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IMPACT ASSESSMENT REPORT

Part 1

Accompanying the document

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS**

Securing our future

**Europe's 2040 climate target and path to climate neutrality by 2050 building a
sustainable, just and prosperous society**

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Glossary

Term or acronym	Meaning or definition
AFOLU	Agriculture, Forestry and Other Land Use, i.e., IPCC sectors 3 (Agriculture) and 4 (LULUCF) combined. The term ‘land sector’ is used as synonym.
BECCS	Bioenergy with Carbon Capture and Storage
BioCCS	Carbon capture and storage of biogenic CO ₂ emissions originated from the combustion of biomass to produce energy (BECCS) or from the processing of biomass in industrial applications
Biogenic carbon	Carbon Dioxide resulting from upgrade of biogas to biomethane
CAP	EU’s common agricultural policy
Carbon capture	CO ₂ captured from industrial processes, power and heat production, biogas upgrade and direct air capture.
Carbon Pool	means the whole or part of a biogeochemical feature or system within the territory of a Member State and within which carbon, any precursor to a greenhouse gas containing carbon, or any greenhouse gas containing carbon is stored
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage (permanently underground and in materials)
CCU	Carbon capture and usage
CH ₄	Methane
Circular Economy	A circular economy moves away from the conventional consumption model and aims to decouple economic activity from the consumption of finite resources. Products, raw materials and resources are kept in circulation through maintenance, recycling, reuse or refurbishment. Thereby the generation of waste is minimized.
CO ₂	Carbon dioxide
DACC	Direct Air Carbon Capture. The carbon captured can be stored (DACCS) or used.
DACCS	Direct Air Carbon Capture and Storage
EAF	Electric Arc Furnace
E-fuels	Electro-fuels, manufactured using captured carbon dioxide or carbon monoxide. Note that e-fuels are not the same as RFNBOs (see RFNBO definition in this glossary).
EJ	Exajoule
ESABCC	European Scientific Advisory Board on Climate Change ESABCC(2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405
ESR	Effort Sharing Regulation
ETS	Emissions Trading System
ETS1	Existing ETS extended to also include maritime shipping
ETS2	New ETS covering buildings, road transport and fuels for additional sectors
EUR	Euro, unless specified otherwise, all monetary figures are expressed in constant 2023 prices (“EUR2023”)
FEC	Final Energy Consumption: the total energy consumed by end users, such as households, industry and agriculture. It is the energy which reaches the final consumer’s door and excludes that which is used by the energy sector itself
Fit-for-55 package	Package of legislation makes all sectors of the EU’s economy fit to meet the 2030 climate target of a reduction of its net greenhouse gas emissions by at least 55% by 2030.
GAE	Gross Available Energy: the overall supply of energy for all activities of a country (defined as: Primary production + Recovered & Recycled products + Imports – Export + Stock changes).

GHG	Greenhouse gas(es)
GHG budget	Total volume of net greenhouse gas emissions that are expected to be emitted over a given period. The European Climate Law refers to the 2030-2050 period.
Greenhouse gases	Greenhouse gases from the Kyoto Protocol: Carbon dioxide (CO ₂); Methane (CH ₄); Nitrous oxide (N ₂ O); Hydrofluorocarbons (HFCs); Perfluorocarbons (PFCs); Sulphur hexafluoride (SF ₆).
Gross Available Energy (GAE)	Overall supply of energy for all activities of a country.
Gross GHG emissions	Total GHG emissions excluding the contribution of industrial carbon removals and of net LULUCF removals.
HFCs	Hydrofluorocarbons
ICE	Internal Combustion Engine
Industrial Carbon Management	Technologies, infrastructures, policies and business models for the capture of carbon dioxide (CO ₂), its transport, storage, and utilisation as feedstock in industrial processes. The CO ₂ can be captured from process or energy emissions of industrial installations, also referred as point source emissions, or directly from the atmosphere with Direct Air Carbon Capture (DACC) installations.
Industrial Carbon Removals	BECCS, DACCS and biogenic carbon
IPCC	The Intergovernmental Panel on Climate Change
Land sector	Synonym for AFOLU sector.
Lignocellulosic Crops	Refers to a range of plants rich in cellulose, hemicelluloses, and lignin including wood from forestry, short rotation coppice, such as willow and poplar, and energy crops, such as energy grasses and reeds. The latter is produced to serve as biomass for the production of advanced / second-generation biofuels.
LNG	Liquefied Natural Gas
LRF	Linear Reduction Factors of the ETS
LULUCF	Land Use, Land Use Change and Forestry
LULUCF net removals	Aggregated emissions from and nature-based carbon removals in the LULUCF sector creates a net removal in the EU, as the sector absorbs more greenhouse gases than it emits.
MACC	Marginal Abatement Cost Curve, which shows the marginal cost of additional reductions in greenhouse gas emissions.
MFF	Multiannual financial framework
Mha	Million hectares
MIDAS	Modelling Inventory and Knowledge Management System of the European Commission
MRV	Monitoring, Reporting and Verification
N ₂ O	Nitrous oxide
Nature-based removals	Nature-based removals are a collection of approaches using the potential of healthy ecosystems to both reduce and remove emissions. They are either enhancing the ability of healthy ecosystems to sequester carbon dioxide by making ecosystems more resilient whilst preserving or enhancing locally adapted biodiversity and the ecosystems' wide range of ecosystem services or restore a degraded ecosystem so that it no longer emits harmful greenhouse gas emissions. Nature-based removals can be one of several functions of nature-based solutions.
Nature-based solutions	Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions. Nature-based solutions must therefore benefit biodiversity and support the delivery of a range of ecosystem services.
NDC	Nationally Determined Contribution

NECP	National Energy and Climate Plans. This analysis uses the NECPs as submitted in 2019 by the Member States and analysed by the Commission in 2020. The current NECP update runs in parallel with the preparation of this Impact Assessment and could not be taken into account.
PFCs	Perfluorocarbons
RFNBO	“Renewable Fuels of Non-Biological Origin” are liquid or gaseous fuels, the energy content of which is derived from renewable sources other than biomass. This term designates renewable hydrogen but also its derivatives (e.g., e-fuels).
RRF	Recovery and Resilience Facility
SDG	Sustainable Development Goal
SF6	Sulphur hexafluoride
Sink / (carbon) removal	Means any process, activity or mechanism that removes a greenhouse gas, an aerosol, or a precursor to a greenhouse gas from the atmosphere via natural and technological solutions. It includes industrial carbon removals and certain nature-based carbon removals that remove carbon dioxide from the atmosphere (CO ₂).
Source / emission	Means any process, activity or mechanism that releases a greenhouse gas, an aerosol or a precursor to a greenhouse gas into the atmosphere
UNFCCC	United Nations Framework Convention on Climate Change

References to policy documents

Policy document	Reference
EU Biodiversity Strategy for 2030	COM/2020/380 final
2030 Climate Target Plan	COM(2020) 562 final
CO ₂ standards for cars and vans	Regulation (EU) 2023/851
Critical Raw Materials Act (proposal)	COM(2023) 165 final
EU's Long-Term Strategy – A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy	COM (2018) 773 final Complemented by: “In-depth analysis in support of the Commission Communication COM(2018) 773”
ETS Directive	Directive 2003/87/EC (amended by Directive (EU) 2023/958)
European Climate Law	Regulation (EU) 2021/1119
Farm to Fork Strategy	COM/2020/381 final
Fluorinated greenhouse gases Regulation (proposal)	COM/2022/150 final
Governance Regulation	Regulation (EU) 2018/1999 on the Governance of the Energy Union and Climate Action
Green paper for a 2030 framework for climate and energy policies	COM(2013) 169 final
Greening Freight Transport package	COM(2023) 440 final
Industrial Emissions Directive (proposal)	COM(2022) 156 final/3
Net Zero Industry Act (proposal)	COM(2023) 161 Final
Regulation of methane emissions reductions in the energy sector (proposal)	COM/2021/805 final
Urban waste-water treatment Directive (proposal)	COM(2022) 541 final
2023 State of the Energy Union Report	COM(2023) 650 final

1 INTRODUCTION: POLITICAL AND LEGAL CONTEXT

1.1 Legal obligation and approach

This report accompanies a Communication on the EU climate target for 2040 in view of implementing the European Climate Law, which enshrines in law the EU's commitment to become climate neutral by 2050 and the EU's 2030 climate target to reduce net greenhouse gas (GHG emissions) by at least 55% in 2030 relative to 1990. This initiative does not aim at developing and committing on the post-2030 policy framework implementing that 2040 climate target at this stage.

The Climate Law mandates the Commission to make a legislative proposal, as appropriate, for a Union-wide 2040 climate target within 6 months of the global stocktake under the Paris Agreement, which will be completed at the Conference of the Parties in December 2023. The 2040 target will also inform the EU's future post-2030 Nationally Determined Contribution (NDC) that all Parties must submit to the UNFCCC by 2025 (under Article 4(9) of the Paris Agreement).

The Climate law also calls on the Commission, when making the proposal for the Union 2040 climate target, 'at the same time, to publish in a separate report the projected indicative Union greenhouse gas budget for the 2030-2050 period' taking into account the advice of the European Scientific Advisory Board on Climate Change (see box).

The **European Scientific Advisory Board on Climate Change (ESABCC)**, set up under the 2021 European Climate Law (article 3), serves as an independent point of reference for the EU on the science of climate change. Its tasks include providing scientific advice and issuing reports on existing and proposed Union measures, climate targets and indicative greenhouse gas budgets. In June 2023, it published advice ⁽¹⁾ recommending a **2040 target for the EU to reduce net GHG emissions in the range of 90-95% compared to 1990**.

The **"GHG budget"** for the EU for 2030 to 2050 is defined in the Climate Law as the total volume of EU net greenhouse gas emissions expected to be emitted in that period ⁽²⁾. It combines a "carbon" budget (cumulative CO₂ emissions) with cumulative emissions of non-CO₂ GHGs ⁽³⁾. The GHG budget is strongly dependent on the level of net GHG emissions reached in 2040, as the intermediate point between 2030 and 2050, and is used to assess the climate performance of the 2040 climate target and the fairness of the EU's contribution to global climate action ⁽⁴⁾.

⁽¹⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405.

⁽²⁾ European Climate Law, Article 4(4).

⁽³⁾ Non-CO₂ GHG emissions defined in the Kyoto Protocol: CH₄, N₂O, SF₆, PFCs and HFCs. They are converted into "CO₂ equivalent" using the global warming potential for a 100-year time horizon from the IPCC Fifth Assessment Report ("AR5").

⁽⁴⁾ According to the IPCC, given the nearly linear relationship between cumulative CO₂ emissions and increases in global surface temperature, cumulative CO₂ emissions are relevant for understanding how past and future CO₂ emissions affect global surface temperature. IPCC Sixth Assessment report (AR6), Working Group 1 "The physical science", Technical summary, Table TS.3 | Estimates of remaining carbon budgets and their uncertainties.

This impact assessment thus assesses different levels of net GHG emissions in 2040 and the associated sectoral pathways bridging 2030 to climate neutrality by 2050. It does not assess the post-2030 energy and climate policy framework, to be developed at a later stage.

The assessment of the 2040 climate target will largely be determined by two main dimensions: on the one hand the *GHG budget* measuring the climate performance of the target and the fairness of the contribution of the EU to the global climate agenda and, on the other hand *feasibility*, including costs, technological deployment and trade-offs.

1.2 Climate change and cost of inaction

Climate change will remain the defining challenge of the coming decades, shaping the future of the global society and economy through its impacts and our response. The harmful impacts of global warming are increasing in scale and frequency, with devastating effects on people, nature, and economic systems across the globe. Droughts, heatwaves, floods, wildfires and storms are becoming more frequent and severe, impacting wider areas and hurting more people, businesses, critical infrastructure, ecosystems, and affecting our ability to sustain prosperity and stability in the long run.

This is happening alongside interrelated challenges of biodiversity loss and natural resource depletion, unsustainable use of natural resources, including water, raw materials, and land, increasing the risk of crossing further planetary boundaries ⁽⁵⁾⁽⁶⁾ and decreasing the stability and resilience of natural and human systems. This reduces their capacity to both mitigate and adapt to climate change and leads to further negative impacts.

As recently confirmed by the work of the Intergovernmental Panel on Climate Change (IPCC) ⁽⁷⁾, the scientific evidence is unequivocal: emissions of greenhouse gases (GHG) from human activities are at the root of global warming observed since at least the 1950s. The scale of changes in the climate system is already unprecedented, but with every additional increase in warming, the risks for society and nature will increase and become more difficult to manage. The last eight years have been the warmest on record at global level and 2023 was the warmest year with several regions of the globe seeing record-

⁽⁵⁾ A safe operating space for societies is defined by planetary boundaries to man-made perturbation of nine critical Earth-system processes: climate change, ocean acidification, stratospheric ozone, global phosphorus and nitrogen cycles, atmospheric aerosol loading, freshwater use, land use change, biodiversity loss, and chemical pollution. Crossing such boundaries can lead to catastrophic impacts for societies. See Rockström J. et al., Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.* 14, 32 (2009). <http://www.ecologyandsociety.org/vol14/iss2/art32/>

⁽⁶⁾ Richardson, Katherine, Will Steffen, Wolfgang Lucht, Jørgen Bendtsen, Sarah E. Cornell, Jonathan F. Donges, Markus Drüke et al. "Earth beyond six of nine planetary boundaries." *Science Advances* 9, no. 37 (2023): eadh2458.

⁽⁷⁾ IPCC, 2023: Sections. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647

breaking temperatures ⁽⁸⁾. Globally, the year 2023 was 1.48°C warmer than the pre-industrial level⁹. According to the World Meteorological Organization ⁽¹⁰⁾, Europe is warming twice as fast as the global average, with annual average temperature reaching 2.3°C above pre-industrial (1850-1900) average in 2022, compared to the global average of 1.15°C.

With current NDCs and policies, the world is not on track to meet the Paris Agreement objectives of limiting the temperature increase to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels. Exceeding this threshold will result in additional adverse impacts, some of which will be irreversible, and further constrain our adaptation options. Accelerated action is essential to avoid the worst impacts of climate change and requires deep, rapid and sustained greenhouse gas emissions reductions in all sectors and regions, while stepping up adaptation efforts ⁽¹¹⁾.

The experienced cost of climate change is continuously increasing, and with increasing global warming, the impacts are expected to become even more severe and widespread in the coming decades. Without urgent climate action globally, several parts of the climate system are increasingly likely to reach irreversible tipping points, with devastating consequences, leading to uncharted and high-risk conditions for human and natural systems. Heatwaves, floods, wildfires, and other climate-related factors are already adversely affecting human health and well-being. All countries and regions are concerned, but least developed regions and low-income population groups are particularly exposed and vulnerable to climate change.

It is estimated that global damages from climate change could reach 10-12% of GDP by the end of the century. However, such estimates are conservative, since they do not include the wider impacts on society and natural systems, notably in the most exposed countries and regions, with likely knock-on regional or global effects on geo-political stability and security. In addition, given the difficulty in doing so, most economic analyses do not represent the impacts of crossing climate tipping points, which are increasingly likely with every incremental increase in global warming, and which will significantly impact the global economy. Looking forwards, the cost of unmitigated climate change will greatly exceed the cost of reducing GHG emissions, both in magnitude and extent. A growing number of analyses and estimates point to the high costs already incurred now by our economies due to floods, droughts, heatwaves and other climate change related events. And this is without taking into account the human suffering caused by these events.

⁽⁸⁾ European State of the Climate 2022 | Copernicus

⁽⁹⁾ <https://climate.copernicus.eu/global-climate-highlights-2023>

⁽¹⁰⁾ World Meteorological Organization, 2023. State of the Climate in Europe. WMO-No. 1320.

⁽¹¹⁾ IPCC. AR6 Synthesis Report: Climate Change 2023; AR6 Climate Change 2022: Impacts, Adaptation and Vulnerability; AR6 Climate Change 2022: Mitigation of Climate Change; AR6 Climate Change 2022: The Physical Science Basis.

1.3 International context

The urgent need for stronger action to tackle climate change comes at a time of multiple global crises. The COVID-19 pandemic severely hit the global economy, especially in 2020, and resulted in temporary GHG emissions reductions in the EU and across the globe. Global emissions rebounded in 2021-2022 and reached a new high in 2022¹². Globally, the longer lasting impacts of the pandemic, including increases in extreme poverty, gender and social inequality, and impacts on health exacerbate vulnerability to climate change and lead to compound impacts. With the Fit-for-55 package, REPower EU, NextGenerationEU and the Multiannual Financial Framework for 2021-2027, the EU has developed a collective response to the economic crisis caused by the pandemic that allows it to continue to drive the twin green and digital transition.

