targets'.

7.4 Industry

In 2019, the industry represented 33% of the final energy demand in the EU, and 21% of total greenhouse gas emissions. In the filtered 36 scenarios, **CO_2 emissions from industrial processes fall by 56-76% between 2019 and 2040** in the EU. These reductions are driven by a decline in energy use, an increasing share of low-carbon energy supply, and some emission reductions with CCUS.

7.4.1 Final energy demand

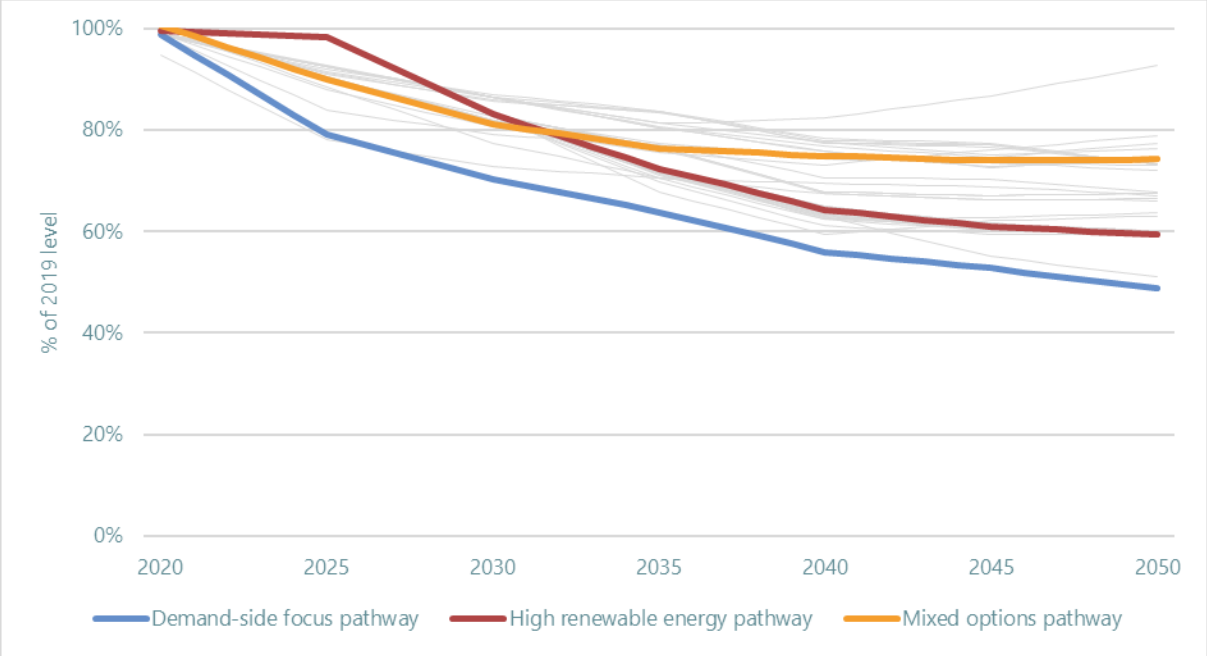
In the filtered scenarios, the **final energy use in industry declines by 18-44%** between 2019 and 2040.

- The Demand-side focus pathway assumes a substantial reduction of the energy intensity of industrial processes, achieved via improvements in energy efficiency, and via significant reductions in material demands and increase in the recycling of energy-intensive materials such as steel (Rissman, J. et al., 2020). This pathway achieves a 43% reduction in final energy use by industry from 2019 to 2040.
- The High renewable energy pathway achieves a 36% reduction in final energy use by industry from 2019 to 2040.
- In the Mixed options pathway, *'efficiency and demand reductions play a critical role'* in reducing emissions from industrial processes. This pathway achieves a 26% reduction in final energy use in the industry from 2019 to 2040.

Moreover, research shows that circular economy measures could help reduce up to 56% of emissions from the steel, plastics and cement industries by 2050 (Material Economics, 2018).

A consistent reduction in the energy use and emissions from the industry sector relies on both domestic and international reductions. The EU should watch out for the risk of carbon leakage resulting from the relocation of energy-intensive industries, such as metals, cement, chemicals or fertilisers.

Figure 22 Final energy use in industry compared to 2019 (filtered scenarios, EU)



Source: Advisory Board (2023).

7.4.2 Decarbonisation options

The full range of industrial decarbonisation options include service and product demand reduction, material efficiency, increased circularity, energy efficiency, fuel switching and direct and indirect (e.g., hydrogen) electrification, CCU and CCS. Electrification and using green hydrogen in the steel and chemicals industries has emerged as a key supply side option in recent years, facilitated by the declining

costs of electricity from photovoltaics and wind. The potentials for demand reduction are relatively unexplored and material efficiency is underutilised (IPCC, 2022e, p. 11).

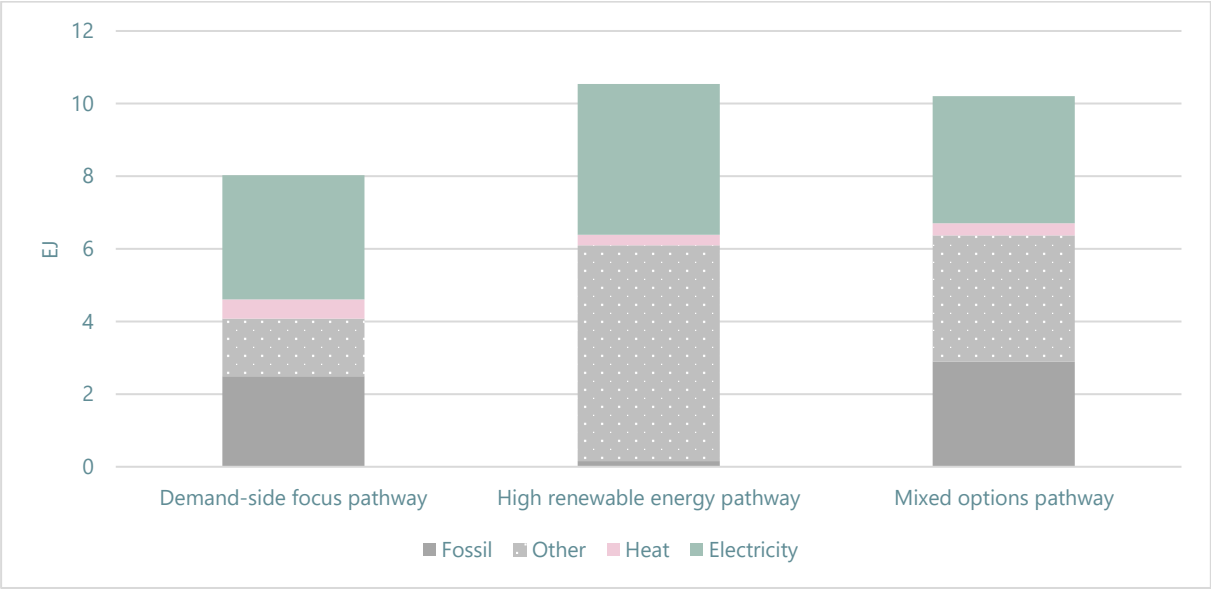
7.4.3 Shift in energy supply: electrification, hydrogen and heat recovery

In 2019, the share of electricity in the final energy use in the industry in the EU was 22%. The 36 filtered scenarios reach between **33% and 61% electrification of final energy use in industry** by 2040.

In the 36 filtered scenarios, the **share of hydrogen reaches between 6% and 23%** of final energy use in industry by 2040 (detailed data on the use of hydrogen is not available for all scenarios).

- The Demand-side focus pathway assumes that 'the transition to clean production methods in industry starts off at modest pace due to the inertia of existing capital stocks', but 'subsequently accelerates, driven by cheaper renewable electricity, using the full potential of demand-side electrification' (Madeddu, S. et al., 2020). This pathway reaches 43% electrification in 2040 (share of hydrogen is unknown).
- The High renewable energy pathway reaches 39% electrification in 2040, and 11% hydrogen energy.
- In the Mixed options pathway, rapid electrification of industrial processes also plays an important role in achieving net-zero emissions. This pathway reaches 34% electrification in 2040 (share of hydrogen is unknown).

Figure 23 Final energy consumption by industry in 2040 (iconic pathways, EU)



Source: Advisory Board (2023).

Bioenergy can also provide an alternative to fossil energy; however its production is limited by land resources, and its use should be limited to specific industrial processes, with no alternative to fossil fuel replacement.

Moreover, various industry sectors have potential to recover waste heat and electrify (e.g. using high-temperature industrial heat-pumps to generate process heat at above 150°C). Finally, demand-side flexibility measures can help manage the energy demand from the industry sector, for example by shifting the consumption to off-peak hours, which can help reduce the reliance on fossil energy.

7.4.4 Carbon capture utilisation and storage (CCUS)

CO_2 emissions from industrial processes can be significantly reduced with CCUS technologies, where emissions produced by industrial sites are directly captured and transported to geological storage sites. The filtered scenarios include between **5 and 70 Mt CO_2/year CCS in industrial processes in 2040**.

The industry can also reduce emissions through carbon capture and utilisation (CCU), where captured carbon is used as feedstock in various industrial processes, for example for synthetic fuels, chemicals or building materials (IEA, 2021). The filtered scenarios include between **0 and 166 Mt CO_2/year CCU in industrial processes in 2040**. It should be noted that CCU does not lead to zero emissions if the reused carbon is emitted (e.g. if used in fuels or through plastics incineration at end-of-life).

CCS technologies can be used to reduce emissions (in the fossil energy industry, or in industrial processes), or to remove carbon (in the case of BECCS, where carbon is removed from the atmosphere via biomass; or in the case of DACCS, where carbon is removed from the atmosphere). More information about the feasibility of the geological storage and the techno-economic deployment of these technologies is included in section 7.7 on 'Carbon removals'.

Figure 24 CCS in industrial processes (filtered scenarios, EU)

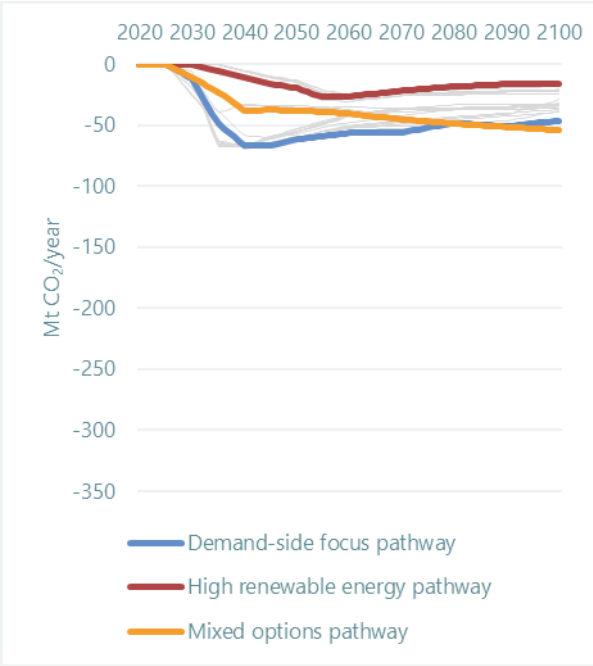
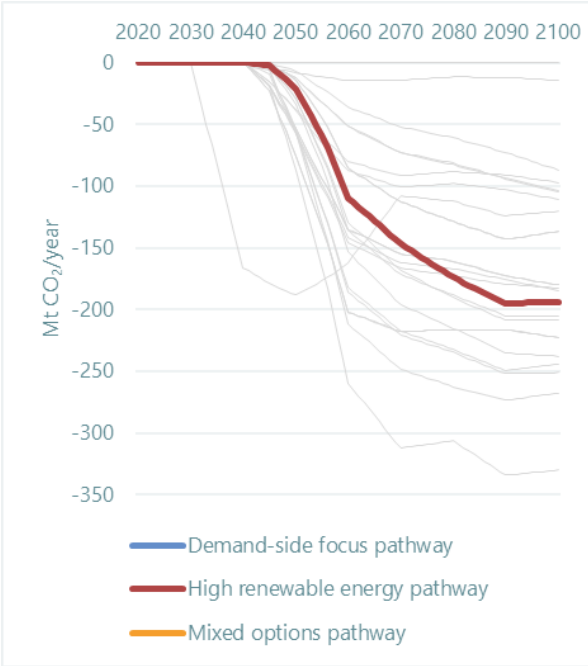


Figure 25 CCU (filtered scenarios, where available, EU)



Source: Advisory Board (2023).

7.4.5 Decarbonisation options in key sectors of the industry

Chemicals industry

Decarbonisation of the chemicals industry can be achieved by switching energy source, switching feedstock to recycled plastics feedstock, biomass, deploying CCUS, or increasing material efficiency. Industry roadmaps generally do not include the option of demand reduction and material efficiency (Kloo, Y., et al., 2023). Research shows that, for the plastics industry specifically, net-zero emissions can be achieved in the plastics industry by using renewable electricity, and combining biomass

and CCU, with a recycling rate of 70% (although the effects of recycling on life cycle emissions depend on studies), and energy savings between 34% and 53% (Meys, R., et al., 2021).

Steel industry

Some of the filtered scenarios include assumptions on the **carbon intensity of steel production, estimating a drop by between 65% and 7%** between 2019 and 2040 (data is not available for all scenarios). Other research shows that steel production could be close to net zero by 2035, based on the replacement of blast furnaces with zero-emission alternatives, the rapid rollout of renewable energies (including green hydrogen), novel low-carbon processes to produce primary steel, increased recycling, rollout of renewable energies and a reduction in the demand for steel (Volg, V., et al., 2021).

Cement industry

Some of the filtered scenarios include assumptions on the **carbon intensity of cement production, estimating a 9-37% drop** between 2019 and 2040 (data is not available for all scenarios). Carbon emissions from both fuel use and feedstock (i.e., calcium carbonate) necessitate CCS unless cement is substituted by other materials. New cement production processes with very high capture rates for CCS can bring emissions and thus carbon intensity close to zero (IPCC, 2022e, p. 11).

Overall, it appears that it is technically possible to reduce carbon emissions and carbon intensities further than what is assumed in the scenario. This implies that it may be possible to reduce EU residual emissions below those derived from the filtered scenarios.