The pandemic has also revealed global supply chain vulnerabilities. Increasing geo-economic and geopolitical tensions, together with Russia's illegal, unprovoked, and unjustified war of aggression against Ukraine, are further impacting global trade and investment flows, increasing the risk of trade restrictions and supply chain disruptions. These developments highlight the vulnerability that can result from dependencies in strategically important sectors, including access to critical raw materials, which are necessary for the twin transition (¹³). As other countries grasp the strategic importance of decarbonising their economies, there is intense competition for the materials, skills, technologies and investments needed to secure essential supply chains and for a share of the global market of the products and services of the future.

As a response, Europe is taking necessary steps towards open strategic autonomy to protect its strategic interests and collective security, and to strengthen the resilience of its supply chains to external shocks, including through stronger international cooperation with likeminded third countries and the proposed Net Zero Industry Act and European Critical Raw Materials Act. The EU is investing in European industrial capacity to manufacture net-zero technologies and in deploying these technologies to meet the EU's 2050 climate objective.

The high energy prices and geopolitical tensions following Russia's military aggression against Ukraine have exacerbated the need for the EU to ensure its energy security and robustness of its supply chains for raw materials and net-zero technologies. This has highlighted the economic and strategic vulnerabilities that come with dependence on fossil fuels, the main drivers of climate change. The energy crisis brought about by the war has made very clear the need to step up the transition to clean energy, energy

(¹²) Total GHG emissions (without LULUCF) reached 53.8 GtCO₂-eq in 2022. See JRC EDGAR database and report: GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953322, JRC134504.

(¹³) 2023 Strategic Foresight Report: Sustainability and people's wellbeing at the heart of Europe's Open Strategic Autonomy.

efficiency and climate neutrality in the EU and globally ⁽¹⁴⁾ whilst avoiding the creation of new strategic dependencies.

The EU has intensified its Climate and Energy Diplomacy, guided by regular Council Conclusions from the EU Foreign Affairs and Environment ministers. The 2022 EU external energy engagement strategy as part of the REPowerEU Plan has been strengthened, outlining how the EU supports a global, clean, and just energy transition to ensure sustainable, secure and affordable energy. Meanwhile, however, in 2022 subsidies for fossil-fuel consumption reached a record \$7 trillion globally (7.1% of world GDP) ⁽¹⁵⁾.

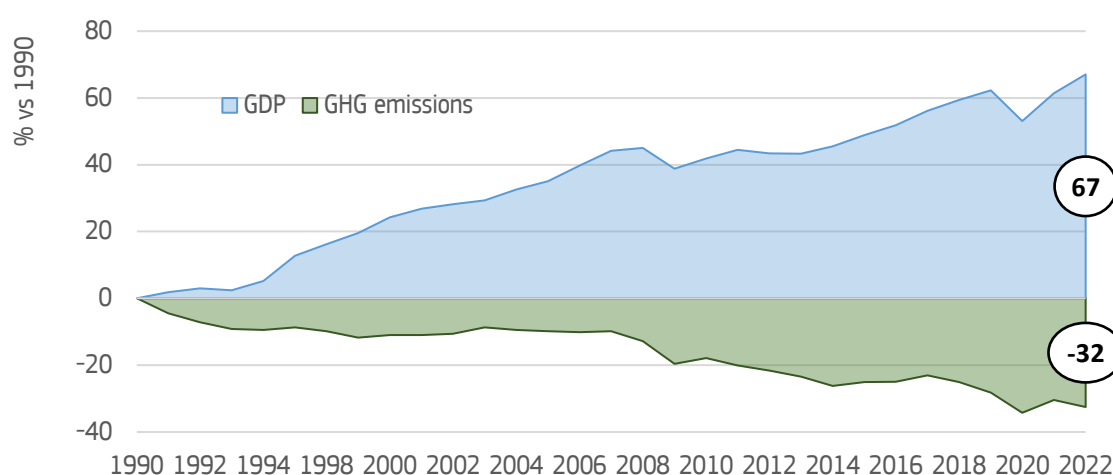
In December 2023 at COP28, the first Global Stocktake (GST) will assess ⁽¹⁶⁾ the progress towards the goals of the Paris Agreement.

1.4 Existing EU policy framework

1.4.1 Progress towards the 2030 climate target

Over the past decades, the EU has developed and regularly updated a comprehensive set of climate, energy, and other relevant enabling policies that have allowed a decoupling of economic activity from GHG emissions (Figure 1) and spurred the development of clean energy ⁽¹⁷⁾.

Figure 1: GHG emissions and GDP development in the EU since 1990



Source: GHG from EEA GHG data viewer (extracted 20/6/2023), GDP in real terms from AMECO and WB

⁽¹⁴⁾ State of the Energy Union 2022. Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions.

⁽¹⁵⁾ Black, Simon, Antung Liu, Ian Parry, and Nate Vernon (2023). “IMF Fossil Fuel Subsidies Data: 2023 Update.” Working paper, IMF, Washington, DC.

⁽¹⁶⁾ [Placeholder for GST conclusions]

⁽¹⁷⁾ Annex 10 provides a summary of the evolution of GHG emissions under the different climate legislation instruments and of the energy system. A more detailed analysis can be found in the Climate Action Progress Report (GHG emissions) and in the State of the Energy Union Report (energy).

Provisional data ⁽¹⁸⁾ for 2022 show that total EU net GHG emissions decreased by around 3% compared to 2021, whilst EU GDP grew by 3.5%. 2022 emissions therefore continued their descending trend with reductions compared to 2019 of 5.6%. Emissions covered by the current ETS reduced by 0.2% compared to 2021 (and are 8% below the 2019 pre-COVID and pre-war level) while emissions under the ESR, decreased by 2.9%. Net removals from the Land Use, Land-use Change and Forestry (LULUCF) sector show a break in their recent declining trend, with an expected increase in carbon sinks of 6% compared to 2021.

Exceptional events over the last 3 to 4 years have made the assessment of GHG emission trends more complex and continue to have an impact on 2022 emissions. The COVID-19 lockdowns and restrictions led to an unprecedented but temporary drop in GHG emissions of 8% in 2020. In 2021, the economic recovery affected regions and sectors differently. Some sectors, such as the transport sector and travel-related emissions, recovered fully only in 2022. The energy crisis that started in 2021 continued in 2022, exacerbated by Russia's unprovoked and unjustified invasion of Ukraine, which drove energy prices to record highs, particularly gas prices.

Overall, the EU's domestic GHG net emissions are on a clear downward path, falling steadily over the last 5 years. The transformation of the energy sector has been the main driver of the decarbonisation of the EU economy over the last decades, through improvement of the energy intensity of the economic activity and decarbonisation of the energy mix ⁽¹⁹⁾.

Still, in view of meeting the 2030 climate target, the pace of emission reductions will need to pick up and almost triple the average annual reduction achieved over the last decade. Relative to past mitigation efforts, the most significant cuts in emissions are needed in buildings and transport, where the pace of decarbonisation has remained sluggish or even moving in the opposite direction. At the same time, action in the LULUCF sector is essential to enhance carbon removals. Although reaching the emissions cuts required from agriculture looks achievable when looking at the evolution over the past three decades, the lack of substantial progress in recent years is a concern, calling for a gear change. ⁽²⁰⁾

The energy crisis highlighted how dependence on imported fossil fuels makes Europe vulnerable to geopolitical threats. The EU responded collectively and effectively to Russia's weaponisation of its energy supplies. A series of emergency legislative measures ensured that Europe avoided major energy supply disruptions and is now better prepared. However, deeper structural changes are needed to mitigate Europe's

⁽¹⁸⁾ The Governance Regulation ((EU) 2018/1999) requires Member States to report approximated GHG inventories annually by 31 July. Based on this reported data, the EEA compiles a Union approximated GHG inventory or, if a Member State has not communicated its approximated GHG emissions by that date, on the basis of EEA's own estimates. This provides an early estimate of GHG emissions ahead of the full GHG inventory.

⁽¹⁹⁾ Climate Action Progress Report 2023 accompanying SWD. Section 3.2

⁽²⁰⁾ Climate Action Progress Report 2023

vulnerability. The EU needs to accelerate the energy transition to ensure affordable, reliable access to energy for households and businesses.

The “Fit for 55” package sets the EU on a path to reach its climate targets in a fair, cost-effective, and competitive way. Most of the key proposals in the package have been adopted by co-legislators and EU policies are now aligned with the updated 2030 target set in the European Climate Law. Implementing the new legislation under the Fit for 55 package will enable the EU and its Member States to reduce net GHG emissions by at least 55% compared to 1990 levels by 2030 ⁽²¹⁾.

1.4.2 *The “Fit for 55” package and the European Green Deal*

The European Climate Law enshrines the EU’s commitment to become climate neutral by 2050 in law, providing a clear direction of travel for the transition. It expresses the EU’s commitment to reduce net GHG emissions by at least 55% in 2030 relative to 1990, as the EU contribution to achieving the Paris Agreement goals. An essential part of the European Green Deal, the ‘Fit for 55’ legislative package provided the policy framework to meet the 2030 climate target, ensuring a just and socially fair transition, while strengthening innovation and preserving the competitiveness of EU industry ⁽²²⁾.

The **Fit-for-55 package** includes the following adopted or agreed proposals: reform of the EU Emissions Trading System (ETS) and the Market Stability Reserve (MSR); a new, self-standing ETS for buildings, road transport and fuels for additional sectors (ETS2); revised Effort Sharing Regulation (ESR); the Carbon Border Adjustment Mechanism (CBAM); the Social Climate Fund (SCF); a revised Land Use, Land-Use Change and Forestry (LULUCF) Regulation; updated CO₂ emission standards for cars and vans; the Alternative Fuel Infrastructure Regulation (AFIR); FuelEU Maritime; ReFuelEU Aviation; the Energy Efficiency Directive (EED); Renewable Energy Directive (RED); the Regulation on methane emissions reduction in the energy sector; and the associated revision of the Regulation on Fluorinated Greenhouse Gases.

The Fit-for-55 and associated proposals that are still under negotiation with the co-legislators at the time of drafting this report are: the Energy Performance of Buildings Directive (EPBD); the Hydrogen and decarbonised gas market package; the proposal for a revised Energy Taxation Directive; and the revision of the Regulation on CO₂ emission standards for heavy-duty vehicles.

⁽²¹⁾ The legislation as adopted is estimated to result in a net domestic reduction of GHG emissions of 57% by 2030 compared to 1990. An overview of targets is presented in Chapter 1 of the staff working document – ‘Technical information’ accompanying the Climate Action Progress Report 2023.

⁽²²⁾ This ambition has been mirrored by the EU’s closest neighbours (Western Balkans, Moldova, Ukraine and Georgia) through the adoption of the 2030 climate targets, in line with the clean energy package, in the framework of the Energy Community Initiative.

REPowerEU plan, the EU's reply to the energy crisis derived from Russia's military aggression against Ukraine, stepped up EU's renewable energy and energy efficiency ambitions. Renewables and energy efficiency measures reduce both emissions and dependency on imported fuels: there is no contradiction between the Green Deal and REPowerEU. The forthcoming final updates of the National Energy and Climate Plans, to be submitted in June 2024, will also be a key instrument for Member States and the EU to achieve the 2030 climate target.

The EU enabling framework to support the transition to climate neutrality has been expanding. The EU Emissions Trading System (ETS) reduces emissions and generated more than EUR 150 billion in auction revenues ⁽²³⁾, which Member States are to use to support climate action. At least 30% of the EU's multiannual financial framework' for 2021-2027 and of NextGenerationEU (potentially, over EUR 670 billion) are to be spent on climate related investments. Increasing provisions to address the needs of the most vulnerable include the Just Transition Fund for the most affected territories that must cease fossil-fuel related activities, transform and restructure carbon-intensive industries, and invest in future-proof jobs opportunities and training. The Social Climate Fund supports social cohesion and will mobilise EUR 86.7 billion from 2026 to 2032 using revenues from the ETS2, alongside the Modernisation Fund that supports clean energy investments in lower-income Member States and the Innovation Fund, one of the world's largest funds for the demonstration of innovative net-zero technologies, with revenues from the EU ETS.

The Green Deal Industrial Plan accelerates the transition to climate neutrality by reinforcing European industry's lead in the supply of clean technologies and products while ensuring global cooperation and making trade work for the green transition. It promotes a simpler and predictable framework for the skills and access to finance needed for the transition. This includes making best use of the Innovation Fund, simplified granting of State aid to accelerate the transition ⁽²⁴⁾, the Net Zero Industry Act to strengthen and scale-up European manufacturing capacity for net-zero technologies and the Critical Raw Materials Act to ensure a secured and sustainable supply of raw materials important for the green and digital transition.

As a follow-up to the Farm to Fork Strategy and the Biodiversity Strategy for 2030, the EU has also made several proposals to enhance nature-based solutions that can mitigate climate change and enhance ecosystems' resilience to climate change. Relevant legislative and policy proposals include the Carbon Removal Certification Framework, the Nature Restoration Law, the Circular Economy Action Plan, the Framework for Sustainable Food Systems, and the Soil Monitoring Law.

⁽²³⁾ Revenues from the ETS calculated in the period 2012-2022 and until 31 August 2023 (COM(2019) 557 final/2, COM(2020) 740 final, SWD(2021) 308 final, and EEX for most recent data).

⁽²⁴⁾ There are possibilities for simplified granting of State aid under the Temporary Crisis and Transition Framework and the recently revised General Block Exemption Regulation. While State aid can help incentivise and accelerate the green transition by supporting relevant initiatives, it needs to comply with the applicable rules, which foresee among others, that it should be limited to the minimum amount necessary and that it should address situations where State intervention is needed, e.g. due to the presence of market failures.

This comprehensive framework should enable the EU to meet its commitments under the Paris Agreement. In doing so, it provides an important example to encourage other Parties to the United Nations Framework Convention on Climate Change (UNFCCC) to take more ambitious commitments and put in place the measures needed to implement these, driving the global transition to climate neutrality.

2 PROBLEM DEFINITION

The core problem this initiative aims to tackle is the absence of an EU-wide, economy-wide ambition level for 2040, in terms of net greenhouse gas emission reduction, as an interim target to climate neutrality in 2050.

An intermediate climate target for 2040 needs to be set to provide much needed predictability for Member States, stakeholders, investors, and EU decision makers for the decisions needed to achieve climate neutrality by 2050, including decisions taken in the coming years to meet the EU's 2030 target.

As set out in section 1.4 above, the EU needs to step up the existing pace of emissions reductions across all sectors to meet its 2030 target. The 'Fit-for-55' legislation' adopted in 2023 allows the EU to exceed the -55% reduction by 2030, when fully implemented, but requires a focus on implementation, including through the updated NECPs that Member States will submit to the Commission in June 2024.

Many decisions taken now by the EU, Member States and other actors have implications for EU greenhouse gas emissions that extend well beyond 2030.

This need for certainty is set out in the European Climate Law, which calls on the Commission to come forward with a proposal for a 2040 climate target within six months of the global stocktake. Implementation of the Climate Law requires an intermediate 2040 climate target to set the pace for EU-wide reductions of net GHG emissions over 2030-2050.

The 2040 climate target will provide essential information to allow the definition in the coming years of the future climate, energy, and wider enabling framework, to meet the 2040 target. The post-2030 policy framework will be designed during the next Commission mandate ⁽²⁵⁾.

Finally, a 2040 target is needed that reflects the scale of the global challenge and that ensures that the EU continues to lead by example to push ambitious global action. Limiting global warming to the Paris Agreement temperature target of 1.5°C requires GHG emissions to be at net zero globally by the early 2050s ⁽²⁶⁾. The remaining global

⁽²⁵⁾ The approach of first agreeing the ambition level and then the policy framework to implement the target was also used in previous cycles to set the 2020 and 2030 climate and energy targets.

⁽²⁶⁾ IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34, doi: 10.59327/IPCC/AR6-9789291691647.001

carbon budget compatible with this objective, estimated at 500 GtCO₂ ⁽²⁷⁾ from the start of 2020, is being depleted at a rate of above 40 GtCO₂ per year ⁽²⁸⁾. As global climate action is delayed and GHGs continue to accumulate in the atmosphere, climate change is accelerating and the risk of reaching irreversible tipping points in the climate system, with unknown and potentially catastrophic consequences for humans and ecosystems, is increasing.

The adoption of a 2040 climate target is needed for the definition of the new NDC that the EU will submit the UNFCCC by 2025 as required under the Paris Agreement. Its absence would compromise the EU's contribution to the global climate agenda at a moment when new momentum for global climate action is urgently needed.