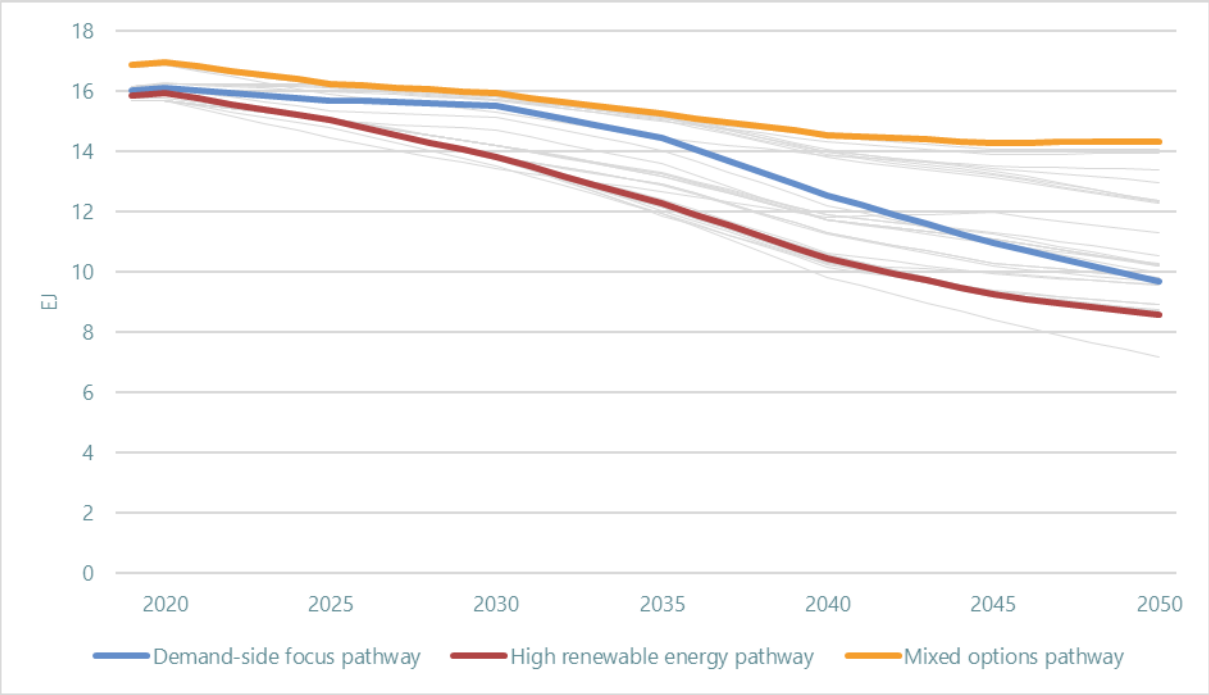
7.5 Residential and tertiary sectors

Greenhouse gas emissions from residential, commercial and public sectors are mostly attributable to building end-uses. Households as well as commercial and public services accounted for **40% of final energy demand** of the EU in 2019 ([21]). Direct emissions from buildings and energy supplied to buildings accounted for **12% and 14% of total EU greenhouse gas emissions in 2019** (EEA, 2020b), respectively. Space heating and cooling, hot water, powering appliances and lighting are main causes of total building emissions. In the 36 filtered scenarios, the **final energy demand from these sectors drops by 13-37%** in the EU between 2019 and 2040 (see Figure 26), while the energy supply is mostly or completely decarbonised.

On the **energy demand** side, a reduction of greenhouse gas emissions from buildings, depends on efficiency and sufficiency measures. Efficiency is supported by the deployment of heat pumps to electrify space heating, cooling, and hot water supply as well as deep energy renovations (Ástmarsson et al., 2013; Cabeza et al., 2022) and improving energy performance standards for new buildings (performance for heating, ventilation and air conditioning), the roll out of demand-side flexibility measures including smart metering systems, and the deployment of highly efficient appliances and lighting. Technology based mitigation is further enabled by, and often dependent on, socio-cultural and lifestyle changes that include sufficiency measures such as optimisation of the use of building, heating and cooling set-point adjustments, and reduced appliance use (Cabeza et al., 2022; IPCC, 2022a).

([21]) NRG_BAL_S (Eurostat, 2023).

Figure 26 Final energy use in residential and commercial sectors (filtered scenarios, EU)



Source: Advisory Board (2023).

The decarbonisation of **energy supply** to buildings depends on switching from fossil gas to low-carbon electricity (with heat pumps), solar thermal energy, as well as low-carbon (renewable and waste heat) district heating solutions, including low temperature district heating (Cabeza et al., 2022)).

In the 36 filtered scenarios, final energy demand in residential and commercial sectors in 2040 comes from:

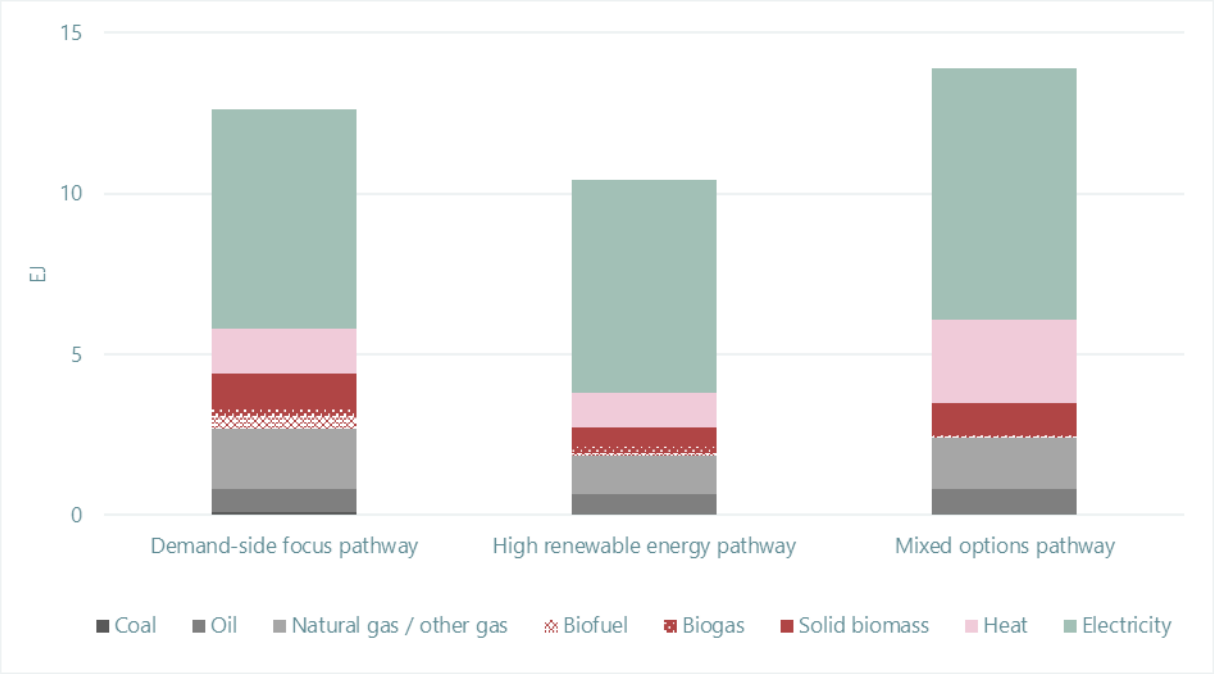
- **53-71% electricity;**
- **7-18% heat;**
- **0-11% bioenergy** (6-9% solid biomass, 0-3% biogas, 0-3% biofuel);
- **0-27% fossil energy** (5-20% natural gas, 4-7% oil, 0-1% coal).

- In the Demand-side focus pathway, the energy demand from residential, commercial, and public sectors is based on a combination of 'technological and lifestyle developments leading to low energy consumption patterns' (Soergel et al., 2021; Levesque, A. et al., 2018; Levesque, A., et al., 2019). This pathway achieves 22% reduction in final energy demand in the residential, commercial, and public sectors between 2019 and 2040. In 2040, these sectors rely on 54% electricity, 11% heat, 9% bioenergy and, and still a high level of fossil energy, which represents 21% of final energy demand.
- The High renewable energy pathway relies on a limited use of bioenergy, assuming the agri-economic and land-use limitations, and potential for sustainably sourced biomass. This pathway achieves a particularly high reduction in final energy demand in the residential, commercial, and public sectors: 34% between 2019 and 2040. In 2040, these sectors rely on a very high level of electrification of 63%, 9% bioenergy, as well as 10% heat and 18% fossil energy.

- The Mixed options pathway achieves a 14% reduction in final energy demand in these sectors between 2019 and 2040. This pathway relies on a high level of direct heat supply, 18%, as well as 54% electricity, 7.5% bioenergy and 15.5% fossil energy.

For comparison of final energy consumption in residential, commercial, and public sectors amongst the iconic pathways see Figure 25.

Figure 27 Final energy consumption in residential and tertiary sectors in 2040 (filtered scenarios, EU)



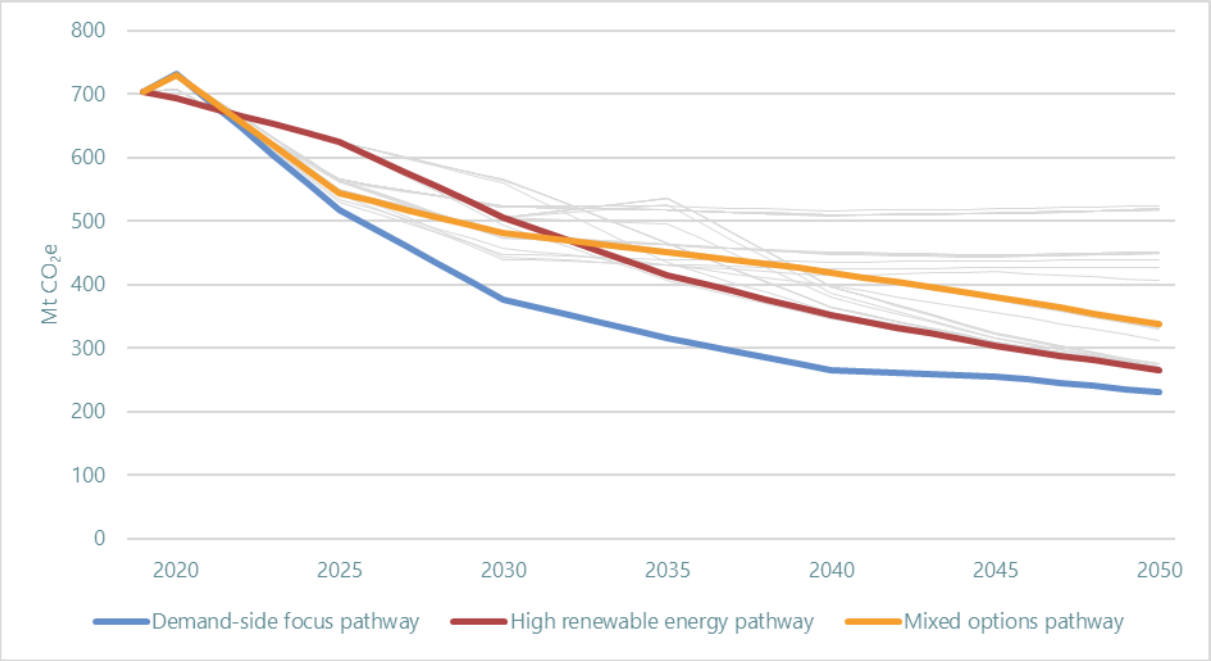
Source: Advisory Board (2023).

7.6 Agriculture and other non-CO_2 emissions

Greenhouse gases other than CO_2 accounted for 19.5% of EU emissions in 2019 (EEA, 2020b) ([22]). These emissions are expected to **fall by 20-62% by 2040** below 2019 levels in the 36 filtered scenarios but represent an increasing share of total greenhouse gases as reductions in net CO_2 emissions occur more rapidly.

([22]) This reference, and other references to 2019 emissions in this section come from the 2022 EU inventory submission (EEA, 2022a). Where greenhouse gas emissions are aggregated the 100-year Global Warming Potential metric from the IPCC 4th Assessment Report is used.

Figure 28 Total non-CO_2 emissions (filtered scenarios, EU)



Note: these emissions are aggregated using the 100-year global warming potential from the IPCC Fourth Assessment Report

Source: Advisory Board (2023).

The EU's main non-CO_2 emissions come from methane and nitrous oxide, which in 2019 accounted for 11% and 6.2% of EU emissions, respectively. In the filtered scenarios, non-CO_2 emissions represent between **41% and 90% of residual gross emissions in 2050**, and hence require to be compensated by carbon removals, in particular from the land sector, in order to reach net zero emissions (Rogelj, J., et al., 2021). However, the capacity of the EU to remove carbon is limited, and hence a rapid reduction of non-CO_2 emissions, in particular from the agriculture sector, is critical to limit the reliance on carbon capture technologies (Soergel et al., 2021).

Options for reducing emissions of both of these gases exist and, in the IPCC AR6, contribute around 13% of emission reductions in pathways that achieve net zero greenhouse gas emissions at global level (IPCC, 2022b). The IPCC also notes that deep reductions in methane emissions would lower the level of peak global warming, since methane has a relatively short lifetime in the atmosphere but contributes 81 times as much global warming as CO_2 over a twenty-year period.

Agriculture accounts for the majority of methane emissions in the EU (55% in 2019) (EEA, 2020b), with emissions mostly from enteric fermentation from livestock, and some from manure management. Nitrous oxide emissions are also predominantly associated with the agricultural sector (73% in 2019) (EEA, 2020b), with emissions mostly caused by the application of nitrogen fertilisers to the soil, both for food crops and feed crops for livestock, and some emissions from manure management.

Across the wider European region ([23]), the filtered scenarios generally achieve methane emissions reductions of 35-50% between 2019 and 2040, with methane emissions from the agriculture sector

([23]) Wider European region results ('Europe R10' region) are used because many of the scenarios provide more granular detail at this resolution.

dropping by 15-40%. The Demand-side focus scenario achieves a higher level of methane emissions reductions at 61%. The filtered scenarios display N_2O emission reductions of 7-52% in agriculture between 2020 and 2050.

7.6.1 Decarbonisation options for non-CO_2 emissions in the scenarios

Shift in diets

A sustainable reduction in agricultural emissions relies on a both a reduction in the production and in the demand in the EU. Lower EU demand can avoid a shift of the production of livestock and feed crops to non-EU countries and their imports to the EU with the related transport emissions.

While methane emissions from agricultural production can be reduced to some extent without altering production patterns, such reduction necessitates a behaviour shift towards plant-based diets with a concurrent reduction in livestock production.

- For example, in the Demand-side focus pathway, the demand for livestock drops by 58% between 2019 and 2040 as the share of livestock in the total food demand (kcal/capita/day) drops from 29% to 13%. The demand for feed crops for livestock also decreases by 41%. This scenario shows a gradual increase in the share of plant-based proteins in the total dietary protein supply, from around 40% to 80% between 2015 and 2050, while avoiding an increase in food prices (Soergel et al., 2021). This scenario assumes a gradual transition of dietary patterns towards a lower consumption of animal calories and processed foods, and a higher consumption of fruits, vegetables, nuts and staples (Soergel et al., 2021), as proposed by the EAT-Lancet Commission (Willett, W. et al., 2019).
- In the 'Mixed options pathway', the demand for livestock for food also drops significantly, by 47% between 2019 and 2040. In this scenario, the share of livestock in the total food demand (kcal/capita/day) drops from 32% to 17% during the same period. The availability of detailed data from other scenarios regarding diets is limited.

Figure 29 Share of livestock in food demand (iconic scenarios, Europe)

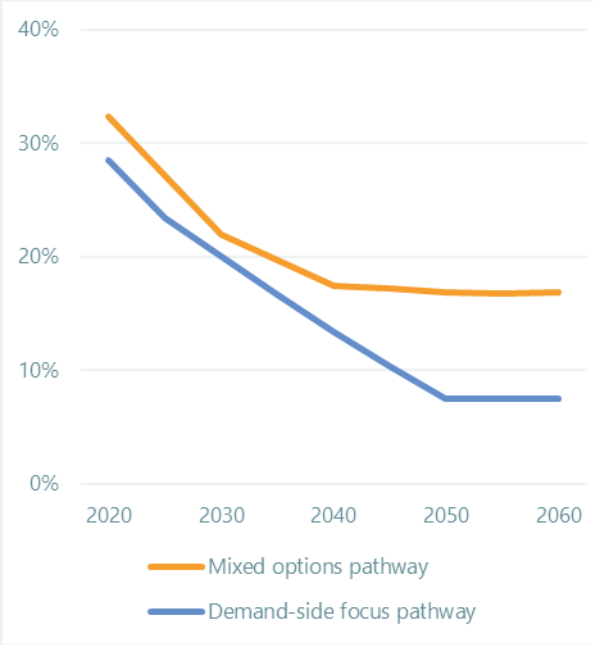
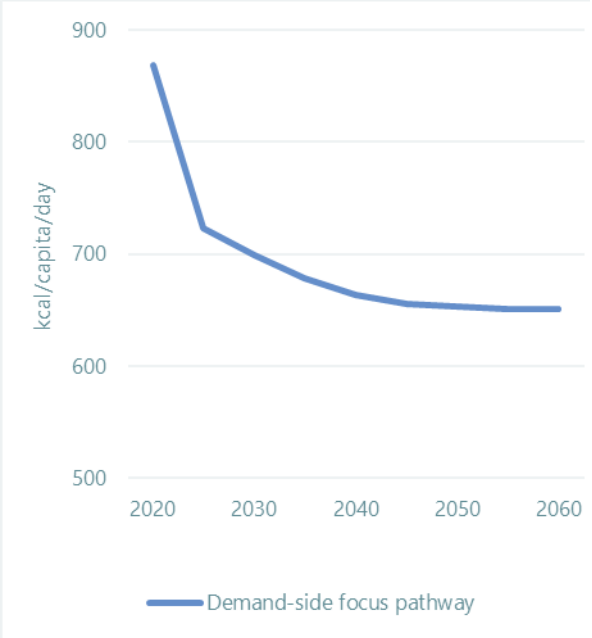


Figure 30 Food waste (iconic scenarios, Europe)



Source: Advisory Board (2023).

Reduction of food waste

Further reduction in emissions from livestock production and croplands can also be achieved via a reduction of food waste.

The 'Demand-side focus pathway' assumes a **24% reduction in food waste** in Europe between 2019 and 2040, which is aligned with the recommendations from the EAT-Lancet Commission (Willett, W. et al., 2019). The availability of detailed data from other scenarios on food waste is limited.

Reducing nitrogen fertiliser use

Some filtered scenarios display up to 26% reduction in nitrogen fertiliser between 2020 and 2030, and up to 34% reduction by 2040. These reductions are aligned with, and go beyond, the EU's Farm to Fork Strategy's objective to reduce fertiliser use by 20% by 2030.

- The Demand-side focus pathway shows 21% reduction in nitrogen fertiliser use between 2020 and 2040 (Soergel et al., 2021).
- The Mixed options pathway also assumes a sharp reduction in nitrogen fertiliser use (-25% between 2020 and 2040).

Figure 31 Nitrogen fertiliser use (iconic pathways, Europe)

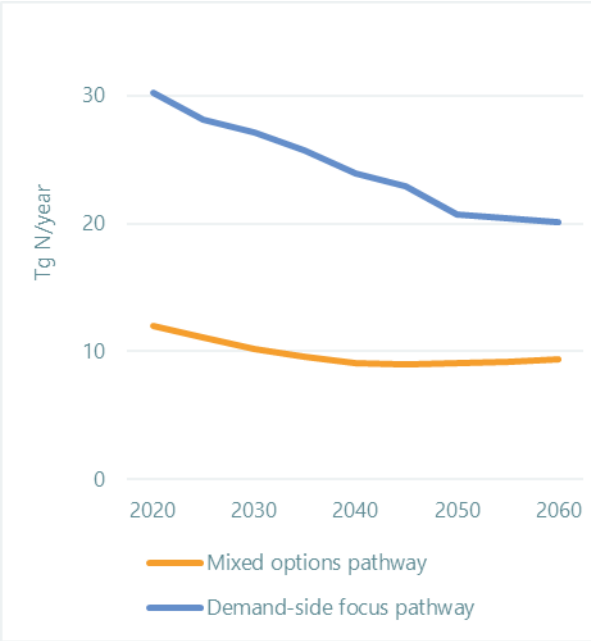
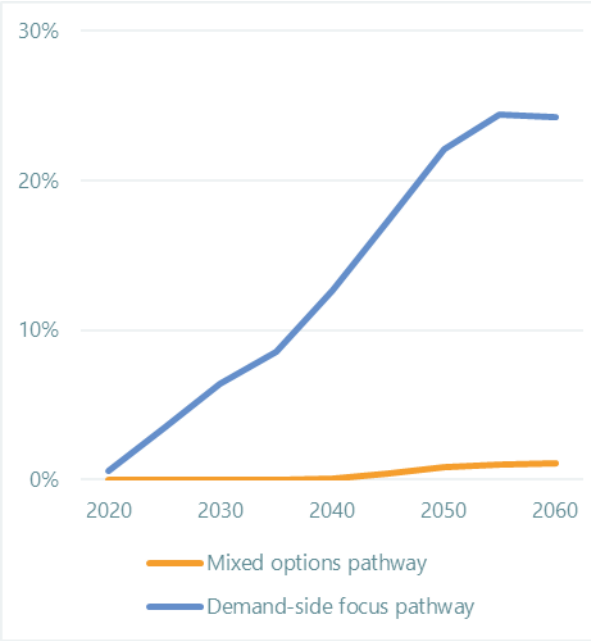


Figure 32 Share of energy crops in crops land cover (iconic pathways, Europe)



Source: Advisory Board (2023).

Effects of biofuel and biogas demand and production

In the filtered scenarios, the production of bioenergy crops in the wider Europe region reaches up to 243 million tonnes per year by 2040, with the upper end of this range coming from the 'Demand-side focus pathway' (Soergel et al., 2021). In the 'Mixed Options pathway', the production of energy crops increases to only 0.6 million tonnes in 2040. In the filtered scenarios, bioenergy crops reach up to 13% of the surface of the total croplands between 2020 and 2040.

Biogas production from crop residues and animal wastes has a large potential for bioenergy production (biomethane) and to the recycling of nutrients to soils, through the use of digestates (i.e. residual organic matter after anaerobic digestion). Biofuel can have diverging climate effects. On one hand, it replaces fossil fuel. On the other hand, increased land-use intensity and land-use change can lead to emissions – both CO_2 and non-CO_2.

Non-CO_2 emissions from the energy and waste sectors

In 2019, waste represented 24% of methane emissions (EEA, 2020b). Methane emissions in the waste sector are caused by landfill sites, sewage treatment or leaks from biogas production. In the filtered scenarios, emission reductions of methane from waste reach 45-59% between 2020 and 2040.

Following agriculture and energy, the third largest emitter of methane emissions is the energy sector, which represented 12% of methane emissions in 2019 (EEA, 2020b). Those are mainly due to methane leaks during the extraction, transport and storage of fossil energy, and from venting and flaring. In the filtered scenarios, methane emissions from the energy sector decrease by 73-91% between 2020 and 2040.

Figure 33 CH_4 emissions from the energy sector (iconic pathways, Europe)

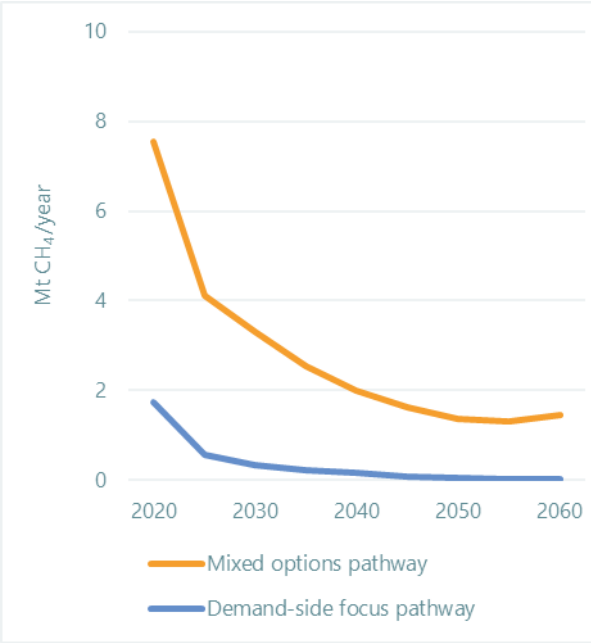
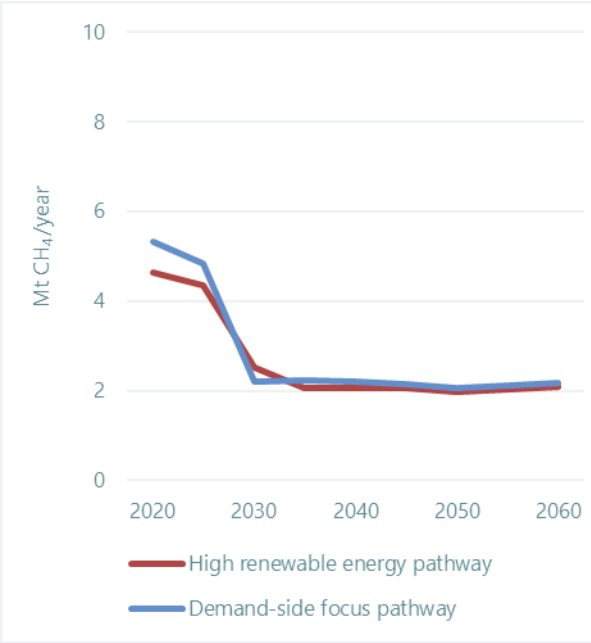


Figure 34 CH_4 emissions from the waste sector (iconic pathways, Europe)



Source: Advisory Board (2023).

7.6.2 Options for further emission reductions in agriculture

Agricultural production methods are currently not optimised for reducing greenhouse gas emissions, meaning that there is scope to reduce emissions to some extent without altering the production mix on individual farms. According to a recent EU-wide study, technological options can reduce agricultural emissions by 10% (Fellmann, T., et al., 2021). Country-specific studies show that the extent of greenhouse gas mitigation is in the range of 10-30% of total agricultural emissions (Lanigan, G. J., et al., 2018; Moran, D., et al., 2011; Pellerin, S., et al., 2017; Vermont, B., De Cara, S., forthcoming). While this reduction alone

is not sufficient to achieve net zero emissions by 2050 in Europe, it is an important additional step along with reducing livestock production and improving the utilisation of agricultural products.

Technology and farm management-based mitigation potential is not well represented in the scenarios. Overall, it appears that it is technically possible to reduce carbon emissions and carbon intensities somewhat further than what is assumed in the scenarios. This implies that it may be possible to reduce EU residual emissions below those derived from the filtered scenarios.

Maintaining crops yields while reducing fertiliser use would require the deployment of resource-efficient agricultural practices e.g. precision agriculture, using fertilisers with lower N_2O emission patterns, higher legume cultivation to increase biological nitrogen fixation and other technological innovation.

Changes in crop yields are and will be even more affected by climate change, with increasing frequency of heat waves, of droughts and of heavy precipitation creating more frequent and more severe shocks to crop yields (EEA, 2019). Crop yields will therefore be increasingly dependent on climate adaptation measures through combinations of changes in cultivars and in management practices, and the use of crop diversification, integrated soil and water management, and agroecological practices (e.g. agroforestry).

Increasing the efficiency of livestock production has the potential to reduce greenhouse gas emissions if the overall production does not increase along with the efficiency changes. Such efficiency changes can be achieved via various farming methods both for ruminants (cattle, sheep) and monograstrics (pigs, poultry), including genetic changes via breeding for higher overall efficiency, changing the herd structure to reduce the number of breeding animals (e.g. earlier calving), improvements in feeding (better feed conversion), and an increase in the overall health of the animals. Furthermore, enteric methane emissions from ruminants can be reduced by using feed additives (e.g. specific algae species, tannin rich forage, authorised chemical additives) and animal breeding (selecting for low-methane cattle and sheep). Direct N_2O and CH_4 emissions from storage and use of livestock excreta can be reduced for both ruminants and monogastrics (pork and poultry) by a number of technologies, including anaerobic digestion, slurry acidification and low-emission slurry spreading.

Much like crop yield, animal production is affected by the changing climate, both directly, with heat waves, and indirectly, through the availability of feed, water and also by changing pests and disease prevalence. Adaptation to these changes is important in maintaining production levels.

7.7 Carbon removals

The filtered scenarios display residual gross emissions between 390 and 1,165 Mt CO_2e in 2050 (344-1,126 Mt CO_2e without bunkers). These represent between 8% and 24% of 1990 emissions level.

These residual gross emissions need to be compensated with carbon removals, both from the land sector and from BECCS or DACCS (and possibly other methods mentioned below), in order to reach climate neutrality. This section explains the feasibility assessment of the carbon removals in the various scenarios, considering scientific evidence on the capacity of different types of carbon removals.

All filtered scenarios display net-negative emissions after 2050, or in some cases earlier, which would support the international balance of greenhouse gas emissions and help manage temperature overshoots.

Land-based removals are competing with BECCS. Therefore, the scenarios can be classified in two categories:

1. High removals from LULUCF and low BECCS;
2. Low removals from LULUCF and high BECCS.

7.7.1 Land use, land use change and forestry (LULUCF)

LULUCF accounted for net removals of 237 Mt CO_2 in 2019 and 212 Mt CO_2 in 2021 (EEA, 2022b). These net values include carbon removals from forest land and harvested wood products (the storage of carbon in biochar or other products is not included), and emissions from croplands, grasslands, wetlands, settlements and other land use changes (the marine environment is not included). The scenarios might not represent the whole potential of agricultural soil carbon sequestration.