3 WHY SHOULD THE EU ACT?

3.1 Legal basis

According to Article 11 of the Treaty on the Functioning of the European Union (TFEU), environmental protection requirements must be integrated into the Union's policies and activities, in particular with a view to promoting sustainable development. Articles 191 to 193 of TFEU further clarify that Union policy shall preserve, protect, and improve the quality of the environment; protect human health; and promote measures at the international level to deal with regional or worldwide environmental problems. Article 191 cites climate change as an example of this type of problem. This initiative responds to the legal requirement under the European Climate Law Article 4(3), which calls on the Commission to make a legislative proposal, as appropriate, for a Union-wide 2040 climate target within 6 months of the global stocktake referred to in Article 14 of the Paris Agreement ⁽²⁹⁾.

3.2 Subsidiarity: Necessity of EU action

Climate change is a trans-boundary problem. For trans-boundary problems, individual action is unlikely to lead to optimal outcomes. Instead, coordinated EU action can effectively supplement and reinforce national and local action. Coordination at the European level enhances the effectiveness of climate action. EU action is justified on grounds of subsidiarity in line with Article 191 of the Treaty on the Functioning of the European Union.

3.3 Subsidiarity: Added value of EU action

A Union-wide climate target for 2040 will have implications across the entire EU economy. It is needed to guide a wide range of EU policies and will require EU level policy responses, beyond climate policy. The impacts on economic activity, employment,

⁽²⁷⁾ with 50% likelihood of limiting global warming to 1.5 degrees

⁽²⁸⁾ Forster, P. M., et al. (2023). Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence, *Earth Syst. Sci. Data*, 15, 2295–2327, <https://doi.org/10.5194/essd-15-2295-2023>.

⁽²⁹⁾ The first global stocktake taking place end of 2023.

cohesion, environment, energy, transport, food security, health, affordability, distributional effects, trade, and international relations are policy areas better considered at EU level.

Coordinated EU policies and support measures have a much bigger chance of leading to a true transformation via 2040 and towards EU climate neutrality by 2050. Through coordinated action it will be possible to take the different capabilities of Member States and regions to act into account and to use the power of the EU single market as a driver for cost-efficient change.

Coordinated climate action at EU level is also of importance for international climate action. Since 1992, the EU has worked to develop joint solutions and push for a global agreement to fight climate change. These efforts helped to reach the Paris Agreement in 2015. International climate policy and climate diplomacy are stronger due to climate policy coordination at EU level, even more crucial in a world in which the EU accounts for only around 7% of global GHG emissions⁽³⁰⁾. The assessment of pathways for setting a Union-wide climate target for 2040 will be a powerful example for the EU's closest neighbours and international community. It is also a necessary step for determining the EU's Nationally Determined Contribution under the Paris Agreement to be communicated in 2025. Without it, the EU and its Member States risk undermining their capacity to stimulate climate action at the global level.

4 OBJECTIVES: WHAT IS TO BE ACHIEVED?

4.1 General objective

The general objective of this initiative is to propose a Union-wide, economy-wide GHG target for 2040 that will put the EU on an effective, cost-efficient, and just trajectory towards climate neutrality by 2050, as called for under the European Climate Law.

What is not an objective of this initiative and Impact Assessment?

This initiative does not:

- Evaluate the suitability or coherence of the existing 2030 energy and climate policy framework (for an overview see Section 1.4) for the period 2031-2040;
- Develop a new post-2030 energy and climate policy framework to implement the 2040 GHG ambition level.

The objectives of this initiative are more like those of the 2013 Green paper for a 2030 framework for climate and energy policies or the EU's 2018 Long Term Strategy than like the 2030 Climate Target Plan of September 2020, as the latter already outlined possible updates of the then existing framework for 2030.

⁽³⁰⁾ Data for year 2021, excluding international shipping and aviation. Source: EDGAR

4.2 Specific objectives

The adoption of a GHG target for 2040 aims at ensuring that the EU achieves its climate neutrality target in 2050 while respecting its other long-term priorities. The analysis in this impact assessment will evaluate the different target options according to their ability to deliver on the following seven specific objectives.

SO1: Ensure that climate neutrality is delivered

Reaching the emissions reduction target of 2030 will largely happen through fast emission reductions in sectors with low abatement costs, such as power generation.

Beyond this date, the contribution of hard-to-abate sectors (e.g., transport, some industrial processes) to the mitigation effort must significantly increase. Some sectors, such as agriculture and air travel, will not be able to cut their GHG emissions to zero in the coming decades, because they deliver goods and services that can only be partially substituted or there are inherent limits to the GHG mitigation options available to them. Science is clear that large amounts of compensating “negative” emissions (“carbon removals”) will be needed in the EU and globally by the second half of the century ⁽³¹⁾ to meet the goals of the Paris Agreement, and, after 2050, the EU economy should generate net negative emissions ⁽³²⁾.

This specific objective thus relates to the degree to which a given 2040 target level entails GHG abatement in the different sectors, including through the contribution of carbon removals, already in the first decade 2031-2040 to avoid delaying such actions to the last decade, which would jeopardize reaching the objective of climate neutrality by 2050.

SO2: Minimise the EU’s GHG budget

According to IPCC AR6 report there is a near-linear relationship between cumulative anthropogenic CO₂ emissions and the global warming they cause. The remaining global “carbon budget” (i.e., the cumulative CO₂ emissions) corresponding to the Paris Agreement temperature goals is decreasing every year (see Annex 14).

The Climate Law refers to the “GHG budget” as the cumulative net GHG emissions over 2030-2050, which is used in this impact assessment to measure the climate performance of the different 2040 target options and the corresponding contribution of the EU to the global climate agenda.

SO3: Ensure that the transition is just

The transition towards climate neutrality will need to be socially just and fair in order to succeed.

The pace of action will have important implications for households, as consumers, investors, and workers. Economic and social inequalities mean that many households do not have the resources or incentives to make the necessary investments in low-carbon

⁽³¹⁾ IPCC (2018). Special Report on 1.5°C. Frequently Asked Questions Chapter 4 (FAQ 4.2).

⁽³²⁾ European Climate Law, article 2

goods (e.g., electric vehicles, building renovations) that would allow them to reduce their energy costs and GHG emissions without measures to support action. Achieving climate neutrality will lead to the disappearance of jobs in fossil fuel extraction and GHG-intensive sectors, but also to the diversification of existing sectors and jobs and the emergence of new ones. The level of ambition for 2040 affects the investments that need to be made already before 2030, for example in manufacturing capacity of net-zero technologies, in building renovations, and in servicing of net zero equipment, which all require additional skilled workers.

Determining the ambition level for 2040 has implications for planning and funding of social, redistributive, education, training, and employment policies, and can serve as an opportunity to address social and employment inequalities.

SO 4: Ensure that the long-term competitiveness of the EU economy is maintained

The transition to climate neutrality will engender deep economic transformations that have important implications for the competitiveness of the EU economy. Some historical European industries, such as car manufacturing and energy intensive manufacturing, will have to invest in new low-carbon production processes and products. The transition will also lead to investment in innovations that drive productivity and competitiveness.

The EU's partners and other key players have understood the strategic importance of investing in the industries and technologies needed for the transition to climate neutrality⁽³³⁾. The global demand for materials, skilled people, technologies, and investments in clean industries will increase steadily as other major economies embark on the climate transition. There is strong competition to seize market shares and first-mover advantages⁽³⁴⁾ in the growing global market clean products and services. The post-2030 policy framework will need to build on the Green Deal Industrial Plan and the Net-Zero Industry Act.

SO 5: Provide predictability for the deployment of best-available, cost-effective, and scalable technologies

Climate neutrality by 2050 and negative net emissions after 2050 hinge on the very important deployment of several climate-neutral technologies that are not currently deployed at scale. The faster these become affordable for companies and households, the easier the path to climate neutrality. This requires removing barriers to innovation, deployment, and finance for key technologies and to develop new skills for new jobs. New supply chains are needed to ensure that affordable and effective clean solutions are available to all, including for sustainable lifestyle choices.

⁽³³⁾ Annex 3 of [the Staff Working Document on investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity \(SWD\(2023\) 68 final\)](#); the US Inflation Reduction Act of 2022 provides major investments to reduce US GHG emissions (USD 370 billion estimated by Congress. In China, support to New Energy Vehicle manufacturers over the past decade (including consumer subsidies and rebates, exemption from sales tax, R&D and public procurement) is estimated at more than USD 100 million.

⁽³⁴⁾ Strategic Perspectives (2023). Competing in the new zero-carbon industrial era. Assessing the performance of five major economies on key decarbonisation technologies.

SO 6: Ensure the security of supply of energy and resources

The COVID pandemic and Russia's military aggression against Ukraine demonstrated how supply chain disruptions and energy crises can negatively affect the EU economy. A sharp decrease in the EU's reliance on imported fossil fuels will be an important co-benefit of the transition towards climate neutrality. However, supply disruptions (e.g., of clean energy technologies, raw materials, water, or components) have the potential to slow the green transition and make it more expensive and the EU needs to avoid replacing one strategic dependence, for example on Russian fossil fuels, with another. The EU's reliance on imports of many critical raw materials and components necessary for the low-carbon transition can lead to vulnerabilities if supply is too concentrated.

SO 7: Ensure environmental effectiveness

The pathway to climate neutrality needs to be one that protects and enhances biodiversity, water resources, air quality, food security, and other essential natural services needed for our sustainable development. It should also reduce the risk of climate disasters and support adaptation to climate change to ensure an adequate response to the increasing impacts of climate change. Setting a 2040 target and pathway from 2030-2050, allows anticipation and exploitation of synergies between climate neutrality, biodiversity, and other environmental objectives.

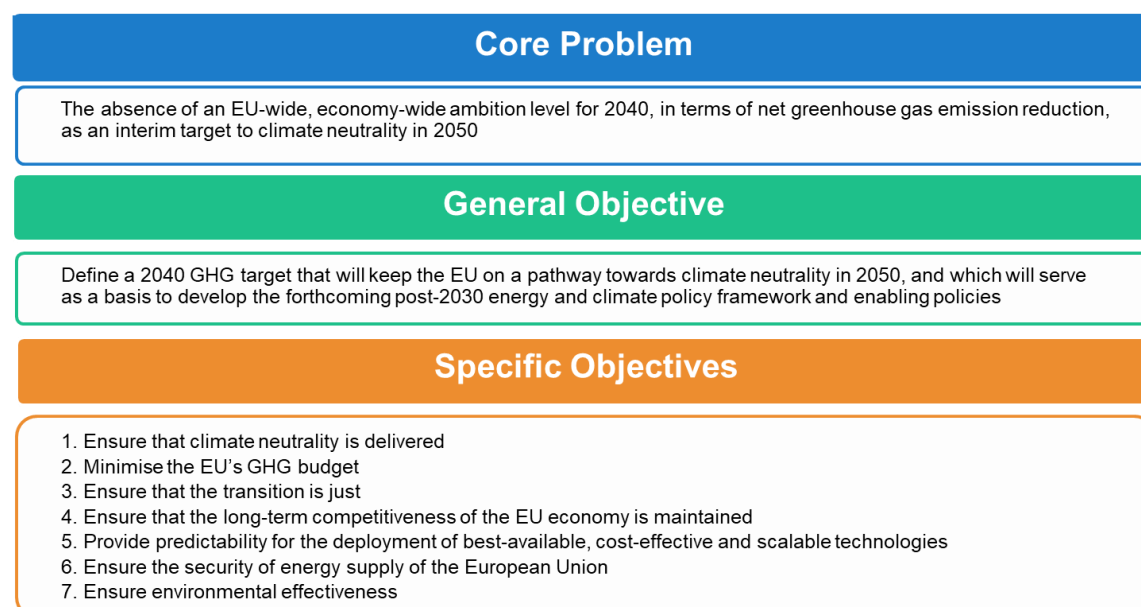
Table 3 maps these seven specific objectives to Article 4(5) of the Climate Law. The consideration (h) "fairness and solidarity between and within Member States" will depend on the future framework.

Table 1: Mapping of the Specific Objectives to Article 4(5) of the Climate Law

Specific Objectives	Climate Law Article 4(5) “When proposing the Union 2040 climate target [...], the Commission shall consider the following:”
SO 1: Ensure that climate neutrality is delivered	(Climate Law article 2)
SO 2: Minimise the EU’s GHG budget	(a) “the best available and most recent scientific evidence, including the latest reports of the IPCC and the Advisory Board” (b) “the [...] costs of inaction” (l) “international developments and efforts undertaken to achieve the long-term objectives of the Paris Agreement and the ultimate objective of the UNFCCC” (m) “existing information on the projected indicative Union greenhouse gas budget for the 2030-2050 period”
SO 3: Ensure that the transition is just	(b) “the social [...] impacts” (c) “the need to ensure a just and socially fair transition for all” (g) “energy affordability”
SO 4: Ensure that the long-term competitiveness of the EU economy is maintained	(b) “the economic impacts, including the costs of inaction” (d) “cost-effectiveness and economic efficiency” (e) “competitiveness of the Union’s economy, in particular small and medium-sized enterprises and sectors most exposed to carbon leakage”
SO 5: Provide predictability for the deployment of best-available, cost-effective and scalable technologies	(k) “investment needs and opportunities” (f) “best available cost-effective, safe and scalable technologies” (g) “energy efficiency and the ‘energy efficiency first’ principle, [...] and security of supply”
SO 6: Ensure the security of energy supply of the European Union.	(g) “energy [...] security of supply”
SO 7: Ensure environmental effectiveness	(b) “the environmental impacts, including the costs of inaction” (i) “the need to ensure environmental effectiveness and progression over time” (j) “the need to maintain, manage and enhance natural sinks in the long term and protect and restore biodiversity”

4.3 Intervention logic

Figure 2 summarises the intervention logic, mapping the core problem to the general objective and the seven specific objectives.

Figure 2: Intervention logic

5 WHAT ARE THE AVAILABLE TARGET OPTIONS?

5.1 Current policy framework

5.1.1 *The Climate Law and the Fit-for-55 package*

This impact assessment aims to identify the most appropriate 2040 target level to bring the EU to climate neutrality by 2050. This 2040 target level is framed by the two existing climate targets, as defined in the European Climate Law: the 2030 climate target and the climate neutrality objective by 2050. The “Fit-for-55” package is the policy framework that implements the 2030 climate target.

5.1.2 *What would happen to the net GHGs emissions by 2040 with a continuation of the current policy framework?*

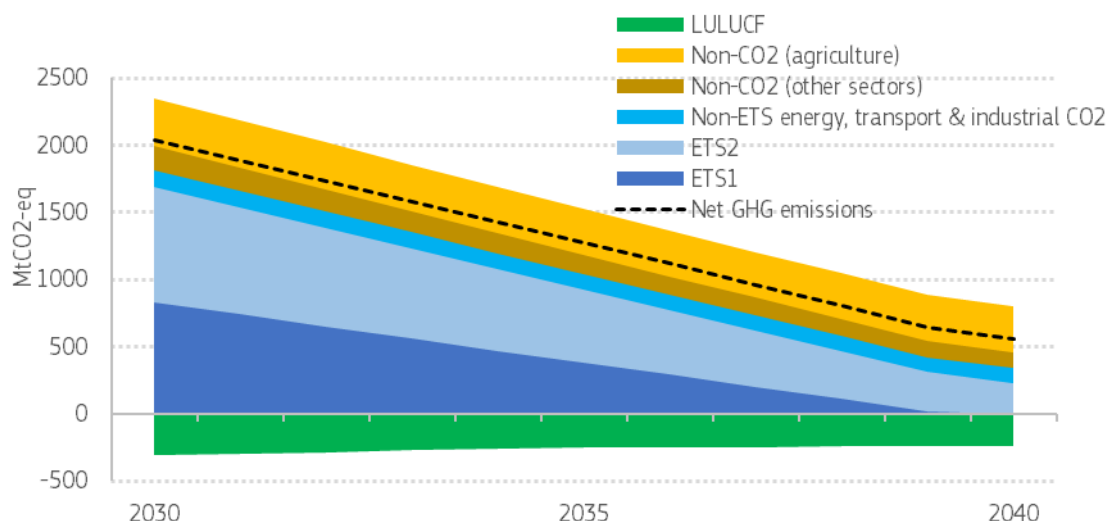
With the “Fit-for-55” policy framework, the EU economy meets its 2030 climate target of a domestic reduction of net ⁽³⁵⁾ GHG emissions of at least 55% compared to 1990 levels. While the “Fitfor-55” policy framework is designed for the period up to 2030, a limited part of the legislative package includes explicit, sectoral, post-2030 GHG emissions targets. In the absence of a review, the current design of the EU ETS Directive also applies beyond 2030.