The filtered scenarios show minimum 266 Mt CO_2 carbon removals from the land sector in 2030, and 273 Mt CO_2 in 2040-2050. However, all scenarios exceed the values from the inventory in 2019-2021, and it is unclear whether climate impacts are integrated in the scenarios. The EU's biogenic carbon pools have decreased by 35% between 2013 and 2021, of which 90% resulted from a decline in forest land. The capacity of biomass and soil to remove carbon is forecasted to be increasingly affected by climate impacts, including:

- Droughts;
- Wildfires;
- Storms;
- Pests.

Some of the scenarios include up to 667 Mt CO_2 biogenic carbon removals in the EU in 2050 (c.f. Figure 35), which is supported by some estimates in the literature (Roe et al., 2019). However, other estimates of the carbon sink are considerably lower. Nabuurs et al. (2017) give an estimate of up to 441 Mt CO_2., while Pilli et al. (2022) give a range of **100 to 400 Mt CO_2 taking into account future impacts of climate change** (Pilli et al., 2022; Böttcher and Hennenberg, 2021; Nabuurs et al., 2017; Roe et al., 2019). This range implies that biogenic carbon sinks could at worst decrease by half of their capacity, and at most double in capacity by 2050, compared to today's level.

In consequence, the scenarios have been further filtered according to this upper bound. This maximum potential is higher than the EU's 2030 target of 310 Mt CO_2 for the LULUCF sector, however it is lower than the maximum capacities reported in the EU's 2030 Climate Target Plan (425 Mt CO_2 from LULUCF in 2050), or in the EU's 2050 '1.5LIFE' scenario (460 Mt CO_2 from LULUCF in 2050).

The coherence of land-based removals in the scenarios with bioenergy use has been verified, by applying an estimated limit of 12 EJ /year of bioenergy use (Ruiz et al., 2019; Creutzig et al., 2015; Frank et al., 2021; Beringer et al., 2011; Cornelissen et al., 2012; Daioglou et al., 2020; Hanssen, et al., 2020; Kalt, et al., 2020; Rogner et al., 2012; Wu et al., 2019) (as per the high concern feasibility indicators, the difference between the EU's bioenergy use and bioenergy production appears to be minor in the scenarios).

Figure 35 Net carbon removals from LULUCF direct and indirect (filtered scenarios, EU)

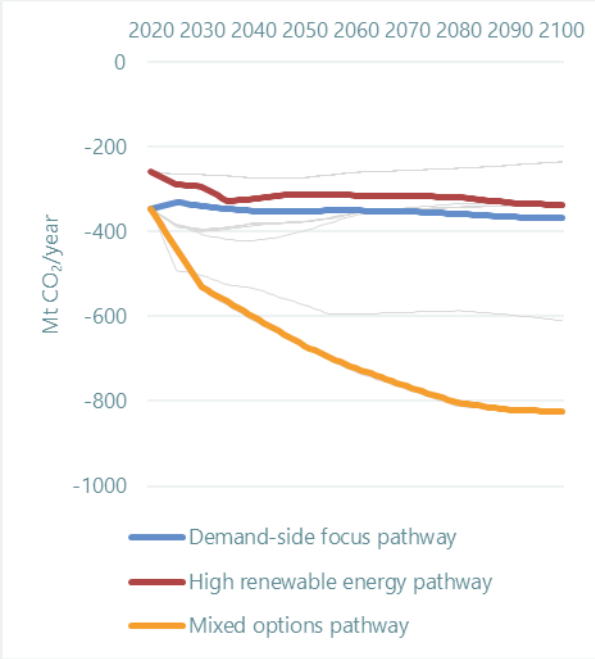
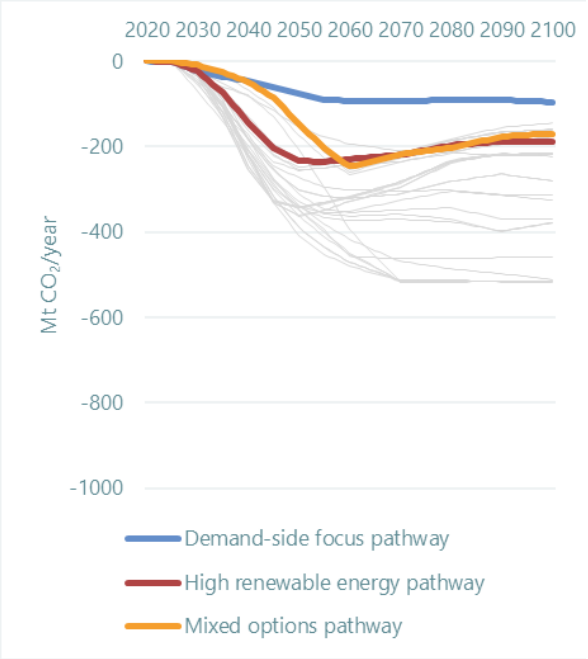


Figure 36 Carbon removals from BECCS and DACCS (filtered scenarios, EU)



Source: Advisory Board (2023).

7.7.2 BECCS and DACCS

As forecasted in the IPCC AR6, CCUS technologies are required in all pathways to climate neutrality. The EU's climate-neutral scenarios rely on a minimum of carbon removals of 8 Mt CO_2 from BECCS in 2030, 46 Mt CO_2 in 2040 and 70 Mt CO_2 in 2050. Some scenarios include DACCS, other do not.

CCUS technologies are used for both emission reductions and removals:

1. Reductions from industrial processes and the fossil energy industry, where carbon is captured directly from the emission source;
2. Removals from BECCS, where carbon is removed from the atmosphere via the land sector and from DACCS, where carbon is removed from the atmosphere.

They are treated together here, in order to assess the total storage capacity, however the first category is not counted as removals. Currently there are 10 planned CCUS projects in the EU, which represent a total planned capacity of 6 Mt CO_2 by 2025 and 18 Mt CO_2 by 2030 (BloombergNEF, 2022). In order to reach the minimum suggested by the scenarios by 2030, this capacity needs to double – which will require rapid investment and a suitable governance system.

Some scenarios assume up to 490 Mt CO_2 removed with CCUS in 2050. However, there are some geophysical limitations: the geological storage capacity is estimated to be limited to 57.2 Gt CO_2 (cumulative threshold, applies to the whole period) (estimated based on various assumptions on carbon prices) (Oei et al., 2014; Vangkilde-Pedersen et al., 2009; Holz et al., 2021; Chiquier, S. et al., 2022; Fuss, S. et al., 2018; Smith, J.E., et al., 2006; IPCC, 2013; Hepburn, C., et al., 2019; Smith, S., et al., 2023; IEA, 2020; Grant et al., 2022). Therefore, the scenarios have been further filtered according to this limit.

There are also some limitations regarding the techno-economic deployment, estimated at maximum 425 Mt CO_2 in 2050 (estimated based on various assumptions on carbon prices) (Holz et al., 2021). In consequence, the scenarios have been further filtered with this level.

From these totals, only BECCS and DACCS are counted as removals. Therefore, in the scenarios where total CCUS does not exceed 425 Mt CO_2e by 2050:

- the **maximum carbon removals achieved with BECCS** are 44 Mt CO_2 in 2030, 207 Mt CO_2 in 2040 and 336 Mt CO_2 in 2050,
- the **maximum carbon removals achieved with DACCS** are 3 Mt CO_2 in 2030, 7 Mt CO_2 in 2040 and 22 Mt CO_2 in 2050 (see Table 16).

Table 16 Annual carbon removals from climate-neutral scenarios and further feasibility analysis (filtered scenarios, EU)

	2019	2030	2040	2050
LULUCF	237 Mt CO_2		100-400 Mt CO_2	
BECCS	-	9-44 Mt CO_2	46-207 Mt CO_2	70-336 Mt CO_2
DACCS	-	0-3 Mt CO_2	0-7 Mt CO_2	0-22 Mt CO_2

Source: Advisory Board (2023).

DACCS plays a minor role in most scenarios. Its technological development is fast, yet uncertain, and there is a high uncertainty on its cost and applicability. Therefore, its potential could be higher, but this cannot be assessed given the knowledge we currently dispose of.

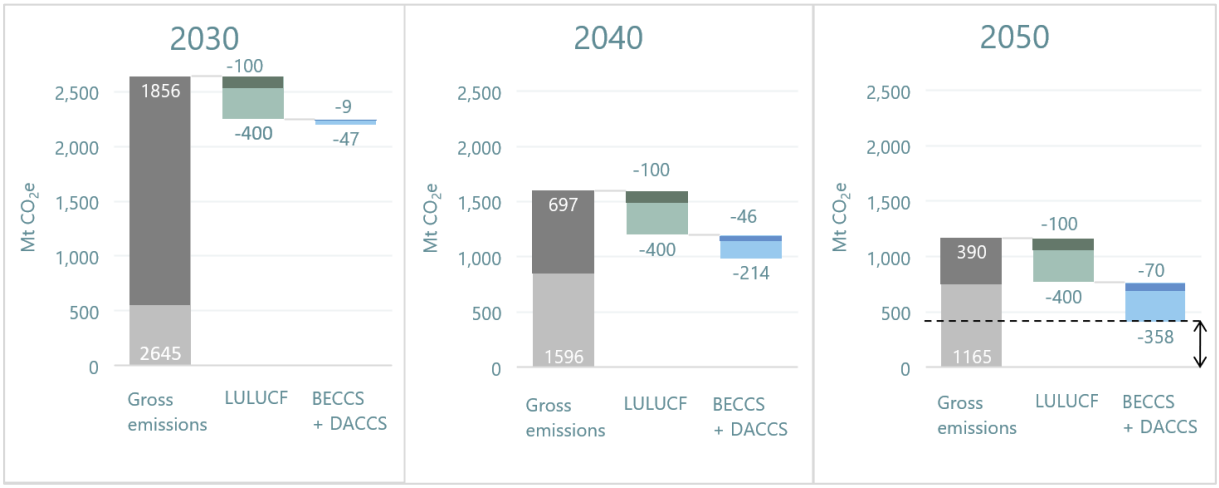
Some categories of carbon removals are not explicitly covered by the scenario analysis. For example, enhanced weathering, some applications for CCUS, or ocean alkalinisation are not included in the analysis.

7.7.3 Comparison with residual gross emissions

The 36 filtered scenarios display **residual gross emissions** (emissions without counting compensation from removals) **between 390 Mt CO_2e and 1,165 Mt CO_2e in 2050** (344 to 1,126 Mt CO_2e without bunkers). These represent between 8% and 24% of 1990 emissions level.

According to the feasibility assessment of the climate-neutral scenarios detailed above, carbon removals have a total maximum potential of 447 Mt CO_2 in 2030, 614 Mt CO_2 in 2040 and 758 Mt CO_2 /year by 2050 (see Table 16 Annual carbon removals from climate-neutral scenarios and further feasibility analysis (filtered scenarios, EU).

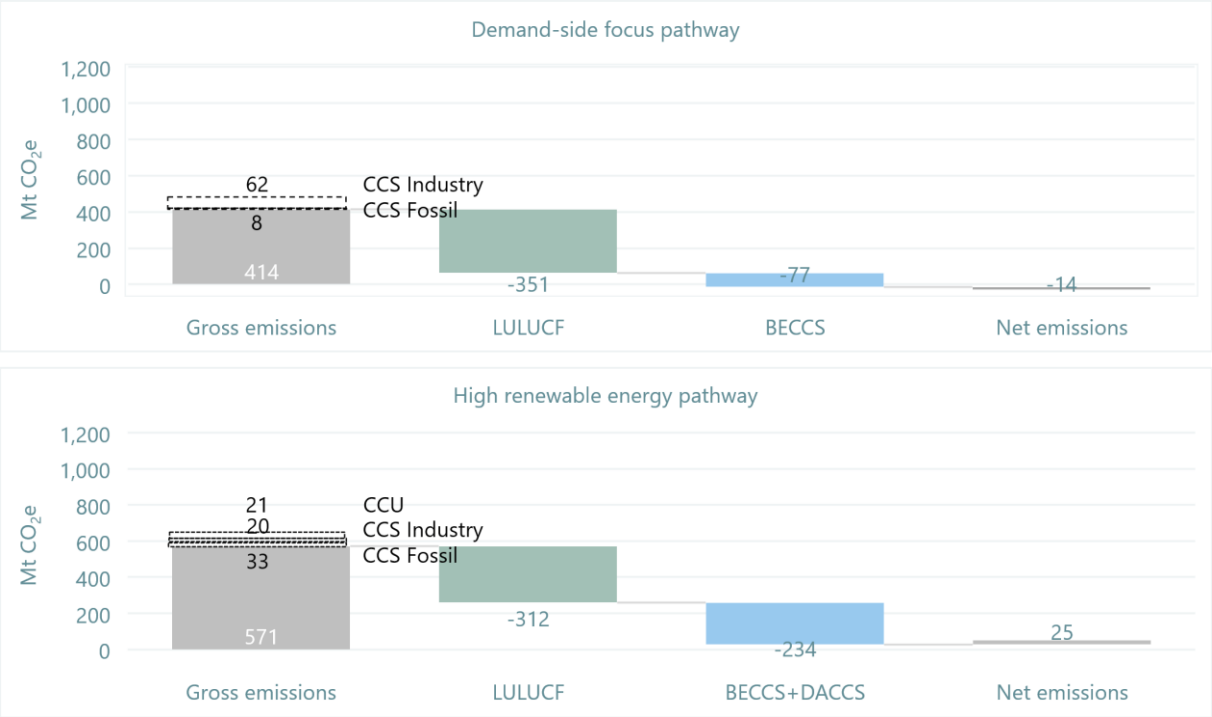
Figure 37 Comparison of gross emissions with removals capacities (filtered scenarios, EU)

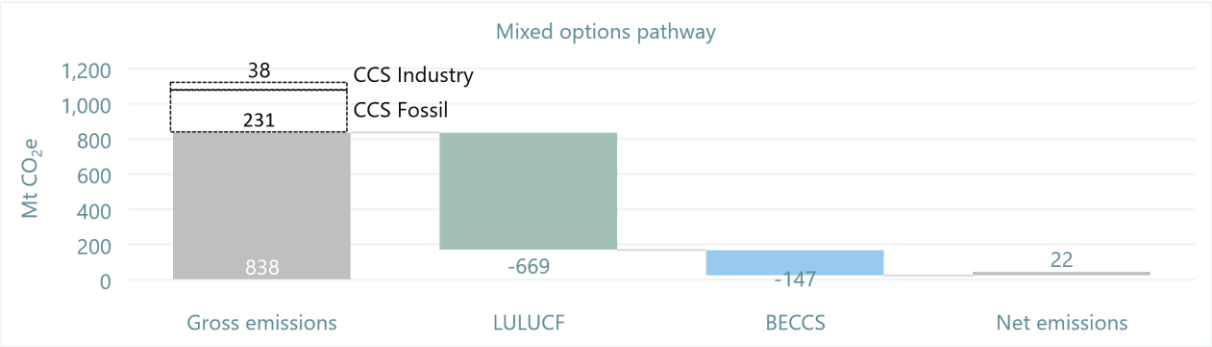


Source: Advisory Board (2023).

The iconic pathways illustrate that there are large disparities between pathways in terms of gross emissions, quantities of land-based removals, BECCS, as well as fossil CCS and industrial CCS. To understand where the residual gross emissions come from, see also Figure 15.

Figure 38 Comparison of gross emissions and removals in 2050 (iconic pathways, EU)





Source: Advisory Board (2023).

Carbon removals and policy incentives in the post-2030 framework

All the scenarios analysed in this report require large-scale deployment of carbon removals by 2050. However, reliance on carbon removals presents several challenges: the feasibility analysis conducted in this report found that several scenarios either deployed CCS (including BECCS) or expanded the land sink to levels considered to be challenging when compared with literature-based estimates.

Deploying carbon removals even below these levels will require particular efforts:

- Increasing the land sink requires changes in land use and management practices, as well as resilience to climate change impacts (Pilli et al., 2022).
- Scaling up other carbon removals technologies requires investment in new capacity to increase at a rate of over 50% per year at global level (Smith, S., et al., 2023), overcoming barriers such as absence of market incentives and governance challenges, as well as technological, social and environmental barriers that remain largely unexplored (Galán-Martín et al., 2021). For example, the development of certain methods of removals, such as DACCS or enhanced weathering, remains limited in most scenarios as it faces a high uncertainty on its cost and applicability.

This presents a dilemma for policymakers who need to find ways to incentivise sustainable carbon removal scale-up, while avoiding the risk of disincentivising greenhouse gas emission reductions in different sectors by more conventional means.

Incentivising both carbon removals and emission reductions could help minimise the EU's overall reliance on carbon removals to meet its climate targets, while taking steps to scale-up the technology sustainably.

For example, to ensure that sufficient mitigation efforts are deployed in sectors other than the LULUCF sector up to 2030, the European Climate Law limits the contribution of net removals to the EU 2030 climate target to 225 Mt CO_2e (EU, 2021). In parallel, the recently adopted LULUCF regulation (EU, 2023b) sets a target of 310 Mt CO_2e for net removals (without removing the limit of 225 laid out in the European Climate Law). This effectively increases the EU's 2030 target (to 57%) and limits the use of the sink as an offset for other sectors, thereby encouraging them to find other ways for reducing emissions.

This report does not provide detailed consideration of how the incentivisation of emission reduction and removals should operate. However, its findings confirm both the necessity of carbon removals scale-up, and the benefits of pursuing pathways with greater focus on other mitigation options, thereby underscoring the need for such incentives. As indicated in its 2023 Work Programme, the Advisory Board is planning to produce advice on carbon removals.

7.8 Economic implications: investment, technology and macroeconomic welfare

All pathways imply several different societal and economic changes. A plethora of aspects are relevant to consider in this regard, of which only a few can be touched upon here.

The IPCC AR6 finds that limiting warming requires **shifting energy investments** away from fossil fuels and towards low-carbon technologies. IPCC scenarios show that substantial investments are in particular required in the energy sector to move away from fossil fuels and towards renewables, nuclear power (in some scenarios), CCS, electricity networks, storage and end-use energy efficiency. Nonetheless, the IPCC also concludes that, at global level, the reallocation of spending within the energy sector is more pronounced than the overall investment increase (IPCC, 2022k).

At European level, Klaasen & Steffen (2023) and Lenaerts et al. (2021) analyse estimates published by the European Commission (among other sources) and find that the investments required for the EU to achieve its 2030 and 2050 climate targets are higher than historic levels, but within 2% of GDP annually. Klaasen & Steffen (2023) identify a need for increased investment above the 2016-2020 level even in the absence of the EU's 55% and climate neutrality targets, but find that this need is intensified by these targets and the more recent ambition to become independent of Russian gas.

The scenarios considered in this report vary in their reporting of economic data. Those that report investment data estimate annual energy supply investment to be equivalent to 1-2% of GDP during this decade, peaking at 1.1-2.1% of GDP in the early 2030s and falling to around 1% of GDP by 2050 ([24]).

The IPCC also finds that the **cost of low-carbon technologies** has declined rapidly over the past decades. It finds that the costs of small unit size technologies, such as solar, wind, batteries have declined faster than larger scale technologies, such as nuclear and CCS. They have also experienced faster adoption. Evidence also shows that the costs of key energy technologies have fallen faster than anticipated by experts (Meng et al., 2021). Today, many of these technologies often provide the more economically attractive investment than fossil-based alternatives. At the same time, growth rates of some other technologies, including CCS and nuclear, have been slower than previously anticipated, and the use of these technologies is related to additional abatement cost.

The **reduction of carbon intensity in production processes** is in a less mature development phase. The IPCC estimates that for basic materials (primary metals, building materials and chemicals), abatement costs are estimated in the range of $100-150 per t CO_2e, and more for the harder to abate components (such as carbon intensity of chemical feedstocks). This results in cost increases for the materials themselves), but translates into lower impacts (less than 1%) on the cost of finished products (like cars or drinks in plastic bottles)[25].

Looking at **welfare economic impacts**, standard macroeconomic estimates of the economic costs of mitigation summarised in the IPCC AR6 give figures of 2.6-4. 2% global GDP loss by 2050 in pathways consistent with 1.5°C compared to a reference scenario. Such estimates are highly dependent on which

([24]) These results are reported for the wider European region ('Europe R10').

([25]) These cost estimates are taken from Figure 11.13 in the IPCC AR6 WGIII report which gives estimates of 15%-115% for primary chemicals, 10%-50% for steel and 35%-115% for cement, equating to cost increases of under 1% for plastic bottles, homes or cars, and houses respectively (IPCC, 2022e).

policy instruments are used to incentivise mitigation action, and may also vary depending on the coordination between countries.

In its 2020 analysis, the European Commission estimated the GDP impact of the EU's 2030 target (a 55% reduction in net greenhouse gas emissions below 1990 levels) to be between -0.7 and +0.55% compared to 2030 baseline levels (EC, 2020a). Looking further ahead, the European Commission's Long Term Vision for 2050, published in November 2018, estimated the transition to climate neutrality would have a modest impact on overall GDP (between -1% and +3% compared to baseline) in both 2040 and 2050.

In terms of **welfare economic benefits and avoided impacts**, the IPCC AR6 Working Group III report found that for the case of limiting warming to below 2°C, global economic benefits outweigh mitigation costs if climate change impacts are assumed to be at the moderate to high end of the assessed range, and before accounting for non-market climate damages and sustainable development co-benefits of climate action (Figure SPM.7 of IPCC (2022k). This conclusion rests on a large body of research spanning numerous fields. However, synthesising these benefits is challenging due to the heterogeneity of this evidence, as noted by (Karlsson et al., 2020) and (Deng et al., 2018).

The IPCC AR6 report also states with medium confidence that the economic benefits of air quality improvement arising from mitigation action can be of the same order of magnitude as mitigation costs, and potentially larger (IPCC, 2022h). Karlsson *et al.* (2020) find that studies of air quality co-benefits are the dominant category in the literature. Global analysis has also found that the local health and local environmental benefits of early coal abatement outweigh the direct policy costs (Rauner et al., 2020). Examples of specific benefits of climate action are discussed in Section 7.9 on synergies and trade-offs with sustainable development.

In its World Economic Outlook, the IMF makes the case that climate action imposes short-term economic costs that are '*dwarfed by the innumerable long-term benefits of slowing climate change*' without quantifying the benefits of a specific mitigation scenario (IMF, 2020, 2022). Its 2020 outlook included an attempt to model the costs and benefits of a global net zero package, including taxes, investments and productivity gains from avoided climate change impacts. The GDP benefit for Europe is this scenario was estimated at 2.7% (in 2050, compared to baseline).

The integrated assessment models underlying the scenarios considered in this report are all inter-temporal energy-economy-environment models that maximise global welfare based on nested regional macro-economic production functions under given climate policy environments (Edenhofer et al., 2009). The models diverge in methodology, level of detail and specific technological and economic assumptions. By comparing models with different representations of the macro economy and energy system and by considering a broad range of scenarios, it is possible to assess the expected range of cost effects. Typically, mitigation costs are expressed as macro-economic consumption losses. These are calculated by comparing macro-economic consumption pathways with a reference pathway (business-as-usual), acknowledging that there are substantial scientific uncertainties regarding the nature of impacts and their monetisation, especially also in regard to the valuation of future effects and the discount rate used. The discount rate also affects the balance of costs and benefits, weighing effects between the short-term (e.g. costs related to mitigation) and long-term (*e.g.* avoided future climate change impacts).

According to IPCC AR6, the **employment effects** of mitigation policies tend to be limited on the aggregate level, but the transition can have significant sectoral, regional and distributional implications, mainly in the short term.

Distributional consequences are also important to consider both globally, but also within the EU. This is relevant in terms of both the experienced damage of climate change, and of the mitigation costs. Careful policy design is therefore needed for a just transition. Analysis of the evidence regarding the relationship between the implementation of a set of decarbonisation policy instruments and distributional outcomes suggests that negative short term distributional impacts on some groups have been identified (Peñasco et al., 2021) although in some cases policies can be designed or complemented to reduce them.

Activities related to **innovation, diffusion and adoption of low-carbon technologies** often create wider benefits to society, e.g. in terms of dynamic technological gains and competition wins (Griliches, 1992; Jaffe et al., 2004, 2005). The IPCC describes technology development and market deployment as two mutually reinforcing cycles that together drive down technology costs (page 889 of IPCC (2011)). Innovation is advanced by a combination of different types of policy instruments, including technology-push policies that stimulate innovation through funding, performing research and increasing the supply of trained scientists and engineers which contribute to knowledge-generation and provide technological opportunities (Mowery and Rosenberg, 1979; Anadon and Holdren, 2009; Mazzucato, 2013) -- and market pull policies that support market creation or expansion and technology transfer, thereby promoting learning by doing, economies of scale, and automation (Section 16.4.1 of IPCC (2022f)). Innovation challenges exist in different dimensions, and must combine technical, economic, financial, and socio-political changes (Scheffran and Froese, 2016). Such combined innovation cycles lead to important capacity building within Europe's economy and key technology sectors.

In an international context, the academic discourse on climate change mitigation has transformed from 'technology transfer' to interactive collaboration and from 'technology diffusion' to systems building (Scheffran and Frose, 2015). In the context of the UNFCC process, low-carbon innovation is seen as a comprehensive and iterative concept where learning and competence-building can enhance synergies between climate change mitigation and socio-economic development (Lema et al., 2015).

7.9 Synergies and trade-offs with sustainable development

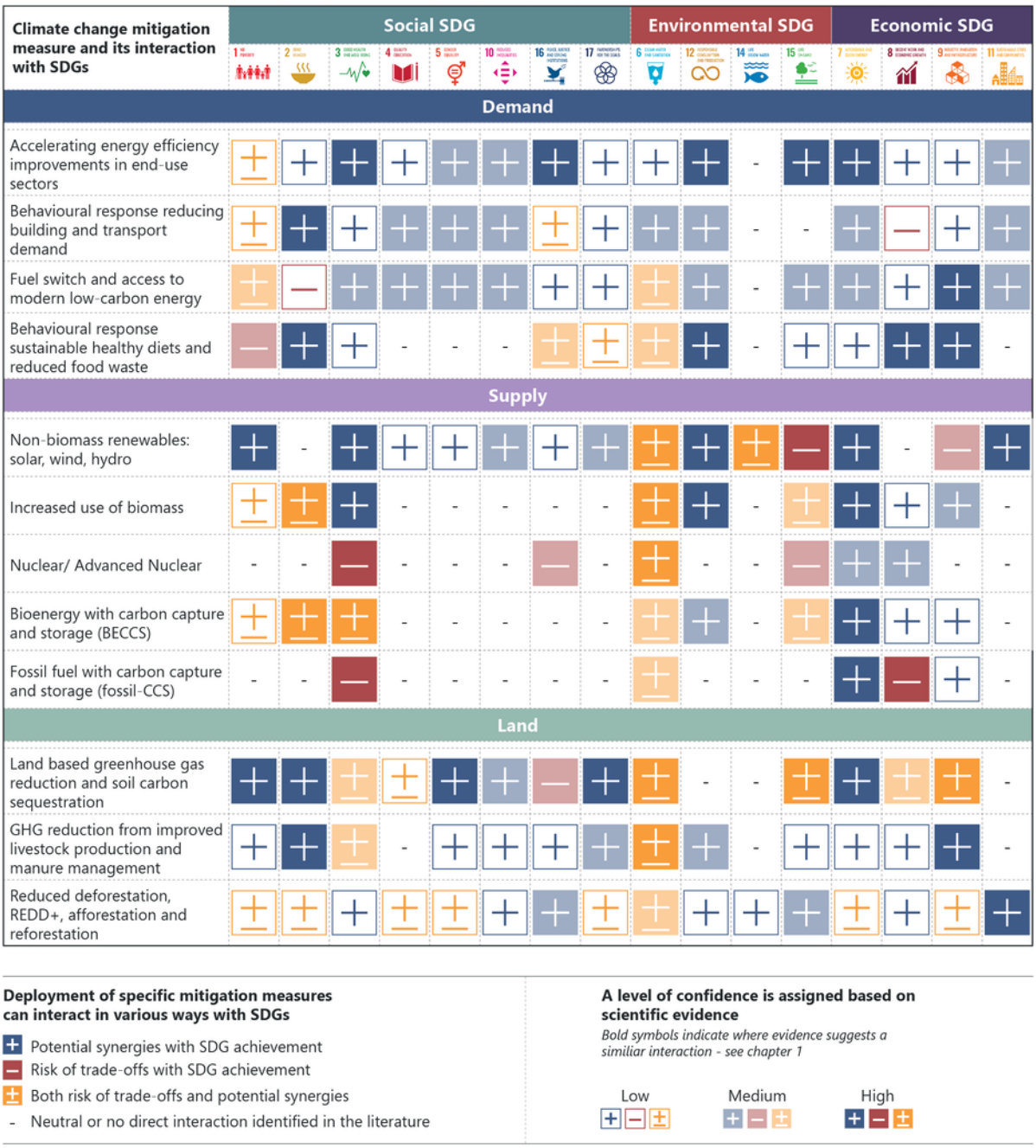
IPCC AR6 finds that accelerated and equitable climate action is critical to sustainable development (IPCC, 2022b). Potential benefits of climate action for sustainable development (often referred to as 'synergies') include reduced pollution, better health outcomes, new employment opportunities, and reduced pressures on land and water resources as well as on natural ecosystems. However, climate action can also produce negative outcomes for sustainable development (often referred to as 'trade-offs') depending on how greenhouse gas emission reductions are achieved. Reducing inequality, and addressing other types of inequity have been identified as ways to help reduce trade-offs, and thereby support deeper ambition for accelerated mitigation efforts (IPCC, 2022b).