This section looks at the net GHG emissions reductions that would theoretically be reached in 2040 with a continuation of this framework. Figure 3 ⁽³⁶⁾ depicts the GHG trajectories for 3 main categories: (1) LULUCF net removals, (2) non-CO₂ emissions, (3) CO₂ from energy, transport and industrial processes, a large part of which are covered by the ETS.

⁽³⁵⁾ GHG emissions after deduction of carbon removals

⁽³⁶⁾ A further description of the implied emission reductions under the prolongation of the current policy framework, including unchanged “linear reduction factors” in the ETS, can be found in Annex 6, section 4.

Figure 3: Theoretical 2030-2040 GHG emissions with the current policy framework



Note: ETS1 and ETS2 apply their respective linear reduction factor in 2030 onwards (corresponding to yearly reductions of about 90 MtCO₂ in ETS1 and 63.2 MtCO₂ in ETS2), “Rest energy, transport & industrial CO₂” is derived from the EU Reference Scenario 2020 ⁽³⁷⁾, non-CO₂ is from GAINS model (assuming no specific mitigation), LULUCF is from GLOBIOM (assuming no mitigation post-2030).

(1) In the absence of a policy for LULUCF beyond 2030, modelling shows that (1) LULUCF net removals would be limited to -220/-230 MtCO₂-eq.

(2) About half of current non-CO₂ emissions ⁽³⁸⁾ currently come from agricultural activities (e.g., enteric fermentation, use of fertilisers and manure management). Without any dedicated post-2030 GHG mitigation policy objective, the agricultural activities would still be significant emitters by 2050. Legislative initiatives such as the review of the fluorinated greenhouse gases Regulation, the Regulation of methane emissions reductions in the energy sector, the revision of the Industrial Emissions Directive, or the revision of the urban waste-water treatment Directive will reduce the “other” non-CO₂ emissions by a third over 2030-2040. By 2040, total non-CO₂ emissions will still be too large (around 460 MtCO₂-eq, 10-15% lower than in 2030), notably in agriculture.

(3) A small part of CO₂ emissions from energy, transport and industrial processes are not under the ETS ⁽³⁹⁾. The revised ETS will cover sectors which currently represent more than 90% of CO₂ emissions from energy, transport, and industrial processes. In the absence of any new post-2030 legislation, the emissions outside the ETS would decrease only very little over time, reaching together around 100 MtCO₂ in 2040. The ETS sets an emissions cap reducing every year by a “Linear Reduction Factor” (LRF) both for “ETS1” (the existing ETS extended to cover also maritime shipping) and for “ETS2” (the new system covering buildings, road transport and the remaining energy-related CO₂

⁽³⁷⁾ https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

⁽³⁸⁾ Excluding non-CO₂ emissions from the LULUCF sector and the very small share of non-CO₂ GHGs covered by the ETS that will follow the same pattern as discussed in the related paragraph.

⁽³⁹⁾ Part of CO₂ emissions from industrial processes, as well as CO₂ emissions from fossil fuel combustion in the agriculture sector (2.6% of total 2021 CO₂ emissions included in GHG inventories categories 1 and 2), inland waterways transport (0.6%) and rail transport (0.1%).

from industry). Without a change to the current LRFs after 2030, the cap under ETS1 reaches almost zero in 2040 ⁽⁴⁰⁾, and the cap under ETS2 reaches zero in 2044.

In addition, *the transport-related emissions under the ETS* are also covered by specific instruments with explicitly defined post-2030 targets: CO2 standards for vehicles in road transport, limits on the GHG intensity on energy used in the maritime sector and shares of sustainable advanced fuels in aviation emissions.

The resulting theoretical net GHG emissions under an unchanged policy framework would amount to -88% in 2040 compared to 1990. This reduction level is therefore considered as the “baseline” climate target for 2040 to which other target levels are compared.

This “baseline” target level goes beyond the reductions of net GHGs corresponding to the “linear” trajectory linking the 2030 climate target and climate neutrality in 2050 referred to in the Climate Law (Article 8)⁽⁴¹⁾, which translates into a reduction of net GHG emissions compared to 1990 of 78% (77.5% if starting from 55% reduction in 2030 or 78.5% in 2040 considering the estimated EU-wide net domestic GHG emissions cut by 57% by 2030 compared to 1990 under the Fit-for-55 legislation as adopted ⁽⁴²⁾).

5.1.3 Approach for the assessment of the 2040 climate target

The impact assessment is framed by the 2030 climate target and by the objective of climate neutrality by 2050. Up to 2030, the impact assessment reflects and fully implements the Fit-for-55 policy framework and associated targets.

Table 2 shows all explicitly defined and impact-assessed policies with concrete impacts on GHG emissions beyond 2030. These policies are included in all 2040 climate target options and accompanying analytical scenarios (see section 5.3), but these policies alone are neither sufficient to meet the 2040 target options considered nor climate neutrality by 2050.

⁽⁴⁰⁾ While the cap in Article 9 of the EU ETS Directive (stationary and maritime) would reach close to zero already in 2039 and zero in 2040, the allowances issued due to Art 3c (aviation) of the Directive are above 0 until 2044 included, getting to zero from 2045.

⁽⁴¹⁾ The Climate Law Article 8(1) refers to an indicative linear trajectory which sets out the pathway for the reduction of net emissions at Union level on which the Commission shall base its assessments on Union progress and measures and national measures.

⁽⁴²⁾ See the Climate Action Progress Report 2023.

Table 2: Pieces of legislation considered in the default post-2030 framework

GHG and sector	Legislation	Status at the time of the analysis
CO2 emissions in transport	CO2 emission standards for cars and vans	Adopted
	CO2 emission standards for heavy-duty vehicles	Proposal
	TEN-T Regulation	Agreed
	Alternative Fuel Infrastructure Regulation	Adopted
	Intelligent Transport Systems Directive	Adopted
	Greening Freight Package	Proposal
	ReFuelEU Aviation	Adopted
	FuelEU Maritime	Adopted
CH4 from the energy sector	Regulation on methane emissions reduction in the energy sector	Agreed
F gases	F-Gas Regulation	Proposal
Methane from waste	Landfill Directive	Not recently reviewed
	Waste Framework Directive	Not recently reviewed
	Urban Wastewater Treatment Directive	Proposal
Methane from agriculture	Industrial Emissions Directive	Proposal
GHG emissions from the energy sector	Energy Taxation Directive	Proposal

Note: “Adopted” means formally adopted by the European Parliament and European Council. “Agreed” means that a political agreement between the co-legislators has been reached. “Proposal” means proposed by the European Commission. “Not recently reviewed” means that this legislation is in force and has not been reviewed in recent years.

The rest of the post-2030 policy framework is still to be defined, or to be reviewed so that it can be aligned with achieving climate neutrality by 2050 and with the 2040 climate target once that target has been set. This applies to the ETS Directive, which already foresees a review ⁽⁴³⁾ in view of being compliant with the 2040 climate target. As a result, this assessment of the 2040 target does not assume a prolongation of unrevised ETS provisions after 2030 within the default post-2030 policy framework.

The impact assessment uses economic modelling to analyse the evolution of sectoral emissions and the contribution of technologies that are necessary to meet different 2040 target levels and climate neutrality by 2050.

5.2 Target options

This impact assessment aims to identify the most appropriate 2040 target level to bring the EU to climate neutrality by 2050 and to contribute to international action to fight climate change. The different target options considered in this impact assessment are therefore focused on different levels of net GHG emissions reduction in 2040 compared to 1990.

⁽⁴³⁾ Including the EU ETS Directive, which foresees a review in 2026, including in view of being in line with the Union’s 2040 climate target (Article 30(3) of Directive 2003/87/EC).

5.2.1 *Discarded target levels*

The assessment discards target levels below 75%. A target lower than 75% has the lowest support in the Public Consultation, from citizens, civil society organisations, businesses, and academic institutions alike, with less than 10% of support across all replies. A target lower than 75% is below the linear trajectory and would imply a complete break in the trend of GHG emission reductions compared to 2021-2030 and even a slowdown compared to the average 2011-2030 (see Table 3). It would also mean that steeper emissions reductions would be needed between 2041–2050, with a substantial risk, due to postponing more of the decarbonisation effort to the last decade, that the EU does not reach its legal objective of net climate neutrality by 2050. This option has the highest corresponding GHG budget (at least 23 GtCO₂-eq), so the lowest climate performance, and is thus not consistent with the EU commitments to global climate action.

The assessment also discards target levels above 95%. In its analysis for the recommendation on the 2040 target, the ESABCC concludes that all scenarios with 2040 emissions reductions above 95% exceed one or more of the environmental risk levels or limits used to rule out pathways not considered feasible, based on levels of carbon capture deployment, carbon removals from the land sink or bioenergy use. No other recently published scientific publication on a 2040 climate target for the EU to get to climate neutrality by 2050 has analysed or projects reductions of above 95% by 2040 (see Annex 13).

5.2.2 *Considered target levels*

The assessment therefore focuses on target levels between 75% and 95%. It looks at three climate target levels articulated around (i) the linear trajectory between 2030 and 2050 and (ii) the 85-95% range for an EU 2040 climate target compatible with the 1.5°C long-term temperature goal that is analysed in the scientific literature, including the ESABCC (see Annex 13).

- Target Option 1: a net GHG reduction target in 2040 of up to 80%

This target option is compatible with a linear trajectory of net GHG emissions between the existing 2030 climate target and the 2050 climate neutrality objective referred to in the Climate Law (Article 8), which would lead to a reduction level of 78% (see section 5.1.2). This option is significantly lower than the “baseline” target level of 88% (see section 5.1.2).

Among the three options assessed, this option gets the largest share of responses to the public consultation from businesses (nearly 30%) and public authorities (37%), but the lowest share among research organisations (15%), individuals (11%) and civil society organisations (8%).

In view of the comparison with the other target options, target option 1 is analysed through scenario S1 described in Section 5.3 and Table 4 and further described in Annex 6.

- Target Option 2: a net GHG reduction target in 2040 of at least 85% and up to 90%

This target option is compatible with the level of net GHG reductions that would be reached in the case of a prolongation of the current policy framework (-88%).

It matches the lower half of the 85-95% range provided by recent scientific literature on 1.5°C-compatible trajectories to bring the EU to climate neutrality by 2050, including the lower end of the range *analysed* by the ESABCC considering the challenges of short-term technological scale-up by 2030 (88-92%). It remains lower than the range *recommended* by the ESABCC (90-95%).

This option gets a large share of responses to the public consultation by research organisation (35%), and some support by businesses (22% for SMEs and 24% for large businesses) and individuals (24%).

In view of the comparison with the other target options, target option 2 is analysed through scenario S2 described in Section 5.3 and Table 4 and further described in Annex 6.

- Target Option 3: a net GHG reduction target in 2040 of at least 90% and up to 95%

This option corresponds to the range *recommended* by the ESABCC. It also matches the higher half of the 85-95% range analysed by recent scientific literature on 1.5°C-compatible trajectories to bring the EU to climate neutrality by 2050.

A target above 90% is the clear preferred option for individuals (46%) and aggregated across all organisations (30%). It is, in particular, favoured by civil society organisations (63%) and is supported by research institutions (35%) as much as option 2. SMEs support this option (21%) as much as the target option 2. It gets 19% of support from public authorities and 13% from large businesses that participated to the public consultation.

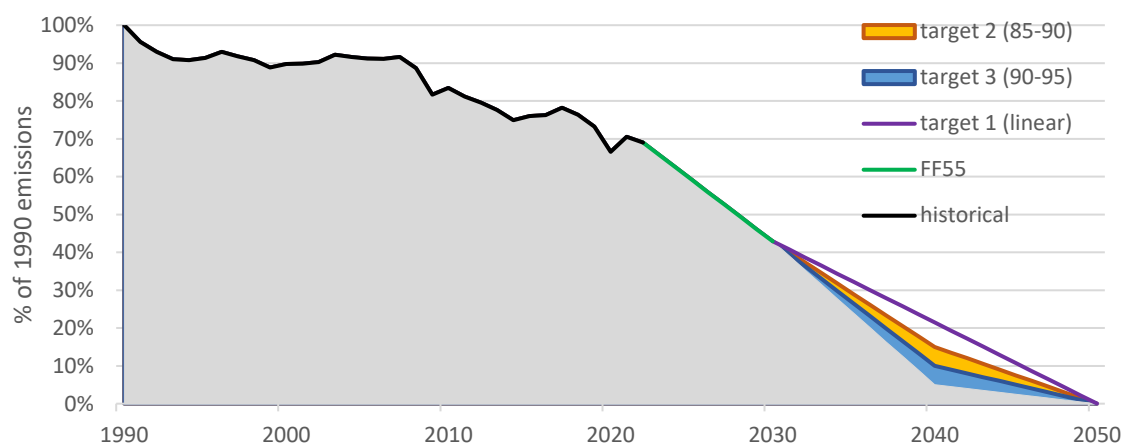
In view of the comparison with the other target options, target option 3 is analysed through scenario S3 described in Section 5.3 and Table 4 and further described in Annex 6.

5.2.3 *Emission profiles and cumulative GHG emissions under the different target options*

Table 3 and Figure 4 allow to compare the different target options in terms of their net GHG reduction profiles and their associated cumulative net GHG emissions of 2030-2050 (the “GHG budget”). Each target option corresponds to a level of net GHG reductions in 2040. For each target option, **the “GHG budget” is calculated assuming net GHG emissions reaching zero in 2050 and linear trajectories of net GHGs between 2030 and 2040 and between 2040 and 2050.**

Table 3: GHG budget and annual reduction of GHG emissions of each target option

	GHG budget 2030-2050 (GtCO ₂ -eq)	Yearly reductions (% 1990 levels)				
		1991-2010	2011-2030	2021-2030	2031-2040	2041-2050
Target level below 75%	More than 23	-0.9%	-2.0%	-2.8%	-1.8%	-2.5%
1 (linear, 78%)	21				-2.2%	-2.2%
2 (at least 85%)	Up to 18				-2.8%	-1.5%
3 (at least 90%)	Up to 16				-3.3%	-1.0%

Figure 4. Profile of the net GHG emissions over 1990-2050

Note: The net GHG emissions reflect the scope of the European Climate Law, i.e., all domestic net emissions (as under the UNFCCC inventories), international intra-EU aviation, international intra-EU maritime, and 50% of international extra-EU maritime from the MRV scope. 2022 values are based on EEA proxies. The intra-EU / extra-EU international aviation split is estimated based on air transport activity data (passenger-kilometres). The intra-EU / extra-EU international maritime split is based on MRV information for recent years and applied backwards to 1990.

Source: EEA, Eurostat.

5.3 The policy scenarios behind the target options ⁽⁴⁴⁾

The quantitative assessment of the target options is done through analysis based on economic modelling, building on three “representative” scenarios (S1, S2, S3), which all reach climate neutrality in 2050 but through different net GHG levels in 2040. These scenarios allow to assess the reduction of GHG across sectors and the contribution of different technologies, like carbon capture, to the different 2040 target levels. Each of these scenarios directly correspond to the three target options assessed, i.e. target option 1, 2, and 3, respectively. They are used to carry out the comparison of the impacts of the

⁽⁴⁴⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework

three target options assessed (section 7) and the choice of the preferred target option (section 8).

Another variant (LIFE) allows an assessment of the sensitivity of the analysis to assumed societal trends that can change the future evolution of GHG emissions. This variant serves to open the debate on the role of such trends in the context of meeting climate neutrality by 2050. In practice for the analysis, the LIFE scenario is set to be compatible with target option 3. However, the associated conclusions are relevant for and can be applied to all the target options.

5.3.1 Scenarios S1, S2 and S3

To ensure comparability across target options, the three scenarios (S1, S2, S3) share the same key assumptions on: 1/ socio-economic assumptions (in terms of population, economic activity, industrial production, and food production), 2/ technology costs (described in Annex 6, section 2.4), and 3/ common “default” policy elements applying post-2030 (described in Annex 6, section 3).

All three scenarios build on the continuation and upscaling of the current trends driving decarbonisation towards 2030, notably electrification of energy demand, deployment of renewables, and improvements in energy efficiency. Specific assumptions on more sustainable lifestyle (see 5.3.2) are not implemented.

The scenarios mainly differ with respect to the uptake over 2030-2040 of novel technologies to meet different levels of net GHG emissions in 2040. These technologies include, among others, advanced biofuels and the development of lignocellulosic bioenergy crops, precision agriculture, e-fuels, or the development of a carbon management industry.

- S1: up to 2040, this scenario relies essentially on the Fit-for-55 **energy trends**, which allow it to deliver a target in 2040 that is the “linear” reduction path of net GHGs between 2030 and 2050. It does not assume specific mitigation of non-CO2 emissions beyond their default evolution within the current framework, for instance in agriculture, or in the LULUCF sector. Beyond 2040 though, all sectors need to drastically reduce GHG emissions in view of meeting the climate neutrality objective by 2050 and all technologies need to be deployed.
- S2: to reach a reduction of at least 85% by 2040, this scenario **combines** the energy trends reflected in S1 with a further deployment of carbon capture and e-fuels as well as substantial reductions of GHG emissions in the land sector, including non-CO2 emissions in the agriculture sector and carbon removals in the LULUCF-sector.
- S3: to reach a reduction of at least 90% by 2040, this scenario builds on S2 and relies on a **fully developed carbon management industry** by 2040, with carbon capture covering all industrial process emissions and delivering sizable carbon removals, as well as higher production and consumption of e-fuels than in S2 to further decarbonise the energy mix.

Table 4 provides a detailed overview of the building blocks of the scenarios S1, S2 and S3. The analysis is based on the 2019 NECPs, and specific national policies until March 2023 are included. More elements can also be found in Annex 6 (section 3).

5.3.2 *LIFE – more sustainable lifestyles*

In addition to the three core scenarios that are used to compare the 2040 target options, a complementary variant (LIFE) looks at the sensitivity of the analysis to key societal trends related to more sustainable lifestyles, resulting from changes in the consumer preferences, from circular economy measures related to the use of energy and materials, as well as from changes in mobility and the food system ⁽⁴⁵⁾. **“LIFE” is not attached to a specific target option and is not used to compare the different target options. It serves to illustrate how these demand-side driven actions can complement the supply-side technology deployment analysed in the core scenarios.**

LIFE assesses the impact of a shift in consumption patterns to more sustainable alternatives leading to a more efficient use of natural resources. For example, consumers use products longer, repair more goods, shift to a “sharing economy” and products as a service, reduce energy consumption by controlling heating and cooling temperature settings, and adopt more sustainable mobility patterns led by shared mobility and active transport modes such as increased bike use. For the food system, LIFE assumes that consumers gradually shift to healthier and more sustainable diets ⁽⁴⁶⁾, while production follows the Farm to Fork Strategy and Biodiversity Strategy objectives, in particular reducing nutrient surplus and fertilisers needed to bring nature and biodiversity back to a healthy state and reducing food waste ⁽⁴⁷⁾. The analysis does not make assumptions on the drivers for these shifts in consumption patterns, which can be the result of societal trends, changing social norms and preferences, voluntary actions, or incentivising policies.

Table 4 describes the main building blocks of LIFE; detailed assumptions are described in section 3 of Annex 6. In practice in this analysis, the LIFE variant is set so that it aims at reaching net GHG reductions of at least 90% compatible with target option 3, in other words providing a different GHG mitigation picture that allows a direct comparison with the overall level of reductions in the core scenario S3. The results provide an indication of the order of magnitude of the reduction in the costs and technological investment needed to reach the 2040 GHG ambition level in the default common set of assumptions used in the three core scenarios, and that can instead be achieved through these demand-

⁽⁴⁵⁾ The food system means the actors and activities involved from the production to the consumption of food products from agriculture and forestry, fisheries, and aquaculture, including food governance actors and institutions and the interactions with neighbouring systems (economic, ecological, social, etc.).

⁽⁴⁶⁾ The right food environment can create and accelerate the shift towards healthier, less resource intensive and more plant-based diets. See for instance: European Commission Group of Chief Scientific Advisors, Scientific Advice Mechanism (SAM), ‘Towards Sustainable Food Consumption – Promoting healthy, affordable, and sustainable food consumption choices’, Scientific Opinion No.14, 2023

⁽⁴⁷⁾ The food waste proposal (COM (2023) 420 final) was not adopted in time to be factored in the core scenarios and is therefore only reflected in “LIFE”.

side changes. The conclusions from the analysis of the LIFE variant are relevant for and can be applied to all the target options.

Table 4: Overview of the scenario building blocks by 2040

	S1	S2	S3	LIFE
Rationale	Continuity of existing decarbonisation trends up to 2040: improvement of energy efficiency, electrification of energy demand, deployment of renewables in the power system	Similar as S1, but S2 also includes a wider diffusion of novel technologies by 2040 (carbon capture, e-fuels)	Similar as S2, but S3 assumes a faster and wider uptake of novel technologies over 2031-2040 (carbon capture, e-fuels)	Assumes more sustainable lifestyles and a move towards a more circular and shared economy. It translates into a different evolution of demand patterns for energy use in buildings, transport, in relation with materials management towards or in the food system
Industry	Electrification of energy consumption, some development of e-fuels by 2040		More e-fuels by 2040 than in S2	Enhanced circularity entails comparatively lower needs for primary production of materials, and so lower needs for carbon capture
	Very limited carbon capture in industrial processes	Deployment of carbon capture	Further deployment of carbon capture	
Buildings	Further electrification through sustained deployment of heat pumps			Lower thermostat settings for heating and cooling temperature deliver additional energy savings
	Low average annual renovation rate in 2031-2040 and high in 2041-2050	Similar average renovation rate in 2031-2040 and 2041-2050	High average annual renovation rate in 2031-2040 and low in 2041-2050	
Transport	EU Sustainable & Smart Mobility Strategy and Action Plan: milestones achieved (particularly with regard to rail, inland waterways and short-sea shipping)			
Road transport	CO2 standards for cars and vans: -100% vs 2021 from 2035 onwards	CO2 standards for cars and vans as in S1 + Higher car occupancy & some shift from car to active modes (walking, cycling) and public transport, driven by a shift towards shared and collaborative mobility services and multimodal travel		As in S3 plus stronger shift towards shared and collaborative mobility services and multimodal travel, including sustainable urban transport; ‘smart’ charging
	CO2 standards for HDVs: -90% vs 2019 from 2040 (-100% for buses), more efficient operation of freight vehicles and delivery of goods by optimising multi-modal delivery solutions, higher use of intermodal freight transport		CO2 standards for HDVs: -100% vs 2019 from 2040, more efficient operation of freight vehicles and delivery of goods by optimising multi-modal delivery solutions, higher use of intermodal freight transport	
Maritime transport	FuelEU Maritime GHG intensity targets: -31% in 2040 and -80% in 2050 (vs 2020)			
	Lower end of the IMO GHG reduction target range (-70% in 2040 vs 2008)	Mid-point of the IMO target range (-75% in 2040 vs 2008)	Higher end of the IMO target range (-80% in 2040 vs 2008)	
Aviation	ReFuelEU Aviation SAF mandates (34% in 2040 and 70% in 2050; including a sub-mandate for synthetic aviation fuels and H2: 10% in 2040 and 35% in 2050)	Slightly more ambitious fuel mandates than in S1 (SAF: 36% in 2040 and 72.5% in 2050; synthetic aviation fuels and H2: 12% in 2040 and 37.5% in 2050), incentives for the deployment of zero-emissions aircraft	Slightly more ambitious fuel mandates than in S2 (SAF: 38% in 2040 and 75% in 2050; synthetic aviation fuels: 14% in 2040 and 40% in 2050), incentives for the deployment of zero-emissions aircraft	As in S3 plus fewer business trips and long trips compared to scenarios, modal shift to rail (particularly for short trips)

	S1	S2	S3	LIFE
Power system	Limited remaining CO2 emissions in 2040, share of renewables in total electricity production increases compared to 2030	Close to decarbonised in 2040, larger deployment of renewables	Fully decarbonised in 2040, the system operates mostly with renewables	
	The deployment of renewables is facilitated by system optimisation (interconnections, storage and demand-side response). Nuclear according to MS policies until March 2023; plays a comparable role in all scenarios.			
Bioenergy	Moderate increase by 2040 compared to current, stabilises over 2041-2050	Larger increase by 2040 compared to current, and slightly declines after 2040		
H2 & e-fuels	Some increase in 2040 above 2030 levels	Stronger increase than in S1, notably in the transport sector	Stronger increase than in S2 in all sectors	
Carbon capture	Limited uptake in 2031-2040 and large deployment in 2041-2050	Deployment in 2031-2040, in particular in industrial processes, maintained in 2041-2050	Further deployment in 2031-2040 to cover remaining energy and industrial process emissions	
Carbon removals	Very limited uptake of BECCS by 2040	Some deployment of BECCS and DACCS by 2040	Higher deployment by 2040 of both BECCS and DACCS	
Circularity				Circular economy trends limiting raw materials needs
Food system	Continuation of current trends based on the Agricultural Outlook 2022			Change towards more sustainable food diets, reduction of food waste objectives leading to additional reduction of agriculture GHG
	Very limited GHG reductions in agriculture	GHG in agriculture decrease further thanks to larger deployment of technological options	GHG in agriculture decrease further thanks to full deployment of technological options	
LULUCF	Small increase of forest land and decrease in grassland	Policy intensity to cover mitigation costs equivalent to meeting the 2030 target		More available land for carbon farming and high-diversity elements such as set aside and fallow land with natural vegetation through land-use change in grassland and cropland
		Higher land-use change with bigger increase of forest land, additional wetland and cropland while stronger decrease of grassland		
Non-land-related non-CO2 GHG emissions	Non-land-related non-CO2 emissions slowly decline, combining current policy framework and transformation of the energy system	Non-land-related non-CO2 emissions decline further thanks to additional mitigation		

6 WHAT ARE THE IMPACTS OF THE TARGET OPTIONS?

The impacts of the different 2040 target options are illustrated by the three scenarios S1, S2 and S3 ⁽⁴⁸⁾ presented in the previous section. Section 6 shows the impact of these scenarios and complements the analysis by quantifying the impact of changing lifestyles as shown by the LIFE sensitivity analysis.

A more detailed analysis on the sectoral GHG evolution and associated technological deployment attached to each scenario can be found in Annex 8.

6.1 GHG emissions

6.1.1 Net GHG emissions

The net GHG emissions analysed in this impact assessment correspond to the Union-wide GHG emissions and removals regulated in Union law ⁽⁴⁹⁾.

Table 5 shows the sectoral net GHG emissions in the different scenarios serving to analyse the 2040 target options. All scenarios achieve climate neutrality in 2050.

⁽⁴⁸⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

⁽⁴⁹⁾ European Climate Law, Article 2. They cover all domestic emissions, LULUCF, international intra-EU aviation, international intra-EU maritime, and 50% of international extra-EU maritime from the MRV scope.

Table 5: Sectoral net GHG emissions

	2015	2040			2050
		S1	S2	S3	S3**
Reduction vs 1990 - %	-24%	-78%	-88%	-92%	-101%
Net GHG Emissions (target scope)*	3592	1051	578	356	-38
Power and district heating ^A	1031	120	8	-10	-39
Other energy sectors ^B	237	71	45	11	-19
Industry ^C	605	267	181	89	16
Residential & services ^D	519	119	92	75	19
Other non-energy sectors ^E	130	33	26	25	22
Domestic transport	780	190	143	120	7
Agriculture ^F	385	351	302	271	249
Waste management	120	65	52	52	28
LULUCF net removals	-322	-218	-316	-317	-333
International transport (target scope ^G)	107	52	46	41	11
International Transport (memo items)					
	233	124	113	106	27

*Note: *Calibration residuals to GHG inventory 2023 are allocated to relevant sectors. A: Includes removals from BECCS. B: Includes removals from DACCS. C: includes CO₂ from fossil fuel combustion in industry and CO₂ from industrial processes. D: Includes fossil fuel combustion CO₂ emissions in agriculture. E: CO₂ fugitive emissions and non-CO₂ emissions from direct use or specific products. F: GHG inventory "category 3". G: international intra-EU aviation, international intra-EU maritime (MRV) and 50% of international extra-EU maritime (MRV).*

***S1 and S2 values for 2050 are similar to S3 and represented in more details in Annex 8.*

Source: PRIMES, GAINS, GLOBIOM.

Scenario S1 projects emissions following a linear trajectory between 2030 and climate neutrality 2050, reaching around 1050 MtCO₂-eq in 2040. This requires limited development by 2040 of advanced mitigation options like carbon capture or e-fuels. A higher uptake under S2 of e-fuels, carbon capture, further abatement in agriculture and dedicated mitigation actions in the LULUCF sector lead to stronger emission reductions of 88%, with net GHG emissions reaching around 580 MtCO₂-eq. S3 achieves a steeper reduction of around 92% (around 350 MtCO₂-eq), compared to S2, based on rapid deployment and scale up of novel technologies by 2040.

LULUCF net removals have experienced rapid changes of the past years, and the future evolution of this sector is uncertain. The level can vary depending on the effect of policies or climate change impacts (see section 1.8 in Annex 8). When this uncertainty is included in the calculation of the net GHG emission reduction in 2040, each scenario still remains within the range of their respective target option, namely S1 corresponding to target option 1 (up to 80%), S2 corresponding to target option 2 (85-90%) and S3 corresponding to target option 3 (90-95%).

The importance of net removals from LULUCF was confirmed in the public consultation, where nearly 50% of citizens asked for a stronger reliance on the LULUCF sink given

uncertainty about the deployment of industrial removals. Among organisations, views were more divided between civil society organisations demanding a stronger reliance on the LULUCF sink, research institutions and public authorities favouring a balanced approach, and business associations and companies favouring either a balanced approach or a stronger reliance on industrial removals. However, when asked about the most relevant solutions for fighting climate change, citizens and all stakeholder groups uniformly indicated nature-based solutions for the LULUCF sector (afforestation, reforestation, and forest restoration, as well as peatland restoration) as being the most important solutions.

Energy supply emissions (“power and district heating”, as well as “other energy sectors”) remain positive (180 MtCO₂-eq) in the case of S1 but get close to zero in S2 (about 50 MtCO₂-eq) and reach zero in S3 in 2040. The decarbonisation of the energy sector is possible thanks to the availability of a broad set of technologies to generate carbon-free electricity (notably renewables) and to the development of carbon capture and carbon removals in S2 and S3 (see 6.1.2), as well as to the reduction of methane emissions from the decreased use of fossil fuels. Emissions in industry are cut by 56-84% compared to 2015, due to electrification, implementation of new manufacturing technologies, innovation in processes, use of alternative materials or sources such as RFNBOs and cleaner supply chains. Contribution of the gradual uptake of hydrogen and development of carbon capture to industrial emission reduction is seen in S2 and goes further in S3, where solid fossil fuels virtually disappear, and all process CO₂ emissions are captured. Residential and service emissions decrease by 77-85% compared to 2015, depending on the scenario, driven by a sustained deployment of heat pumps and renovation of building envelopes.

Transport emissions drop by 69-78% compared to 2015, primarily due to large-scale deployment of electric vehicles in road transport in all scenarios, along with a further switch from fossil fuels to e-fuels and advanced biofuels in maritime, aviation and road transport in S2 and S3.

In the agricultural sector, where GHG emissions remained relatively stable over the last 10 years, GHG emissions decrease by around 10% compared to 2015 in S1 and by between 22% and 30% with more ambitious reductions in S2 and S3, driven by technological improvements in breeding, mitigation of enteric emissions, manure management and fertiliser application. The waste management sector reduces CH₄ emissions in all scenarios by more than half compared to 2015. These results are broadly in line with the public consultation results, which show that energy supply, agriculture and transport are expected to be the sectors most affected by the green transition after 2030 (⁵⁰).

⁵⁰ In the energy supply sector, the public consultation respondents expect a strong decrease in fossil fuel consumption coupled with a transition to renewable energy sources. In the agriculture sector, respondents expect significant changes in production methods, land management practices and consumer behaviour. Finally, in the transport sector, they expect a transition to electric vehicles and alternative fuels, along with a modal shift to the lowest carbon-intensive modes.

6.1.2 *Carbon capture and carbon removals*

The role of **carbon capture** and **carbon removals** is an important differentiating factor for the 2040 climate ambition, which is in general also acknowledged by stakeholders in the public consultation. While civil society organisations, research institutions and citizens largely agree on the need for separate targets for GHG emissions, nature-based removals and industrial removals, businesses and public authorities' views are more evenly divided between three separate targets and one single target. The nature of this divergence lies in different opinions on the potential and challenges to scale up industrial removals and to which extent removals should be used to compensate for residual GHG emission reduction.