To better understand the degree to which the three iconic pathways can lead to potential synergies or trade-offs between climate change mitigation and sustainable development, we apply a method based on a similar analysis that was carried by the IPCC to underpin Figure 2..28 in its Special Report on 1.5°C (Rogelj et al., 2018a) ([26]). This analysis allows to illustrate the interactions, be they synergies or trade-

([26]) This assessment applies a method that is adapted from a similar analysis in Chapter 2 of the IPCC Special Report on Global Warming of 1.5°C (SR1.5) (Rogelj et al, 2018) and as described in Section 2.SM.1.5 in chapter's supplementary material (Forster et al., 2018). The outcome of the IPCC analysis was illustrated in Figure 2.28 of the IPCC SR1.5. A more detailed synergy and trade-off matrix is included in the AR6 report (IPCC, 2022b), but this matrix does not supplementary material that facilitates its use as a performance comparison between scenarios.

offs, of individual mitigation measures with sustainable development goals (SDGs), as shown in Figure 39Figure 39.

Figure 39 IPCC illustration of interactions of individual mitigation measures with Sustainable Development Goals (SDGs), showing potential synergies and risks of trade-offs



Source: Figure 2.28 from the IPCC Special Report on Global Warming of 1.5°C (Rogelj et al., 2018b).

The analysis in support of this advice compares the outcomes of the three iconic pathways against the deployment of mitigation measures across the range of 36 filtered scenarios described in Section 4.4. It identifies their relative performance in terms of potential synergies and trade-offs with the SDGs. The method used in this advice is described in detail in Annex B. Potential synergies are portrayed in the

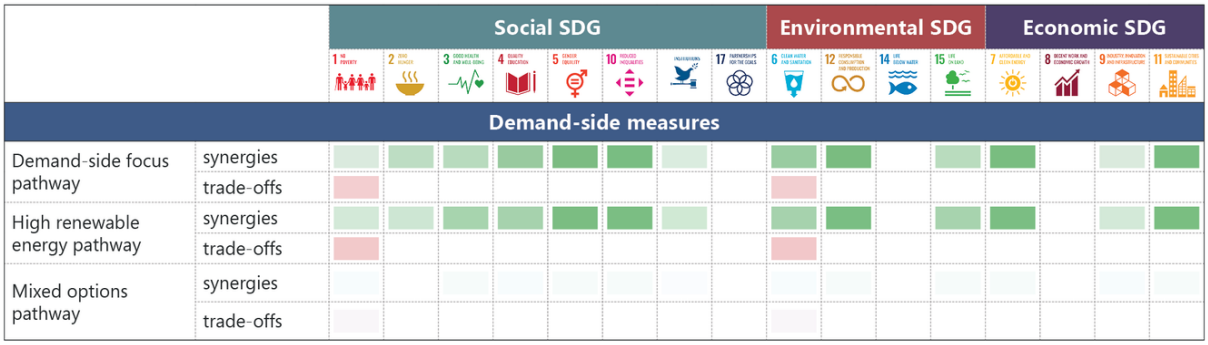
figures below using green, with darker shades denoting stronger synergy. Similarly, potential trade-offs are portrayed using red, with darker shades denoting greater trade-offs.

7.9.1 Demand-side measures

The IPCC assessment finds that **demand-side measures** have potential synergies across a range of social, environmental, and economic SDGs, and relatively few trade-offs. This can be seen by glancing at the top panel of Figure 39 above and is reiterated when the iconic pathways are compared (in Figure 40 below). The Demand-side focus and High renewable energy pathways have greater deployment of such demand-side measures compared to the Mixed options pathway, suggesting greater potential to support the achievement of the SDGs. The strongest identified synergies are related to health and well-being at a local level, such as gender equality (SDG 5), affordable and clean energy (SDG7), reduced inequalities (SDG10), sustainable cities and communities (SDG 11) and responsible consumption and production (SDG 12). This corresponds to evidence in AR6 that indicates that sustainable behaviour change measures are likely to lead to synergies with the SDGs and that their achievement may also be accelerated (IPCC, 2022d). Moreover, literature indicates that renewable energy will also lower the chances of climate-induced curtailment of energy production due to climate change impacts on water (IPCC, 2022m) while helping the preservation of river ecological integrity (IPCC, 2022c)(IPCC, 2022, Chapter 18 CRDT).

Besides synergies also potential trade-offs are identified with eliminating poverty (SDG 1) and clean water and sanitation (SDG 6), highlighting the need to manage the transition carefully.

Figure 40 Potential SDG synergies and trade-offs from demand-side mitigation measures in Iconic pathways



Note: The SDGs listed are 1 – No poverty, 2 – Zero hunger, 3 – Good health and well-bering,4 – Quality education, 5 – Gender equality, 10 – Reduced inequalities, 16 – Peace, justice and strong institutions, 6 – Clean water and sanitation, 12 – Sustainable production and consumption, 14 – Life below water, 15 – Life on land, 7 – Affordable and clean energy, 8 – decent work and economic growth, 9 – Industry, innovation and infrastructure, 11 – Sustainable cities and communities.

Source: Advisory Board (2023).

7.9.2 Supply-side measures

Supply-side measures also contain synergies with multiple SDGs, but are associated with a greater number of potential trade-offs. This feature is seen across all iconic pathways, but most strongly in the Mixed options pathway which has greater deployment of nuclear power and fossil CCS. These measures bring potential synergies and trade-offs with SDG 6 (clean water and sanitation) as also identified in AR6 (IPCC, 2022, WGII Chapter 17) due to high water consumption, potential synergies with SDG 7 (affordable and clean energy), and potential trade-offs with health (SDG 3) and life on land (SDG 15). One still has

to consider that the expansion of renewable energy potential impact on ecosystems (IPCC, 2022 WGII Chapter 13 Europe). Nevertheless, modular and distributed renewable energy generation and storage can provide enhanced resilience to the shocks and stresses from climate change (IPCC, 2022 WGII Chapter 18 CRD).

The Demand-side focus and High renewable energy pathways display a similar profile of potential synergies and trade-offs. However, compared to the Mixed options pathway, the contributions to this result are more evenly spread across the different supply-side measures shown in Figure 41 .

In all three iconic pathways, it is notable that **BECCS deployment** contributes relatively little to the synergies and trade-offs. This is largely because the iconic pathways were selected while already being mindful of the environmental risks of BECCS, resulting in markedly lower BECCS deployment in the iconic pathways compared to the other scenarios in the comparison set. AR6 and other literature have also indicated trade-offs between carbon capture services and the provisioning of other services like bioenergy or competition for natural resources like water (Hu et al., 2020; Krause et al., 2020; Stenzel et al., 2021).

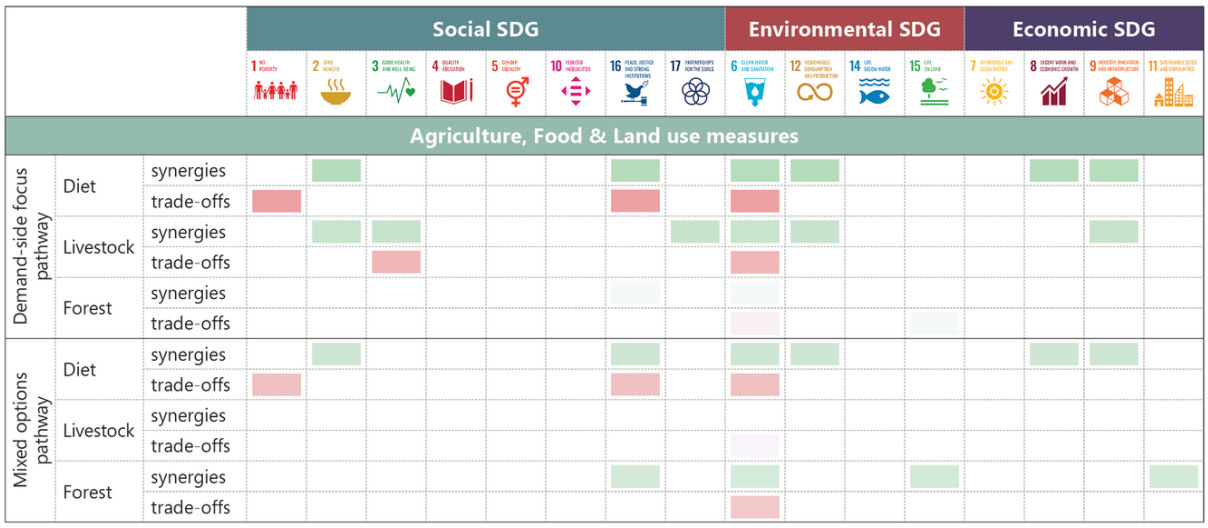
Figure 41 Potential SDG synergies and trade-offs from supply-side mitigation measures in Iconic pathways

Note: The SDGs listed are 1 – No poverty, 2 – Zero hunger, 3 – Good health and well-bering,4 – Quality education, 5 – Gender equality, 10 – Reduced inequalities, 16 – Peace, justice and strong institutions, 6 – Clean water and sanitation, 12 – Sustainable production and consumption, 14 – Life below water, 15 – Life on land, 7 – Affordable and clean energy, 8 – decent work and economic growth, 9 – Industry, innovation and infrastructure, 11 – Sustainable cities and communities**.**

Source: Advisory Board (2023).

The **agriculture, food and land-based measures** are available only for the Demand-side focus and Mixed options pathways, due to differences in how variables are reported across models. These pathways show diversity in the profile of SDG co-benefits. The Mixed options pathway makes much greater use of expanding the land sink, absorbing twice as much CO_2 in 2050 as the Demand-side focus pathway. However, the Demand-side focus pathway makes greater use of improvements of low emission livestock production techniques (measured by lower emissions of methane and nitrous oxide per unit of production). For sustainable diet, reduction in the share of livestock in overall food demand is used as a proxy indicator. This measure is deployed in both pathways, producing potential synergies across multiple SDGs, but also trade-offs, for example in communities where livestock production is considered to represent the best use of available land.

Figure 42 Potential SDG synergies and trade-offs from agriculture, food and land-based mitigation measures in iconic pathways



Note: agriculture and land-use data are not available for the High renewable energy pathway. The SDGs listed are 1 – No poverty, 2 – Zero hunger, 3 – Good health and well-bering,4 – Quality education, 5 – Gender equality, 10 – Reduced inequalities, 16 – Peace, justice and strong institutions, 6 – Clean water and sanitation, 12 – Sustainable production and consumption, 14 – Life below water, 15 – Life on land, 7 – Affordable and clean energy, 8 – decent work and economic growth, 9 – Industry, innovation and infrastructure, 11 – Sustainable cities and communities.

Source: Advisory Board (2023).

7.9.3 Local implementation

Scales are increasingly identified as important in relation to synergies and trade-off for local implementation. As Alcamo et al. (2020) has identified there is evidence of a detachment between national planning and actual local implementation, which can lead to an SDG trade-offs between these scales, and how 'synergy driver' i.e., policies and measures that positively advance two or more goals are particularly important.

Thus, as identified by the IPCC (2022 WGII Chapter 18) enhancing the coordination of adaptation and mitigation can strengthen regional and local development pathways to support climate resilient development. Furthermore, some objectives can only be addressed at the sub-national scale or at a more regional level, for example, in the case of ecosystems which are location specific (Renaud et al., 2022).

7.9.4 Just transitions

Just transitions provide a framework that combines climate, energy and environmental justice scholarships (McCauley and Heffron, 2018). This approach has to also incorporate different mitigation strategies under future climate scenarios transition paths embedded in mitigation (IPCC WGII Chapter 13, 2022; Aparicio, 2017). Just transitions consider distributional aspects on how different groups benefit or experience impacts from the changes required, from a social justice perspective. For example, development of industrial just transition policies consider structural inequalities, social issues, race, gender, and socio-economic status (Allwood, 2020).

Another key element to consider in just transitions are procedural aspects. For example proactive and anticipatory planning of large-scale infrastructure development or programmes to avoid lock-in effects and economic development strategies that consider needs for workforce skills and training. According to Frantzeskaki (2019) pathways that 'are robust to future scenario uncertainty are those that shift Europe towards sustainable lifestyles, support and strengthen good governance for sustainability and promote adaptive resource management for water, agriculture and energy'. In this context, policy makers have a critical opportunity to act on all-encompassing and just transitions like the one led by the EU Green Deal and the EU climate neutrality target (IPCC WGII Chapter 13, (Filipović et al., 2022).

7.9.5 Health synergies

Climate action has many associated positive health synergies. In particular in Europe, it has the synergy of reduced air pollution, one of the most important public health concerns. According to the EEA (2023a) in 2021, 97% of the urban population was exposed to concentrations of fine particulate matter above WHO guidelines. Furthermore, the health of children and adolescents is also impacted with over 1,200 premature deaths per year in people under the age of 18 in Europe which significantly increases the risk of disease later in life from the negative impacts of air pollution (EEA, 2023a). Thus, mitigation policies could help reduce health impacts, from e.g. increases in temperature and changes in precipitation that would impact future air quality due to increased risk of wildfires and related air pollution episodes, and increasingly for mental health (IPCC, 2022 WGII Chapter 13).

Therefore, there are substantial health benefits from cleaner air and improved well-being. It is also aligned with the EU´s Zero Pollution action plan (EC, 2021b) for reducing air, water and soil pollution to levels no longer considered harmful to health and natural ecosystems by 2050. The action plan introduces a 2030 target of improving air quality to reduce the number of premature deaths caused by air pollution by 55% with a possible forthcoming revision of the EU Ambient Air Quality Directives (AAQDs(EU, 2008).

Some of the most important health and well-being synergies associated with climate action come from investing in key basic infrastructure like clean energy, thermal comfort, clean drinking water and sanitation, public transport, and access to healthy diets and improved air quality from transformative solutions across economic sectors including agriculture, energy, transport, and buildings (Chang et al., 2017; Underhill et al., 2020). The net health co-benefits resulting from meeting the Paris Agreement targets in terms of air quality were estimated at health co-benefits-to-mitigation ratios of between 1.4 and 2.5 (Markandya et al., 2018). Thus, electrification and renewable energy deployment combined with building retrofits, clean mobility and redesigned urban spaces, can create many health synergies (IPCC, 2022 WGIII). In a few cases of relatively low-polluted jurisdictions, a carbon price could increase mortality risks due to emissions increases from bioenergy use and land-use changes; hence institutional and governance factors have to be considered to secure health co-benefits of climate action (Huang et al., 2023).