The modelling results in Table 6 show that while annual capture remains lower than 100 MtCO₂ in S1, it reaches around 220 MtCO₂/year in S2, and around 350 MtCO₂/year in S3, where most emissions from the power system and industrial processes are captured and industrial carbon removals technologies are well deployed. The crucial role of carbon capture to reach high levels of decarbonisation of the industrial system by 2040 is a common finding across the various models used for the detailed analysis (see Annex 8) and in line with the public consultation, where all stakeholder groups would prioritise capturing CO₂ from non-energy industrial processes over other applications. The captured carbon is used to produce e-fuels (the consumption of which varies across scenarios – see section 6.1.3) or stored, with injection rates for storage in 2040 close to 150 MtCO₂/year in S2 and 240 MtCO₂/year in S3. CO₂ implemented in materials is projected to develop mostly in the 2041-2050 decade.

Table 6: Industrial carbon capture and use

	2040			2050
Carbon Captured – MtCO₂/year	S1	S2	S3	S3*
By Source	86	222	344	452
Industrial Processes	37	123	137	136
Power (fossil fuels)	26	41	32	55
Power (biomass) and DACC**	16	54	153	232
Biogenic (upgrade of biogas into biomethane)	7	4	22	30
By Application (use and storage)	86	222	344	452
E-fuels	43	75	101	147
Synthetic materials	0	0	0	59
Underground storage	42	147	243	247

Note: *S1 and S2 values for 2050 are similar to S3 and represented in more details in Annex 8. **Includes carbon for storage (DACCS) and use.

Source: PRIMES.

As described in the results of the public consultation ⁽⁵¹⁾, alongside deep reductions of **gross GHG emissions**, **carbon removals** are expected to play an important role in the coming decades to get to climate neutrality by 2050 and negative emissions thereafter (Table 7).

Table 7: Industrial removals and net LULUCF removals

	2040			2050
	S1	S2	S3	S3**
Gross GHG emissions (MtCO₂-eq)	1273	943	748	411
Total Removals (MtCO₂-eq)	-222	-365	-391	-447
<i>Industrial Removals (MtCO₂)</i>	-4	-49	-75	-114
<i>LULUCF net removals (MtCO₂-eq)</i>	-218	-316	-317	-333

Note: **S1 and S2 values for 2050 are similar to S3 and represented in more details in Annex 8.

Source: PRIMES, GAINS, GLOBIOM.

Gross GHG emissions ⁽⁵²⁾ are projected to reduce by between 75% (S1) and 85% (S3) in 2040 and around 92% in 2050 compared to 1990, providing the biggest contribution to

⁽⁵¹⁾ 61% of the position papers analysed, commented on carbon removals, with many of them indicating removals would be instrumental to reach climate neutrality, if complementary to GHG emission reduction at source.

⁽⁵²⁾ Gross GHG emissions are defined as the actual GHG emissions excluding the contribution of industrial removals and LULUCF net removals, that are included of the calculation of “net GHG” emissions as measured for the EU’s climate objectives in 2030 and by 2050.

climate neutrality, but still leaving residual GHG emissions. This result, in line with the lowest gross GHG emissions by 2050 of 390 MtCO₂-eq presented by the ESABCC ⁽⁵³⁾, shows that removals are required to compensate emissions that cannot be abated due to extremely high abatement costs or technical unfeasibility. Carbon removals can either be achieved through the LULUCF sector as nature-based removals or technically as industrial carbon removals derived from carbon capture.

LULUCF net removals are projected to contribute significantly over 2030-2050 in scenarios S2 and S3 with net removals of around -320 MtCO₂-eq (see Table 7).

The role of industrial removals remains much more limited in the short run, given the need to fully develop some aspects of the technology to ensure large-scale deployment ⁽⁵⁴⁾. They become significant by 2040 to meet higher climate targets, with about -50 MtCO₂ in S2 and -75 MtCO₂ for S3, representing close to 25% of the total carbon capture. To reach climate neutrality by 2050, the analysis projects industrial removals of more than -100 MtCO₂, complementing land-based removals in the LULUCF sector. All pathways modelled therefore need a strong LULUCF net removal complemented by industrial removals to put the EU on the path towards climate neutrality.

Table 8 provides an overview of the GHG emissions from agriculture, forestry and other land use (“AFOLU”, combining net emissions from agriculture and LULUCF) across the different scenarios. Emissions in the sectors reach net zero ahead of 2040 in S2 and S3, later in case fossil fuel related CO₂ emissions in agriculture are included in S1.

Table 8: Emissions from the agriculture sector and LULUCF net removals

	2040				2050			
	S1	S2	S3	LIFE	S1	S2	S3	LIFE
Agriculture (category 3) + LULUCF net removals	133	-14	-46	-150	-92	-83	-84	-195
Agriculture (categories 3 & 1) + LULUCF net removals	165	15	-19	-122	-73	-64	-66	-175

Note: Category 3 refers to the UNFCCC agricultural sector; category 1 to energy use in agriculture.

Source: GAINS, GLOBIOM, PRIMES.

6.1.3 GHG emissions in the LIFE sensitivity case

Table 9 summarises the impact of the LIFE sensitivity analysis on GHG emissions. The case achieves the same reductions in net GHG emissions as S3, but through a different distribution of emissions across sectors.

The difference of emissions in LIFE compared to S3 results from a more sustainable food system and associated land use, which reduces the net emissions from the land sector by about 100 MtCO₂-eq, combining a cut in emissions from agriculture of about 60

⁽⁵³⁾ ESABCC, Figure 37.

⁽⁵⁴⁾ Key barriers for the roll-out of carbon capture are investment and operating costs, regulatory implementation, complexity of full chain infrastructure projects, as well as public acceptance.

MtCO₂-eq and significant additional removals from the LULUCF sector of around 40 MtCO₂-eq in 2040. This lowers the need for carbon capture and industrial carbon removals. In parallel, an increased Circular Economy and more sustainable mobility contribute to limiting the emissions in the energy and industry sector, which are intermediate between S2 and S3.

Table 9: Comparison of GHG in the LIFE case with the core scenarios

MtCO ₂ -eq	2040			
	S1	S2	S3	LIFE
Net GHG emissions	1051	578	356	353
of which from the land sector*	133	-45	-46	-150
of which from agriculture	351	302	271	209
of which from energy and industry**	918	593	402	503
Carbon capture	86	222	344	278
Carbon removals	-222	-365	-391	-387
of which industrial removals	-4	-49	-75	-27
of which LULUCF net removals	-218	-316	-317	-360

*Note: *Emissions from agriculture and net removals from the LULUCF sector. **Includes other non-land sectors like waste management, as well as industrial carbon removals*

Sources: PRIMES, GAINS, GLOBIOM

6.2 Evolution of the energy system and associated raw material needs

6.2.1 The energy system

Climate policy and energy security go hand in hand as the decline of fossil fuels has profound consequences for the EU's energy dependence. Import dependency (the share of imports in GAE), decreases from 61% in 2019 to 34% in S1, 29% in S2 and 26% in S3 in 2040. Due to the decline of domestic production and a continued need for oil imports, a large decrease in import dependency requires deeper decarbonisation. In 2050, the dependency is reduced to only 15%, more than half associated with non-energy uses of fuels. High demand for renewables, storage and novel technologies may lead to new dependencies for raw materials or technology imports from non-EU countries.

Table 10 summarises the main results for the evolution of the energy system from the PRIMES model. These results are validated by the findings of four other energy system models that have been used in the context of this impact assessment (i.e., POTEnCIA, METIS, EU-TIMES and POLES – see Annex 6). More details on the evolution of the energy system can be found in Annex 8.

Deep changes in the energy mix underpin the decarbonisation of energy supply. Continued energy efficiency improvements reduce the need for energy. Gross available energy (GAE) decreases from approximately 1450 Mtoe (or 61 EJ) in 2021 to around 1020 Mtoe (43 EJ) in 2040 (around 30% reduction), with limited differences across scenarios S1, S2 and S3. LIFE entails further reduction of GAE by 24 Mtoe (1 EJ). After 2040, GAE remains practically constant as energy savings are compensated by the additional energy required for renewable hydrogen production by electrolysis, and direct air capture.

Fossil fuels use decreases and renewable energy increases (in particular, wind and solar power). By 2040, fossil fuel supply for energy use will decrease by more than 70% compared to today. The measures foreseen in LIFE reduce fossil fuel use by an additional 10 Mtoe (0.4 EJ); by 2050 only small amounts of fossil fuel remain (approximately 150 Mtoe or 6.2 EJ), in large part used for non-energy purposes and long-distance transport. More than half of all fossil fuels used in the EU in 2050 are used in the non-energy sector as feedstock for chemical processes (plastic, fertilisers, etc.). The phase out of fossil natural gas imports from Russia accelerates the transition trajectory. The consumption of natural gas, biomethane and biogas reaches approximately 105 – 155 Mtoe by 2040 (4.5 – 6.5 EJ). In 2050, the consumption of those gaseous fuels in the EU is still between 70 and 80 Mtoe for all scenarios (3.0 – 3.5 EJ). Oil is the last fossil fuel to reduce, and consumption in 2050 is estimated at approximately one fourth of that in 2020. Coal is almost completely phased out by 2040.

Climate policy and energy security go hand in hand as the decline of fossil fuels has profound consequences for the EU's energy dependence. Import dependency (the share of imports in GAE), decreases from 61% in 2019 to 34% in S1, 29% in S2 and 26% in S3 in 2040. Due to the decline of domestic production and a continued need for oil imports, a large decrease in import dependency requires deeper decarbonisation. In 2050, the dependency is reduced to only 15%, more than half associated with non-energy uses of fuels. High demand for renewables, storage and novel technologies may lead to new dependencies for raw materials or technology imports from non-EU countries.

Table 10: Summary of key energy indicators

	2030	2040			2050
		S1	S2	S3	S3**
Policy relevant indicators					
Energy-related CO2 reductions vs 2005	-58%	-83%	-90%	-94%	-103%
RES share in Gross FEC	42.4%	65%	72%	75%	89%
FEC reduction vs 2015 ⁽⁵⁵⁾	-19%	-34%	-34%	-36%	-40%
Energy indicators – Supply					
Gross Available Energy (Mtoe)	1160	1022	1021	1018	1032
- Fossil fuels	663	375	311	275	150
- of which for non-energy use	96	96	96	96	80
- of which captured	1.8	11.5	13.2	13.3	24
- Nuclear	139	129	129	129	142
- Renewables	328	482	544	613	691
Net imports (Mtoe)	572	347	298	267	153
Import dependency (%)	50%	34%	29%	26%	15%
Hydrogen production (Mtoe)⁽⁵⁶⁾	9	60	76	100	185
e-Fuels production (Mtoe)	2	15	27	37	60
Energy indicators – Power generation					
Gross electricity generation (TWh)	3362	4563	4899	5212	6922
Net installed power capacity (GW)	1617	2181	2377	2525	3256
- Fossil fuels	238	172	164	156	142
- Nuclear	94	71	71	71	71
- Renewables	1285	1939	2142	2298	3027
Storage and flexibility options (GW)	172	213	254	275	238
Final Energy					
Final Energy Consumption (Mtoe)	764	622	614	604	555
Electricity share in FEC	33%	48%	50%	51%	62%
e-Fuels share in FEC	0%	1%	3%	5%	7%

*Note: GAE does not include ambient heat from heat pumps. E-Fuels include power-to-liquid and power-to-gas fuels but not hydrogen. Storage technologies include only battery and pumped-hydro storage, whose decline between 2040 and 2050 is due to the projected increased use of power-to-X technologies. The analysis is based on the 2019 NECPs and national legislation as of March 2023. **S1 and S2 values for 2050 are similar to S3 and represented in more details in Annex 8.*

Source: PRIMES.

⁽⁵⁵⁾ Note that the 2030 energy efficiency is expressed as % reduction compared to the projection of the 2020 Reference scenario (not compared to 2015).

⁽⁵⁶⁾ Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 in this table reflects the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024.'

Renewables gradually become the backbone of the EU energy system. The share of renewables in GAE grows from 17% in 2021 to 50% – 60% in 2040. The share of wind and PV in GAE increases to 27% – 34% in 2040. The use of biomass and waste is also projected to increase by 30% in S2 and S3 representing approximately 20% of the GAE share in 2040 ⁽⁵⁷⁾. This evolution is mostly driven by advanced liquid biofuels and biomethane, while direct consumption of solid biomass is projected to decrease. The future role of bioenergy will have to be integrated into a sustainable circular bioeconomy, following the cascading principle. The conviction of renewables becoming the backbone of the EU energy system is shared throughout the public consultation, where across all stakeholder groups and citizens renewable energy from wind, solar or hydro was consistently rated as the most relevant solution for the energy transition towards carbon neutrality. This notion was also supported in many position papers arguing for an enhanced use of renewable energies. Stakeholders, in particular from science, civil society, and EU citizens identified the expansion of renewable energies as among the most important challenges for the EU to reach its climate ambition.

Renewable **hydrogen** as energy vector appears as a key technology of the future EU energy system, including to produce e-fuels (both gaseous and liquid) and to contribute to decarbonise the hard-to-abate sectors (such as aviation and maritime transport, among others). In the next two decades, there are large differences in hydrogen scale-up across scenarios. In 2040, the S3 scenario projects more than 60% more hydrogen production than S1, with most of the difference related to demand for e-fuels. LIFE reduces demand for renewable hydrogen by around 15 Mtoe with circular economy measures and consumption patterns (that reduce the need for certain materials). In 2050, hydrogen consumption reaches up to 185 Mtoe (7.7 EJ). Imports of RFNBOs pick up after 2035, but in low amounts due to still relatively high costs. Hydrogen and the development of clean fuels are regarded as particularly important for the EU's energy transition towards climate neutrality by business associations and companies (both SME's and large industries).

⁽⁵⁷⁾ In the scenarios considered, the “gross available energy” from biomass is capped at 9 EJ, the environmental risk level for “primary bioenergy use” indicated by the ESABCC – see Annex 6. Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

Member States revision of their nuclear energy policy

Recent announcements by several Member States show a renewed interest in nuclear energy. A “nuclear alliance” has been set up by some Member States and is led by France. Among other policy changes, France has adopted a law in June 2023 that abolishes the objective of reducing the nuclear power share in the electricity mix to 50%, as well as the capping of nuclear production capacity at 63.2 GW. In addition, several operators have either already obtained licence or announced plans for further lifetime extensions of nuclear plants. Other changes include life extension of nuclear plant in Hungary and Finland. These legal changes added approximately 18 GW of capacity to the European nuclear fleet in 2040 (of which France accounts for about 17 GW), compared to the assumptions Section 2.5.2.2 of Annex 6 (that already include the plans adopted up to March 2023 and in particular additional nuclear capacity in Bulgaria, Czechia, Finland, Hungary, Netherlands, Poland, Romania, Slovenia and Slovakia). Due to the lead time of new nuclear plants, nuclear capacity in 2030 is unchanged compared to the original policy assumptions.

This scenario variant discusses how this legal revision changes the energy system and GHG emissions compared to the results in the S3 scenario.

With the new French legislation of June 2023, the installed capacity of nuclear plants in France reaches 54 GW by 2040 (an increase compared to 37 GW projected before the change of the law). In 2040, the share of nuclear energy in the power mix of France reaches 38% of total electricity generated compared to 27% before the June 2023 change of the law. (This compares to a share of nuclear in power generation in 2020 of 72%. This difference between 2020 and 2040 is mainly due to the electricity consumption increasing considerably - which is partly matched by more renewables). With the new French policy, the installed capacity of nuclear plants in Europe reaches 88 GW by 2040 (compared to 71 GW in the previous S3 scenario and 94 GW in 2030).

Compared to the results shown in Climate policy and energy security go hand in hand as the decline of fossil fuels has profound consequences for the EU’s energy dependence. Import dependency (the share of imports in GAE), decreases from 61% in 2019 to 34% in S1, 29% in S2 and 26% in S3 in 2040. Due to the decline of domestic production and a continued need for oil imports, a large decrease in import dependency requires deeper decarbonisation. In 2050, the dependency is reduced to only 15%, more than half associated with non-energy uses of fuels. High demand for renewables, storage and novel technologies may lead to new dependencies for raw materials or technology imports from non-EU countries.

Table 10 for the S3 scenario, the additional nuclear plants increase the share of nuclear power in the energy mix from 13% of GAE to 15% in 2040 (or approximately 160 Mtoe). This increase of nuclear energy leads to a slightly slower growth of renewables that reach 600 Mtoe in 2040 (or 10 Mtoe difference). Net installed capacity follows a

The coming decades require a significant increase in electricity supply, mainly due to the increasing electrification of end-use sectors, but also to the power needed for the production of RFNBOs and DACC. Electricity generation increases from 2905 TWh in 2021 to about 4565 TWh in S1, 4900 TWh in S2 and 5210 TWh in S3 in 2040.

In 2040, S1 requires around 13% less electricity than S3. This is explained by substantial differences in production of RFNBOs and in industrial removals by DACC. In 2040, electrolyzers, RFNBO synthesis and DACC combined consume approximately 600 TWh more electricity in S3 than in S1. In S2 consumption is approximately 270 TWh more than S1 for the same purposes. Due to the lower hydrogen production (thanks to circular economy measures and consumption patterns) LIFE allows to save almost 390 TWh of total electricity production in 2040. Projections for electricity, hydrogen and RFNBOs consumption in 2050 are similar across all scenarios.

The share of fossil-fired power generation steadily decreases by 2040, from 36% in 2021 to 8% in S1 and 3% in S3. Residual fossil-fired generation consists almost solely of gas-fired power plants (equipped with CCS or used for peak demand). Renewables increase their contribution to total electricity generation from about 40% in 2021 to 81%-87% in 2040 (wind and solar accounting for the largest shares of renewable capacity). The analysis results in nuclear power generation decreasing from 730 TWh in 2021 to around 495 TWh in 2040 with nuclear capacity assumptions in line with the Member State policies as in 2019 National Energy and Climate Plans and national policies as of March 2023⁽⁵⁸⁾. Net imports of electricity from outside the EU remain very small (around current levels).

As wind and solar PV generation have relatively low full load hours, replacing fossil fuels with renewables requires higher installed power capacity. Total installed capacity grows more than two times faster than electricity generation between 2015 and 2040. There are large differences in renewable capacity across scenarios. In 2040, S3 and S1 requires 6% more and 8% less capacity than S2, respectively (2300 GW in S3, 1940 GW in S1 and 2140 GW in S2). The circular economy measures and behavioural changes in LIFE significantly decrease the amount of generation capacity, by around 200 GW in 2040.

Balancing the high share of variable renewable electricity generation requires a flexible power system. Flexibility needs are increasingly met by storage solutions (mainly pumped hydro storage and batteries) reaching 275 GW in S3 in 2040 and by demand side measures including demand management technologies such as the production of hydrogen with electrolyzers and – to a lower extent – the production of other RFNBOs. There is a marked difference with scenarios S1 and S2 requiring significantly less storage and electrolyser capacity than S3 in 2040.

⁽⁵⁸⁾ These assumptions reflect the situation until March 2023. In June 2023, France has adopted a law which removes the objective of reducing the share of nuclear power in the electricity mix. additional 3.3 GWe nuclear capacity was officially announced for deployment by mid-2030s. See Annex 8 for more details. Future analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted.

Final energy consumption (FEC) shows a large reduction already this decade, reaching 765 Mtoe in 2030 (32 EJ: the Energy Efficiency Directive target), further reducing in 2040 to 622 Mtoe (26 EJ) in S1, 614 Mtoe (25.7 EJ) in S2 and 604 Mtoe in S3 (25.3 EJ). The share of renewable energy in gross FEC increases from 42% in 2030 (in line with the Renewable Energy Directive target) to 65% in S1, 72% in S2 and 75% in S3 in 2040.

The share of fossil fuels in total FEC decreases from above 60% in 2015 to 30% in S1, 25% in S2 and 23% in S3 in 2040, and further down to only 5% in 2050. Electricity becomes the dominant energy vector in final energy sectors. The share of electricity in FEC increases from 23% in 2015 to above 45% in 2040 (approximately 280-290 Mtoe across scenarios or 11.7 – 12.1 EJ) and up to 57% (320 Mtoe – 13.4 EJ) in 2050. This increase is mainly driven by the uptake of electric vehicles, the penetration of heat pumps and electrification of low and medium temperature industrial processes. Fossil fuels start to be partially replaced by hydrogen and other RFNBOs in industry and transport (representing more than 10% and 20% of sectoral demand in S2 and S3 in 2040), while the consumption of RFNBOs in the building sector remains limited throughout the period. Across all sectors, RFNBOs account for approximately 5-10% of total FEC in 2040 and 16% in 2050.

Under existing energy efficiency policies, all end-use sectors are expected to reduce energy consumption significantly in the current decade. Energy consumption continues to decrease in the decade 2031-2040 albeit at a slower pace (except for the transport sector that sees considerable improvements after 2030 thanks to accelerated electrification). Compared to 2021, energy consumption decreases by 42% in 2040, in the transport sector ⁽⁵⁹⁾, 45% in the residential sector, approximately 30% in the services and industrial sectors and by 25% in agriculture. Only small additional reductions in final energy consumption occur by 2050 in all sectors.

6.2.2 Raw materials needs

The manufacturing and deployment of net-zero technologies will increase the needs for Critical Raw Materials (CRMs).

With scenario S3, the deployment of five net-zero technologies (wind turbines, solar PV, batteries, electrolyzers, and heat pumps) would imply a need for up to 500 000 tonnes of copper each year in the decade 2031-2040, including 125 000 tonnes for wind alone. This compares with a global copper demand of 26 million tonnes in 2022 according to the IEA, including 370 000 tonnes for electric vehicles and 1.2 million tonnes for wind and solar ⁽⁶⁰⁾. The global supply for copper is expected to exceed 30 million tonnes in 2030 ⁽⁶¹⁾.

⁽⁵⁹⁾ Including international aviation but excluding international maritime transport.

⁽⁶⁰⁾ IEA (2023), Critical Minerals Data Explorer, IEA, Paris <https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer>. Accessed on 05 December 2023.

⁽⁶¹⁾ IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, Paris <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>

Batteries for electric vehicles and stationary batteries would create needs of up to 80 000 tonnes of lithium and 60 000 tonnes of cobalt per year in 2040. As a comparison, global lithium demand in 2022 was 130 000 tonnes, including 69 000 tonnes for electric vehicles, and cobalt demand was around 200 000 tonnes ⁽⁶⁰⁾. By 2030, global supply for lithium and cobalt are expected to be as high as 721 000 and 380 000 tonnes, respectively ⁽⁶¹⁾.

In S1 and S3, raw material needs would be lower and higher than in S2, respectively, as in 2040 net installed renewable power capacity is lower by 8% in S1 and higher by 6% in S3 compared to S2.

6.3 Environmental and health impacts

6.3.1 Benefits of climate change mitigation

It is estimated that climate damages could cost EU GDP by up to 1% annually already in the next few years, with damages strongly increasing afterwards, reaching up to 2.3% of EU GDP by mid-century, and possibly getting much higher in only a few decades in case of uncontrolled climate change with estimates for the EU in this analysis reaching 7% by the end of the century. Such estimates are conservative since they do not include the wider impacts on society and natural systems (see Annex 7).

To compare the avoided cost of climate change across options, Table 11 below provides a comparison of the monetisation of the externalities associated to GHG emissions. It considers the difference across target options in cumulative emissions over 2030-2050 and a “cost of carbon” capturing these externalities.

Table 11: Difference across options in cumulative GHG emissions and cost of climate change

	Comparison to target option 2					
	2031-2040		2041-2050		2030-2050	
	Option 1	Option 3	Option 1	Option 3	Option 1	Option 3
Cumulative GHGs* (GtCO ₂ -eq)	1.7	-1.3	1.4	-1.1	3.1	-2.4
Climate change cost** (Lower valuation)	26	-20	31	-24	29	-22
[Bn EUR 2023 per year] (Higher valuation)	49	-38	58	-44	53	-41

Note: *Considering 2040 reductions of 85% for T2 and 90% for T3. **Cost calculations based on the “Handbook on the external costs of transport (Version 2019 – 1.1)” following the avoidance cost approach. The cost of carbon is interpolated from the Handbook: EUR 155 per tonne of CO₂ in 2030-2040 and EUR 224 per tonne in 2041-2050 (central value of the handbook, used for the “Lower” valuation) and EUR 291 per tonne in 2031-2040 and EUR 416 per tonne in 2041-2050 (high value of the handbook, used for the “Higher” valuation), in EUR 2023.

Note that the methodology used for the monetisation of the external costs of climate change is subject to discussions and that there is a high level of uncertainty associated with such estimates and their use. Some studies conclude that the costs used are

(significantly) underestimated. In some other organisations ⁽⁶²⁾, a cost of carbon of above €800/ tCO₂ is suggested by 2050.

In addition, given the difficulty in doing so, analyses, including this one, do not represent the impacts of crossing climate tipping points, which are increasingly likely with every incremental increase in global warming. Looking forward, the cost of unmitigated climate change will greatly exceed the cost of reducing GHG emissions, both in magnitude and extent.

6.3.2 *Health impacts*

The transformations required to reduce GHG emissions in the EU have positive impacts on air quality because they lead to lower energy consumption and a shift to non-emitting renewable energy sources and to less polluting combustion fuels. According to projections produced using the GAINS model ⁽⁶³⁾, the S1, S2 and S3 scenarios have very similar impacts, with primary air pollutant emissions in the EU decreasing by 16%-77% (depending on the pollutant) between 2015 and 2040 (see Table 12). This results mostly from the projected strong decline in fossil fuel use in the energy system and lower consumption of solid biomass in residential buildings, combined with clean air policies. Consequently, the impacts on public health also decline. In general, the most harmful air pollutants for human health are PM_{2.5}, tropospheric ozone and NO₂⁽⁶⁴⁾. Between 2015 and 2040, the number of premature deaths per year caused by PM_{2.5} and ozone exposure in the EU dropped by 58% ⁽⁶⁵⁾ and the costs associated to premature mortality caused by PM_{2.5} and ozone exposure decreased by 55% or 61%, depending on the valuation method employed.

LIFE yields additional co-benefits in terms of lower air pollutant emissions and a greater reduction in premature mortality, mainly as a result of lower air pollutant emissions from agricultural activities, in particular lower NH₃ emissions, which has been found to result in economic benefits from improved health ⁽⁶⁶⁾. Additional indirect air quality benefits also stem from reduced methane emissions as a precursor of ozone emissions. In addition to improved air quality, a shift in diet as in LIFE would deliver significant health

⁽⁶²⁾ EIB, France, Germany, UK for example

⁽⁶³⁾ The methodology used is similar to the one used in the Third Clean Air Outlook (COM(2022) 673).

⁽⁶⁴⁾ According to the Third Clean Air Outlook. Note that tropospheric ozone is not emitted directly into the air. It is created by chemical reactions between oxides of nitrogen (NO_x) and volatile organic compounds (VOC), in the presence of sunlight. The analysis of clean air impacts will be presented in more details in the COM 4th Clean Air Outlook report (forthcoming, 2024).

⁽⁶⁵⁾ The analysis considers the direct effects of PM_{2.5} (full exposure range) and ozone on human health, together with the indirect effects of NO_x as precursors of particulate matter and ozone. However, the direct effects of NO₂ are not considered to avoid the risk of double counting, since there is conflicting scientific evidence on the extent to which the health impacts of PM_{2.5} and NO₂ overlap.

⁽⁶⁶⁾ Shift to flexitarian diets could reduce ammonia emissions by 33% in the EU. Through avoided premature mortality, economic losses in the agricultural sector from dietary shifts could be mitigated by 39% in the EU in such a scenario. Himics et al. 'Co-benefits of a flexitarian diet for air quality and human health in Europe', 2022

benefits, reducing for example the risk of cardiovascular diseases ⁽⁶⁷⁾, cancer ⁽⁶⁸⁾, diabetes, and obesity ⁽⁶⁹⁾.

Table 12: Primary air pollutant emissions, impacts on premature mortality and costs associated to premature mortality

	2015	2040				Change 2015-2040			
		S1	S2	S3	LIFE	S1	S2	S3	LIFE
Primary air pollutant emissions (kt)									
SO2	2316	525	529	529	529	-1791 (-77.3%)	-1787 (-77.1%)	-1787 (-77.1%)	-1787 (-77.1%)
NOx	7392	2140	2140	2114	1913	-5252 (-71.1%)	-5252 (-71.1%)	-5277 (-71.4%)	-5478 (-74.1%)
PM2.5	1380	521	524	521	517	-859 (-62.2%)	-857 (-62.1%)	-859 (-62.2%)	-863 (-62.5%)
VOC	6362	4503	4501	4497	4259	-1860 (-29.2%)	-1861 (-29.3%)	-1865 (-29.3%)	-2103 (-33.1%)
NH3	3690	3086	3090	3091	2346	-604 (-16.4%)	-600 (-16.3%)	-599 (-16.2%)	-1345 (-36.4%)
Premature mortality caused by PM2.5 and ozone exposure									
Expressed in 1000 death cases per year	466	197	198	196	188	-268 (-57.6%)	-268 (-57.6%)	-269 (-57.8%)	-277 (-59.5%)
Expressed in 1000 life years lost per year	5977	2667	2668	2650	2544	-3309 (-55.4%)	-3309 (-55.4%)	-3326 (-55.7%)	-3432 (-57.4%)
Costs associated to premature mortality caused by PM2.5 and ozone exposure (EUR 2023 billion/year)									
Higher valuation method (VSL*)	1724	677	677	673	646	-1047 (-60.7%)	-1046 (-60.7%)	-1051 (-61.0%)	-1077 (-62.5%)
Lower valuation method (VOLY*)	686	306	306	304	292	-380 (-55.4%)	-380 (-55.4%)	-382 (-55.7%)	-394 (-57.4%)

*Note: * The valuation follows the same methodology used in the Third Clean Air Outlook. The "higher valuation" is done using the value of a statistical life (VSL) methodology (where the VSL is assumed to be EUR 4.36 million, in EUR 2023), and the "lower valuation" is done using the value of a life year (VOLY) methodology (where the VOLY is assumed to be EUR 114 722, in EUR 2023). Note that, in the Third Clean Air Outlook, these values are expressed in EUR 2015.*

Source: GAINS.

In addition to direct effects, climate action should mitigate the increasing negative effects that climate change has on air quality and human health, due notably to heatwaves and wildfires ⁽⁷⁰⁾ and the climate-induced spread of vector-borne diseases.

⁽⁶⁷⁾ Koch et al. (2023) Vegetarian or vegan diets and blood lipids: a meta-analysis of randomized trials. European Heart Journal

⁽⁶⁸⁾ Chan, Doris SM, Rosa Lau, Dagfinn Aune, Rui Vieira, Darren C. Greenwood, Ellen Kampman, and Teresa Norat. "Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies." *PloS one* 6, no. 6 (2011): e20456.

⁽⁶⁹⁾ Tukker et al. (2011) Environmental impacts of changes to healthier diets in Europe. Ecological Economics

⁽⁷⁰⁾ World Meteorological Organization, *WMO Air Quality and Climate Bulletin*, No 3, September 2023.

6.3.3 Environmental impacts

Air pollution causes acidification and eutrophication, damaging ecosystems and crops. As shown in Table 13, in the S1, S2 and S3 scenarios, the decrease in SO₂, NO_x and NH₃ emissions reduces the total area affected by severe acidification in the EU by around 80% between 2015 and 2040. Moreover, the total area affected by severe eutrophication decreases by around 23.5% over the same period, mainly as a result of the decrease in nitrogen-related emissions. LIFE brings complementary co-benefits in terms of reduced acidification and eutrophication because of the lower NO_x and NH₃ emissions from agricultural activities.

Table 13: EU ecosystem area where acidification or eutrophication exceed critical loads

	2015	2040				Change 2015-2040			
		S1	S2	S3	LIFE	S1	S2	S3	LIFE
Acidification (1000 km ²)	157	31	31	31	19	-126 (-80.4%)	-126 (-80.4%)	-126 (-80.4%)	-137 (-87.7%)
Eutrophication (1000 km ²)	1164	891	892	890	742	-273 (-23.5%)	-272 (-23.4%)	-274 (-23.5%)	-422 (-36.3%)

Source: GAINS.

S2 and S3 show a higher demand for bioenergy compared to today. Due to the higher reliance of S3 on industrial carbon removals (including DACCS) and e-fuels than S1 or S2, S3 may involve greater need for bioenergy if BECCS and liquid biofuels were to substitute a limited deployment of these technologies.

The future demand for biomass in 2040 compared to today is driven by an increased demand for advanced/ second generation biofuels, and is satisfied through a higher supply of lignocellulosic crops, which to a large extent substitute crops for first generation biofuels ⁽⁷¹⁾. In 2040 total cropland remains unchanged in S1 compared to today and increases by 1.2 Mha in S2 and S3. In S2 and S3, forest land increases by about 4.9 Mha compared to 3.3 Mha in S1 and (rewetted) wet- and peatlands increase by about 1.4 Mha from a conversion of grassland in S2 and S3 (compared to 0 Mha in S1).