7.9.6 Conclusion

In conclusion, the analysis of the iconic pathways largely echoes the conclusions from the underlying literature and IPCC assessments that climate action can contribute to multiple improvements in health, well-being and environmental protection, and that it can also produce trade-offs in these same areas that need to be addressed and managed by policymakers. Implementation of the iconic pathways would reduce future climate risks, thus reducing future adaptation costs and losses and damages (IPCC, 2023). Some unavoidable climate change impacts will still pose a threat to human health and prosperity and the natural environment, as discussed in Section 7.8.

The analysis also goes beyond the IPCC conclusions by demonstrating that the three iconic pathways have important differences in their respective synergy and trade-off profiles. In particular, the analysis shows that focussing on demand-side actions that promote modest use of natural resources offers more synergies and fewer trade-offs across multiple SDGs.

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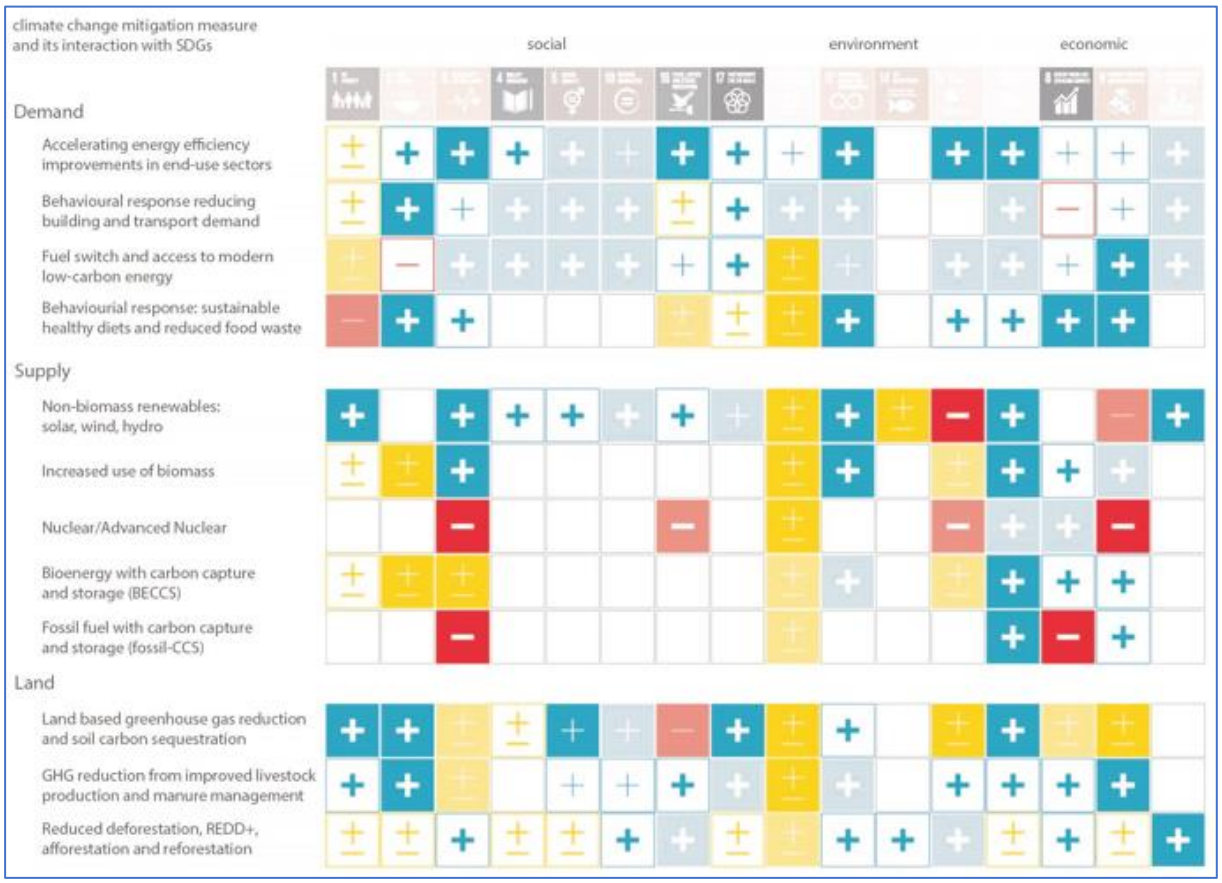
Annex A. Sustainable Development Analysis Methodology

This annex provides a step-by-step summary of the methodology used to conduct the sustainable development benefit and trade-off analysis contained in Section 7.9 of this report.

As a first step, 11 relevant mitigation actions were identified, and their deployment was recorded in each of the iconic pathways and the wider collection of assessed scenarios. This deployment profile is summarised in Table 17 below, and documented in greater detail in Table 18.

As a second step, the pathways' implications for each of the UN Sustainable Development Goals was estimated by using an IPCC-assessed synergy and trade-off matrix (see Figure 43 below). Across the three iconic pathways, every mitigation option was given a deployment score reflecting the level of deployment in the pathway, relative to the median deployment level in the assessed scenarios. This deployment score was then multiplied by +1 for each identified synergy, and -1 for each identified trade-off. Potential synergies and trade-offs are displayed separately (i.e. no attempt is made to combine positive and negative into a net benefit estimate).

Figure 43 Extract from IPCC matrix, mapping sustainable development synergies and trade-offs against mitigation options



Source: Figure 2.28 from the IPCC Special Report on Global Warming of 1.5°C (Rogelj et al., 2018b).

Table 17 Mitigation actions used in sustainable development analysis, and summary of their deployment in iconic pathways

	Mitigation Measure	Deployment in iconic pathways and across assessed scenarios
Demand-side measures	Accelerating energy efficiency improvements in end-use sectors	• The **Demand-side focus** and **High renewable energy pathways** have greater deployment of these options. • The **Demand-side focus pathway** has the greater behavioural response (extensive margin), while the **High Renewable pathway** demonstrates greater efficiency gains (intensive margin).
	Behavioural response in buildings and transport	
	Fuel switch and access to modern low-carbon energy	
Supply-side measures	Non-biomass renewables: solar, wind, hydro	Different pathways emphasise different supply-side options. • **The Demand-side focus pathway** deploys the most bioenergy of all the assessed scenarios but has the lowest BECCS deployment (77 Mt CO_2 captured in 2050). • **The High renewable energy** has deployment close to the average across scenarios for most of these supply-side options • **The Mixed options pathway** deploys the most nuclear energy of all the assessed scenarios and among the highest in deployment of fossil CCS.
	Increased use of biomass	
	Nuclear/advanced nuclear	
	BECCS	
	Fossil fuels with carbon capture and storage (fossil-CCS)	
Measures related to agriculture, food and land use	Behavioural response: Sustainable healthy diets and reduced food waste	• **The Demand-side focus pathway** has the greatest deployment of all assessed scenarios in the behavioural response and improved livestock production options. • **The Mixed options pathway** has the highest deployment of afforestation of all assessed pathways (for which we use the amount of net removals from land as a proxy). • [Several scenarios, including *the High renewable energy pathway*, do not include suitable proxy variables for the first two options]
	Greenhouse gas reduction from improved livestock production and manure management systems	
	Reduced deforestation, REDD+, afforestation and reforestation	

Note: REDD+, reducing emissions from deforestation and forest degradation in developing countries.

Source: Advisory Board (2023).

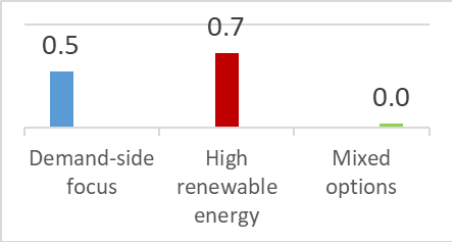
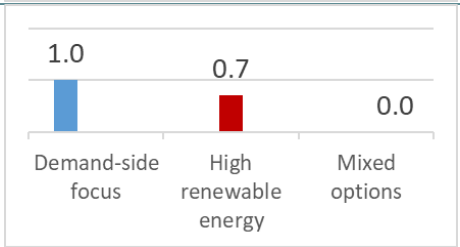
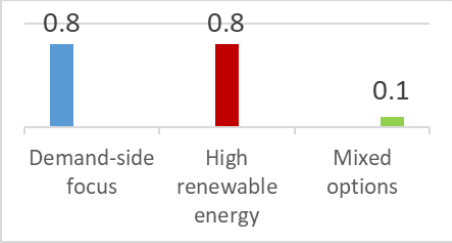
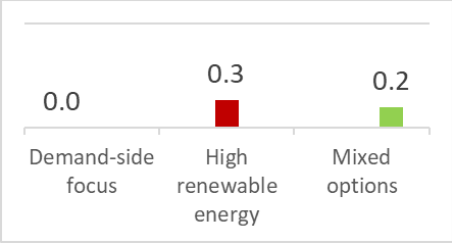
This section summarises results of the SDG analysis of the iconic pathways. In the figures below, potential synergies are portrayed using green, with darker shades denoting stronger synergy. Similarly, potential trade-offs are portrayed using red, with darker shades denoting greater trade-offs.

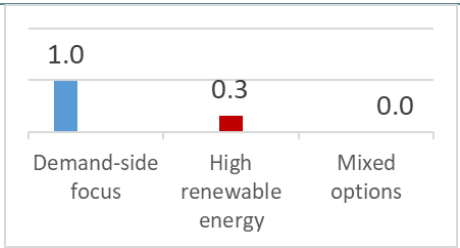
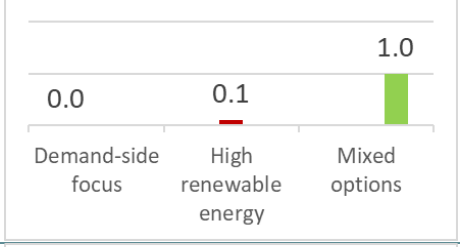
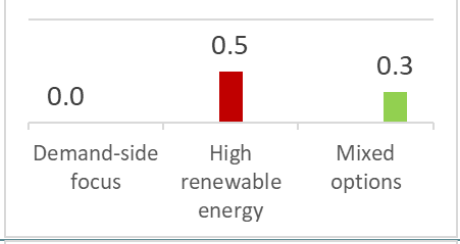
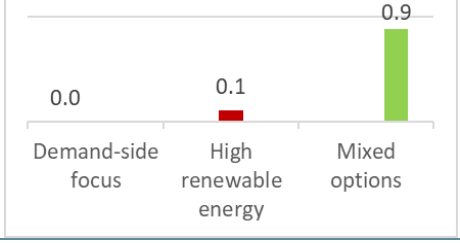
Table 18 below shows the mitigation measures considered in the sustainable development analysis, together with the proxy indicators that were used to observe their deployment across the assessed scenarios. It also shows information about the level of deployment in the assessed scenarios and iconic pathways.

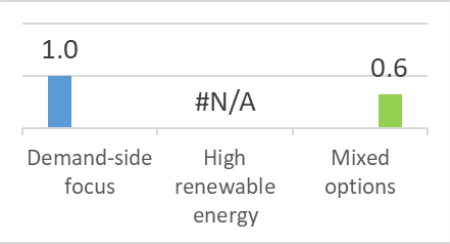
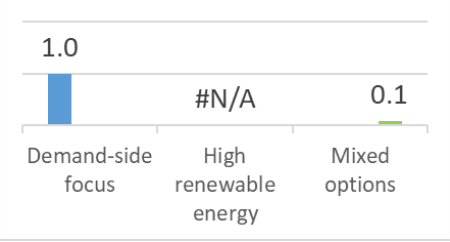
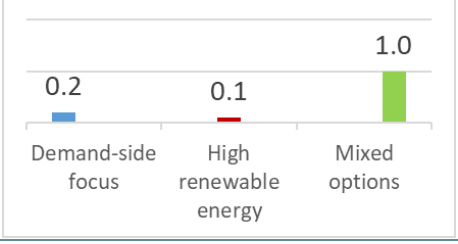
The following details should be noted (and are labelled in the table):

- The median deployment level referred to in the table refers to the 'median of model medians'. As a first step, we calculated the median deployment across scenarios produced by the same model family. As a second step, we calculated the median of these model medians, which is the value shown in the table.
- For measure 2, *behavioural response in buildings and transport*, final energy demand produced by electricity is multiplied by three in order to approximate total useful energy across electricity and other energy carriers. The same approach is followed in Soergel *et al.* (2021).
- For the variables related to diet and livestock

Table 18 Mitigation measures and proxy indicators used in sustainable development analysis.

	Mitigation Measure	Proxy indicator	Value across assessed scenarios (minimum, median[1], maximum)	Iconic pathway deployment relative to maximum (= 1) and minimum (=0) from assessed scenarios
Demand-side measures	Accelerating energy efficiency improvements in end-use sectors	Electrification rate in 2050 (highest percentage of electricity in final energy demand scores highest)	(48%, 54%, 66%)	
	Behavioural response in buildings and transport	Final energy demand from transportation and residential and commercial sectors[2] (greatest % reduction between 2015 and 2050 scores highest)	(-21%, -8%, +21%)	
	Fuel switch and access to modern low-carbon energy	CO_2 intensity of final energy demand in 2050 (lowest gross CO_2 emissions per unit of demand scores highest)	(0.1, 12.7, 21.2) kg CO_2/GJ	
Supply-side measures	Non-biomass renewables: solar, wind, hydro	Primary energy from solar, wind, hydro (highest deployment in 2050 scores highest)	(15, 20, 32) EJ	

	Increased use of biomass	Primary energy from biomass (highest deployment in 2050 scores highest)	(5, 8, 13) EJ	
	Nuclear/advanced nuclear	Primary energy from nuclear (highest deployment in 2050 scores highest)	(0, 2, 5) EJ	
	BECCS	CO_2 captured in 2050 (highest deployment in 2050 scores highest)	(70, 230, 376) Mt CO_2	
	Fossil fuels with carbon capture and storage (fossil-CCS)	CO_2 captured in 2050 (excl BECCS and industrial) (highest deployment in 2050 scores highest)	(5, 131, 260) Mt CO_2	

Measures related to agriculture, food and land use	Behavioural response: Sustainable healthy diets and reduced food waste[3]	Non-livestock share of food demand in 2050 (lowest share scores highest)	(70%, 77%, 93%)	
	Greenhouse gas reduction from improved livestock production and manure management systems[3]	Methane and N2O emissions from livestock production in 2050 [lowest emissions score highest]	(3.2, 4.1, 4.8) t CO_2e/tDM	
	Reduced deforestation, REDD+, afforestation and reforestation	Land sink: net removals from LULUCF (direct and indirect): % increase in 2050 vs 2015 [highest net sink increase scores highest]	(-15%, +52%, +110%)	

Note: REDD+, reducing emissions from deforestation and forest degradation in developing countries.

Source: Advisory Board (2023).

Annex B. Implications of including international aviation and maritime transport in EU targets

As mentioned in Section 7.3, emissions from international aviation and maritime continue to grow both within the EU and globally, reaching 270 Mt CO_2e (7.4% of emissions) in 2019 (EEA, 2022a) ([27]).

In all of the filtered scenarios, ambitious mitigation is assumed to occur in the aviation and maritime sectors, to reflect an economy-wide transition to a 1.5°C-consistent world ([28]). The sectors' emissions therefore begin to fall from 2030 and by 2040 account for CO_2 emissions of between 149 Mt CO_2 and 227 Mt CO_2 per year.

Figure 44 shows the effect of emissions from these sectors, and also considers what would happen in a less ambitious scenario where aviation and shipping emissions continue to increase out to 2050 (the European Commission's EU Reference Scenario (Capros et al., 2020) ([29]). If aviation and maritime emissions develop as per the EU Reference Scenario rather than a 1.5°C-consistent path, this would add an additional 116-239 Mt CO_2 to the emissions from these sectors in 2050. Although small in today's terms, this would represent a significant quantity of additional emissions for an economy that aims to be climate-neutral by this time. Other sectors of the economy may therefore have to compensate for remaining emissions from this sector through additional mitigation or CO_2 removal.

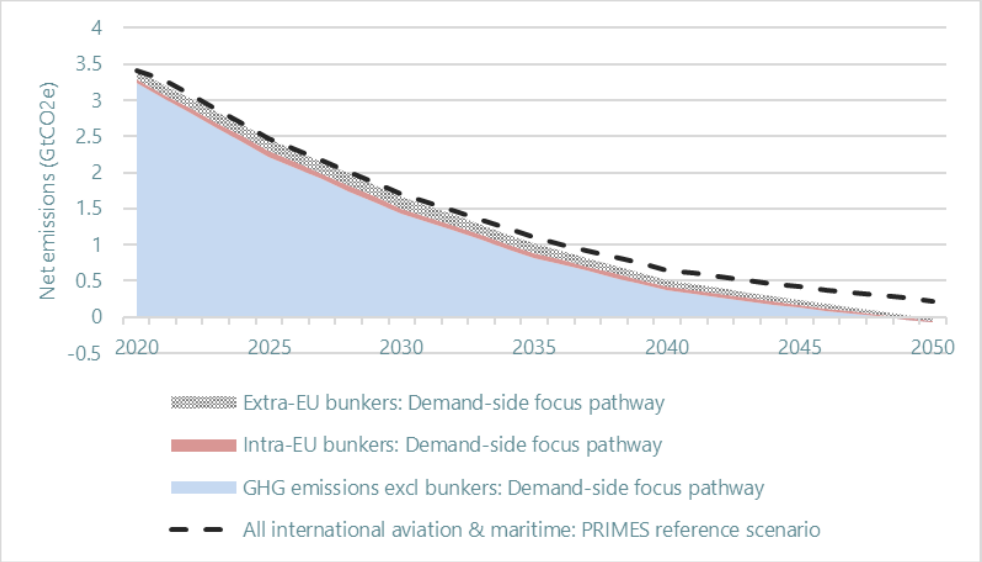
Having established that international aviation and shipping represent a significant source of emissions, it is important to consider how this affects the EU's 2040 target and accompanying greenhouse gas budget.

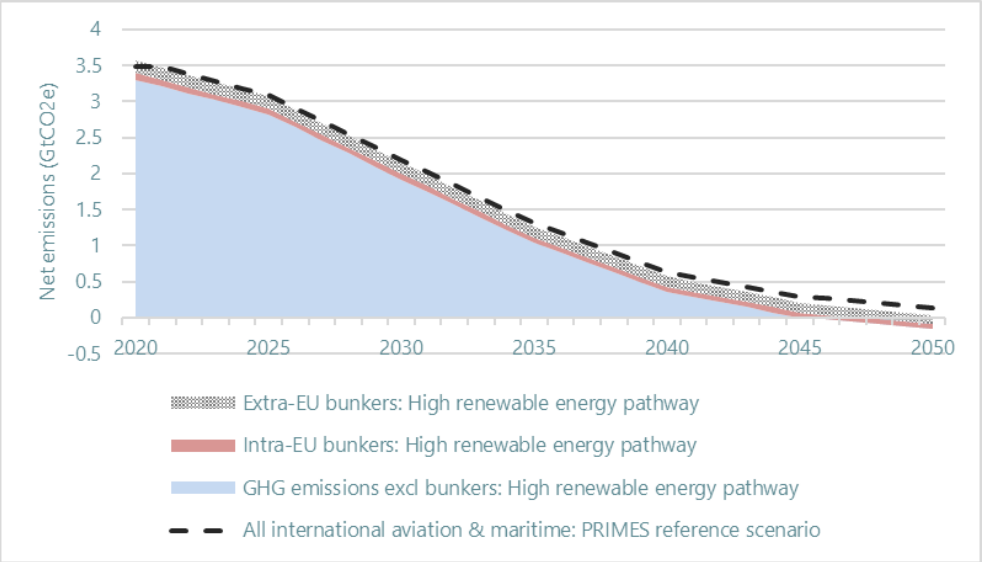
From a **scientific and ethical point of view**, emissions from aviation and shipping clearly contribute to global climate change and the depletion of the global carbon budget. They are therefore included in the Advisory Board's fair share analysis (see Section 5.1).

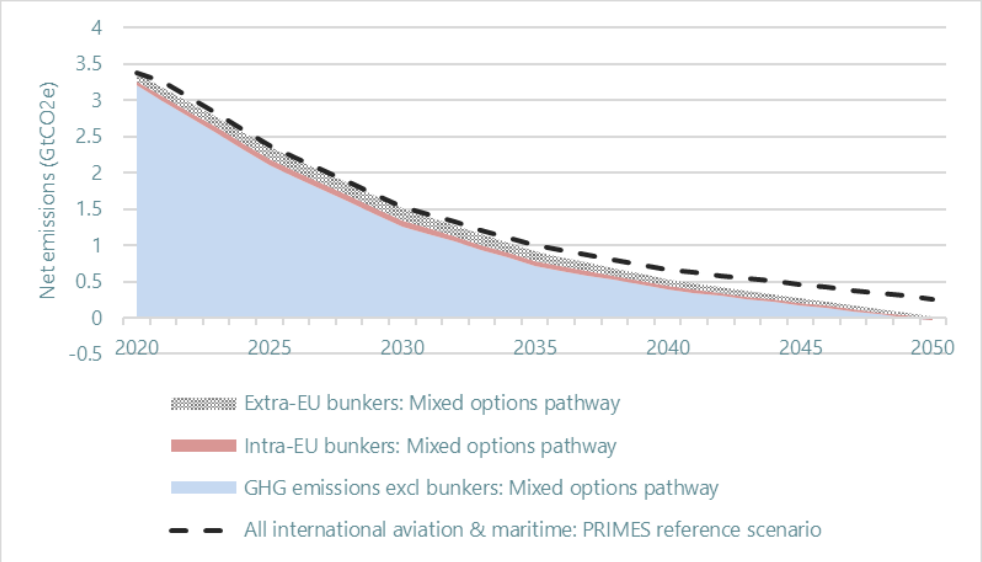
For analysis purposes EU targets, budgets and comparable scenario results mentioned in this report refer predominantly to net greenhouse gas emissions including *only intra-EU* aviation and shipping. This is in line with the approach taken in the original European Commission proposal for a 2030 target of at least 55%, which stated that *'the EU should continue to regulate at least intra-EU aviation emissions and include at least intra-EU maritime transport in the EU ETS'* (EC, 2020b). This scope is also used by the European Commission in the 'MIX' scenario of the accompanying impact assessment (see Figure 45 below). To the best of our knowledge, this is the most up-to-date post-2030 climate target scenario published by an EU institution at time of writing.

([27]) This figure, and most aviation and shipping emissions in this section refer to emissions associated with international bunker fuel sales, as reported as a memo item in the EU official greenhouse gas inventory. Emerging EU policies in this area are based on reporting of actual voyages. The difference between these bases for regulating the sector are not considered in this analysis.
([28]) In cases where models did not allocate international transport emissions regionally (which is most cases), a reduction pathway based on EC modelling for the Sustainable and Smart Mobility Strategy communication was assumed (EC, 2020c). This trajectory appeared to be more ambitious than other sectoral assessments consulted, and was therefore considered a reasonable proxy for the sector's contribution in a 1.5°C scenario. This assessment includes only CO_2 emissions.
([29]) This is a scenario that is used as a baseline for EU policymaking and is updated regularly.

Figure 44 Impact of intra-EU and extra-EU bunker emissions on overall greenhouse gas emissions in the iconic pathways







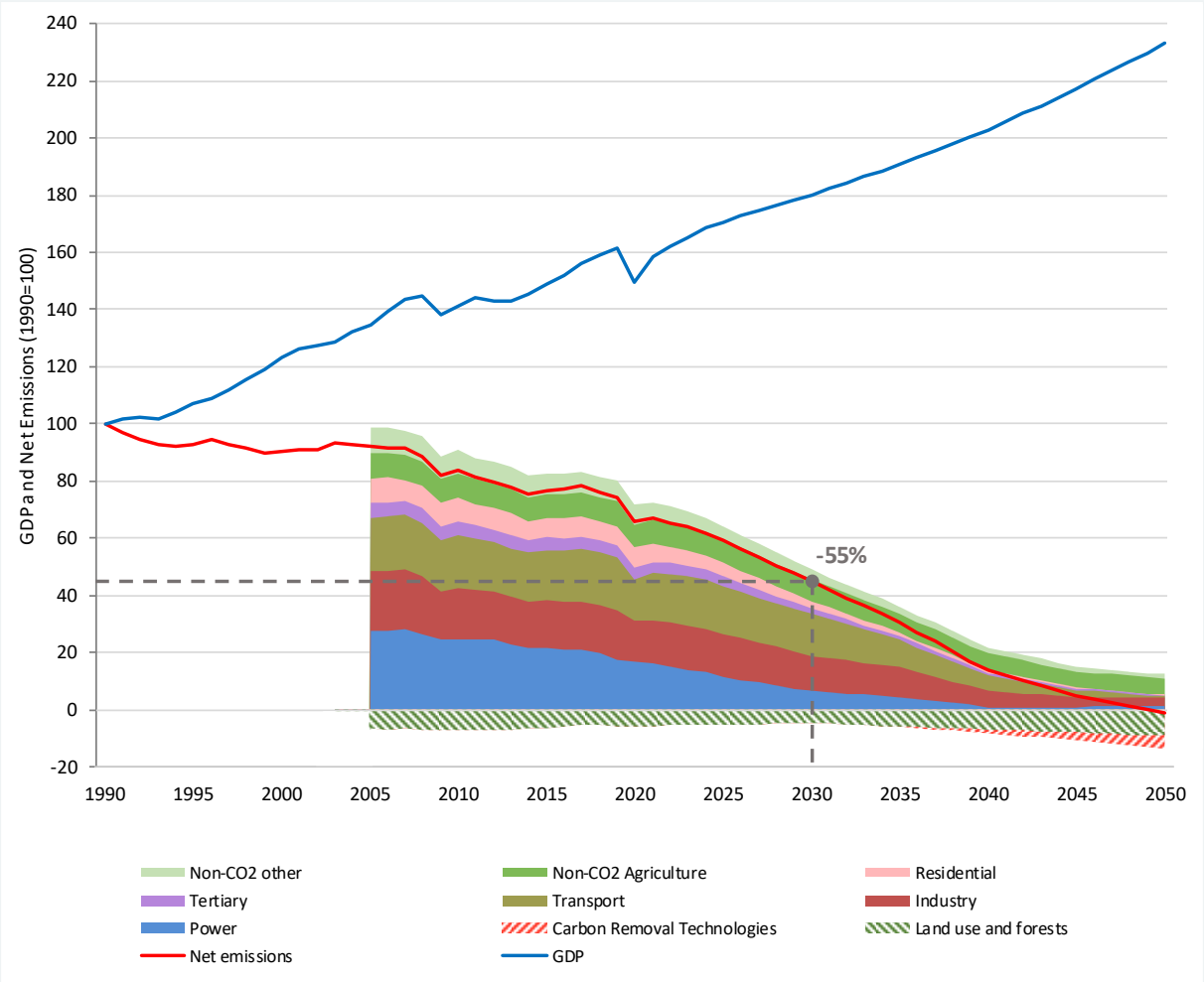
Notes:

For the Demand-side focus and Mixed options pathways, international bunker emissions are assumed to follow a path based on the EC Sustainable and Smart Mobility Strategy (EC, 2020c). For the High renewable energy pathway, regional bunker emissions are estimated by the model itself.

In all cases, intra-EU bunker emissions are assumed to account for 33% of total bunker emissions. This split is based on the EC Climate Target Impact Assessment (EC, 2020b)

Source: Advisory Board (2023).

Figure 45 MIX scenario of the European Commission's 2030 Climate Target Plan impact assessment (including intra-EU aviation and maritime emissions)



Source: European Commission (2020a)

The **implications of choosing one scope or another** on the iconic pathways' 2040 reduction numbers and the accompanying budgets is shown in Table 19 and Table 20 below. Each option (1-5) features the same underlying emissions. The difference is only a matter of which sectors are included.

Across the filtered scenarios, including all bunker emissions is estimated to increase the 2030-2050 greenhouse gas budget by 2.1-3.1 Gt CO_2e.

Table 19 Effect of aviation and maritime coverage on 2040 net greenhouse gas emission reductions (percentage reduction compared to 1990)

		'Demand-side focus' pathway	'High renewable energy' pathway	'Mixed options' pathway
1	Excl. international transport	-92%	-92%	-92%
2	1 + intra-EU aviation	-92%	-92%	-91%
3	2 + intra-EU maritime	-91%	-91%	-91%
4	3 + extra-EU maritime	-90%	-90%	-90%
5	4 + extra-EU aviation	-89%	-88%	-89%

Source: Advisory Board (2023).

Table 20 Effect of aviation and maritime coverage on cumulative greenhouse gas emissions between 2030 and 2050

		'Demand-side focus' pathway	'High renewable energy' pathway	'Mixed options' pathway
1	Excl. international transport	10.6	12.3	10.1
2	1 + intra-EU aviation	11.1	12.8	10.6
3	2 + intra-EU maritime	11.7	13.8	11.1
4	3 + extra-EU maritime	12.7	14.3	12.1
5	4 + extra-EU aviation	13.8	16.8	13.2

Note: the calculated cumulative emission estimates include the years 2030 and 2050.

Source: Advisory Board (2023).

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