The impacts on biodiversity resulting from land use change are very limited across scenarios and remain between -1% (S1) and +4% (S2) of average suitable habitat increase in 2040 compared to 2020. The practices put in place to increase LULUCF net removals can actually positively impact biodiversity: reforestation, polyculture afforestation under close-to-nature practices and rewetting of peatlands play out more favourably for habitats and ecosystems than monocultures. Different biomass demand does not significantly alter biodiversity across scenarios, however, for lignocellulosic crops to be fully environmental beneficial, impacts on land-use and water-use should be minimised, by showing higher yields and lower water use than feed crops and through applying limitation in their use.

⁽⁷¹⁾ In 2040 total cropland remains unchanged in S1 and increases by 1.2 Mha in S2 and S3, because around 80% of the required area for lignocellulosic crops comes from crops for first generation biofuels or other crops.

Building on a shift to healthier diets and more sustainable practices, LIFE leads to complementary changes in the agricultural land area, where allowing part of the land to be freed up from livestock, fodder activities and intensively grazed land and converted into extensive grassland, high diversity landscape features with – in comparison to S2 and S3 – more natural vegetation (+6.8 Mha), forest land (+4 Mha) and rewetted organic soils (+0.3 Mha). This change in land use is accompanied by a reduction in nutrient surplus and use of pesticides, and an increase of organic farming in line with the Farm to Fork Strategy. The land use change has a positive effect on LULUCF net removals, which can be expected to create additional income opportunities for farmers through carbon farming, as well as significant co-benefits for biodiversity: the likelihood to find agricultural areas with a high value for biodiversity and ecosystems improves by 14% within the EU ⁽⁷²⁾ compared to S2 and S3.

Biodiversity is also affected by climate change. High-latitude and freshwater ecosystems, the prevailing domains in southern European and Boreal areas, are particularly vulnerable to climate change (see Annex 7). Climate change mitigation reduces the likelihood of larger climate change impacts on biodiversity and natural systems and, in so doing, helps to increase resilience and adaption to climate change. More biodiverse ecosystems (e.g., biodiverse forests), are more resilient, multifunctional, deliver more ecosystem services and may function better to remove carbon ⁽⁷³⁾ ⁽⁷⁴⁾.

6.4 The socio-economic implications of mitigation ⁽⁷⁵⁾

6.4.1 Macro-economic impacts

The impact assessments for the 2030 Climate Target Plan and the long-term strategy for 2050 concluded that the respective objectives were projected to have limited impacts on broad macro-economic aggregates, including GDP and total employment. These conclusions were reached while assessing impacts relative to a baseline with significantly lower climate ambition. The benchmark used for the comparison of the macro-economic modelling in this impact assessment is the S2 scenario.

At aggregate level, the three models used in this impact assessment consistently show that a higher level of mitigation in 2040 only has a slightly negative, transitory impact on GDP, while a lower level of mitigation yields a minor positive effect. In 2040, GDP for S3 is at worst 0.8% lower than in S2 under the E-QUEST model (see Table 14 and

⁽⁷²⁾ Using the ‘Biodiversity Friendly Practices’ (BFP), a biodiversity indicator capturing the likelihood to find High Nature Value farmland in a region. The total index is an area weighted average of the partial indices for arable crops, permanent crops, grassland and set aside / fallow land. Partial indices for different land use categories are therefore weighted according to their proportion of total utilised agricultural area.

⁽⁷³⁾ Mori, Akira S., Laura E. Dee, Andrew Gonzalez, Haruka Ohashi, Jane Cowles, Alexandra J. Wright, Michel Loreau et al. "Biodiversity–productivity relationships are key to nature-based climate solutions." *Nature Climate Change* 11, no. 6 (2021): 543-550.

⁽⁷⁴⁾ Liang, Jingjing, Thomas W. Crowther, Nicolas Picard, Susan Wiser, Mo Zhou, Giorgio Alberti, Ernst-Detlef Schulze et al. "Positive biodiversity–productivity relationship predominant in global forests." *Science* 354, no. 6309 (2016): aaf8957.

⁽⁷⁵⁾ All figures quoted in this section are expressed in constant EUR 2023.

Annex 8) while output is at best 0.6% higher in S1 than in S2 (JRC-GEM-E3 model). By 2050, GDP levels almost converge for the three scenarios.

However, the limited impacts on broad aggregates do not reflect the transformations that the economy will undergo, and the required reallocation of capital and employment in the coming decades across sectors and actors. The macro-economic models indicate that a higher GHG ambition in 2040 shifts the composition of GDP from consumption towards investment (consistent with the investment needs identified in section 6.4.2). Nevertheless, the impacts on private consumption remain small across models and levels of ambition. In addition, the composition of consumption should evolve over time, with a gradual decrease in the share of energy consumption and an increase in the share of other goods in total consumption. This compositional shift would be positive from a welfare perspective, as energy-related services would not be negatively affected by lower energy consumption (*e.g.*, a better insulated house provides the same – or likely better – level of comfort than a poorly insulated one, with a lower energy consumption).

In terms of sectoral output, a higher level of climate ambition in 2040 is associated with a faster decline in the output of fossil fuel industries, though all scenarios reach broadly similarly low levels of output by 2050 (see Table 14 and Annex 8). The impact on the output of energy intensive industries is also somewhat larger with more ambition, even though the effect under S3 is limited with a decline of 0.2% relative to S2 in 2040 and 2050, both under a scenario where the rest of the world implements policies in line with the current NDCs (fragmented action setting) and under a scenario where the rest of the world acts in line with the 1.5°C objective (global action setting).

Table 14: Sectoral output and GDP in 2040, deviation vs. S2 (% change)

	S1 fragmented	S3 fragmented	S1 global	S3 global
<u>GDP (*)</u>	<u>0.5%</u>	<u>-0.2%</u>	<u>0.6%</u>	<u>-0.2%</u>
Fossil fuel industries	10.2%	-5.6%	15.0%	-5.2%
Energy intensive industries	1.4%	-0.2%	-0.3%	-0.2%
Transport equipment	0.7%	-0.5%	0.6%	-0.4%
Other equipment goods	0.5%	0.2%	-1.3%	0.3%
Consumer goods industries	0.7%	-0.6%	-0.8%	-0.8%
Transport	2.0%	-1.0%	1.0%	-1.1%
Construction	0.0%	0.5%	0.0%	0.6%
Market services	0.5%	-0.2%	1.1%	-0.2%
Non-market services	0.2%	-0.2%	0.4%	-0.2%
Agriculture	2.0%	-1.0%	1.0%	-1.1%
Forestry	-10.9%	0.5%	-13.1%	-1.4%

(*) The GDP impacts reported in this table are only those from the JRC-GEM-E3 model.

Source: JRC-GEM-E3.

While the output of energy intensive industries is somewhat larger under S1 than under S2 in 2040 under a fragmented action setting, it is actually lower in a global action setting. This is driven by the earlier adoption of decarbonised technologies in EU industry relative to the rest of the world under S2, which results in an increase in its competitiveness in a setting where the rest of the world also needs to invest in low-carbon processes. It must be noted also that the output of energy intensive industries is projected to continue growing across all scenarios in future decades. The growth rate

between 2015 and 2040 is projected to range between 25.5% and 27.6% (fragmented action setting).

A higher level of ambition in 2040 (S3) would entail somewhat lower private consumption, which would affect notably road and air transport, equipment goods and consumer goods industries. However, under a global action setting, these sectors could actually be positively impacted by 2050 as global demand for equipment goods and technological know-how linked to decarbonisation increases and as the EU gains competitiveness and export market shares, thereby also driving up transport activity.

Overall, the difference in the evolution in the EU's global export market shares across scenarios is marginal, which points to limited differences in competitiveness impacts across target options (Table 15). While the EU is expected to represent a gradually declining share of global exports in the coming decades, this is driven mainly by the smaller relative size of its population and economy and not by the level of climate ambition. As indicated above, a more relevant factor for the impacts on competitiveness is the level of ambition in mitigation policies in the rest of the world, with a higher level of ambition susceptible to increase market shares for EU companies.

Table 15: EU share in global exports (% of world trade)

	2040			2050		
	S1	S2	S3	S1	S2	S3
Fragmented action						
<u>All exports</u>	<u>16.4%</u>	<u>16.2%</u>	<u>16.1%</u>	<u>15.9%</u>	<u>15.9%</u>	<u>15.9%</u>
Energy intensive industries	17.4%	17.1%	17.1%	16.9%	16.8%	16.8%
Transport equipment	25.3%	25.1%	25.0%	24.1%	24.1%	24.1%
Other equipment goods	17.5%	17.3%	17.1%	16.7%	16.7%	16.7%
Consumer goods industries	12.6%	12.5%	12.3%	12.0%	12.0%	12.0%
Market services	22.7%	22.8%	22.7%	21.5%	21.5%	21.5%
Agriculture	7.2%	7.0%	7.0%	6.2%	6.3%	6.3%
Forestry	4.4%	4.3%	4.3%	3.1%	3.1%	3.1%
Global action						
<u>All exports</u>	<u>16.9%</u>	<u>16.7%</u>	<u>16.6%</u>	<u>16.9%</u>	<u>16.9%</u>	<u>16.8%</u>
Energy intensive industries	17.9%	17.6%	17.6%	17.6%	17.5%	17.5%
Transport equipment	25.3%	25.2%	25.0%	24.4%	24.4%	24.3%
Other equipment goods	18.1%	17.9%	17.8%	18.7%	18.7%	18.7%
Consumer goods industries	13.3%	13.2%	13.0%	13.6%	13.6%	13.6%
Market services	21.7%	21.7%	21.7%	19.1%	19.1%	19.1%
Agriculture	7.8%	7.6%	7.5%	6.4%	6.5%	6.9%
Forestry	4.4%	4.3%	4.3%	3.1%	3.1%	3.2%

Source: JRC-GEM-E3.

The transition to climate neutrality and the level of ambition for 2040 will also impact the EU's main trading partners. While the level of total EU imports is similar across scenarios, the composition of imports and their carbon intensity will change with the transition. Imports of fossil fuels will decline sharply in the coming decades, with an even sharper and faster decline under S3. For market services and agro-forestry goods, the share of EU imports is expected to grow during the transition. A broad-based

assessment suggests that the share of EU imports coming from Africa and Asia (excluding China and India) will increase.

The extent to which public finances could be affected by the transition itself and by the scenarios in this impact assessment will depend on a multiplicity of factors, many determined at Member State level. On the revenue side, environmental taxes play a key role in decoupling economic growth and environmental impacts. In 2021, environmental taxes represented about 2.2% of GDP or 5.5% of the total revenues of EU Member States from taxes and social contributions, the bulk linked to energy taxes for fossil fuels. The base of carbon taxes will erode as the EU progresses towards climate neutrality. Revenues from carbon pricing or other taxes aiming at reducing emissions should increase over the transition before declining as the EU economy moves towards climate neutrality. In that context, phasing out fossil fuel subsidies will be all the more important. These trends will have implications for the design of tax and revenue systems.

On the expenditure side, the impact will be affected, among others, by the extent to which Member States directly fund or support investment in climate change mitigation and adaptation. In turn, the risks to government finances arising from fossil fuel price shocks, as recently experienced following Russia's war of aggression in Ukraine, would be much lower under a higher target for 2040. Simulation with the JRC-GEM-E3 model of a stylised shock resulting in doubling of fossil fuel prices (coal, oil and gas), without knock-on effects on electricity prices, shows that the negative impact on GDP, private consumption and employment is halved if it takes place in an economy with a largely decarbonised energy system projected for 2040, compared to the same shock taking place in 2025 (GDP impact of -0.4% vs. -0.8% and private consumption impact of -1.3% vs. -2.6%).

The risks from climate-related hazards for public finance are becoming increasingly obvious, though these will be determined by the success of global mitigation efforts and the extent to which private insurance can provide adequate coverage ⁽⁷⁶⁾. Insurance cover for climate-related natural catastrophes is low - at about 25% at EU level, with large disparities among Member States ⁽⁷⁷⁾.

Finally, it is critical to assess the potential impacts of the climate transition alongside its co-benefits (section 6.3) and the costs of inaction. Co-benefits in terms of human health, strategic independence, quality of life and environmental sustainability cannot all be adequately measured in financial terms or as economic impacts; however they are large and affect welfare in many ways. In addition, the damaging impacts of global warming are becoming increasingly stark and immediate, both for our economies and people. Short-term costs are soaring due to the occurrence and intensity of extreme weather-related events. While estimates of long-term economic losses are shrouded with

⁽⁷⁶⁾ The Commission's [Fiscal Sustainability Report 2021](#) highlights that extreme weather and climate-related events already pose risks to fiscal (debt) sustainability in several countries, while further stressing that the assessment is based on an incomplete view of risks and is therefore likely to underestimate the negative fiscal impacts.

⁽⁷⁷⁾ Based on the [dashboard on insurance protection gap for natural catastrophes](#) from the European Insurance and Occupational Pensions Authority.

uncertainty and will depend to some extent on our ability to adapt to a changing climate, they all point to impacts that are several times the estimated impacts of mitigation policies.

6.4.2 *Investment needs*

The EU energy system needs to be decarbonised to a large extent by 2040 in all scenarios. This requires the modernisation of many facets of our economy. All scenarios imply an intensification of efforts to replace fossil fuels with renewable and carbon-free sources of energy, achieving higher energy efficiency across the economy, and increasing innovation. Existing capital assets (*e.g.*, fossil-based power plants, heating and cooling systems or industrial processes) will be progressively replaced with renewable technologies, carbon-free or electricity-based assets, whose capital intensity may be larger than fossil-based assets. New industrial capacities such as critical raw material processing or clean steel, will be built, to supply the decarbonisation needs. The transition of the energy system will require sustained investment including in research, industry, and supply chain capacities. This will trigger innovation.

All scenarios require similar significant investment needs for the energy system over the period 2031-2050, although with different time profiles over the two decades, and different sectoral composition. This highlights the necessity to ensure enabling conditions that make such a level of investment feasible and that avoid investment decisions that are not compatible with the transition.

The three scenarios imply annual energy system investment needs (excluding transport) above 3% of GDP for the period 2031-2050 (Table 16). This amounts to an additional 1.5 percentage points of GDP compared to average energy system investment in 2011-2020, a period during which overall investment levels in the EU were historically low (see Annex 8). It is also comparable to the level of investment that will be needed in the current decade to achieve the objectives of the Fit-for-55 package. The resulting evolution of investment as a proportion of GDP is not exceptional in historical terms, though the increase would need to be sustained over a prolonged period of time: the ratio between gross fixed capital formation (GFCF) and GDP in the EU has fluctuated between 20-23% since the mid-90s, dropping to a 20% low between 2010 and 2020 before bouncing back in more recent years towards the average of 22% seen in 2000-2010. In the 1970s and 1980s, the average ratio was at 25.8% and 23.1%, respectively.

The electricity sector (generation and grid) dominates investment needs on the supply side given the increasing electrification in the economy. On the demand side, the residential sector accounts for the largest share of investment needs at about two-thirds of the total (excluding transport).

Table 16: Average annual energy system investment needs (billion EUR 2023).

	S1			S2			S3			ΔLIFE		
	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050
Supply	236	377	306	289	328	308	341	281	311	-59	-14	-36
Power grid	79	88	84	88	81	85	96	75	85	-15	-2	-9
Power plants	97	187	142	128	157	142	151	133	142	-28	-6	-17
Other	59	102	81	72	90	81	94	73	83	-16	-6	-11
Demand excl. transport	332	377	354	355	357	356	372	338	355	-23	1	-11
Industry	38	31	35	46	24	35	48	22	35	-7	-3	-5
Residential	225	250	237	237	242	239	248	230	239	-12	4	-4
Services	49	78	63	53	73	63	57	67	62	-4	1	-2
Agriculture	19	19	19	19	19	19	20	18	19	0	0	0
Transport	866	875	870	861	885	873	856	882	869	-80	-85	-82
Total	1433	1629	1531	1505	1570	1537	1570	1501	1535	-162	-97	-129
Total excl. transport	567	754	661	644	685	664	713	619	666	-82	-12	-47
Memo:												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Note: "ΔLIFE" compares the cost of the LIFE scenario to the S3 scenario, which both meet the same overall net GHG reductions by 2040.

Source: PRIMES.

More ambition in 2040 (S3) requires higher annual investment needs in 2031-2040 and a faster deployment of decarbonisation technologies on the supply and demand side, but also comparatively lower investment levels in 2041-2050. The opposite is true for scenario 1, relative to scenario 2, with a significant delay in the deployment of investment that would entail a great deal of catching up with annual investment (excluding transport) of EUR 755 billion in 2041-2050, i.e. 6% higher than what is required under scenario 3 in 2031-2040. The difference across scenarios takes place notably in energy supply (+18% and -18% compared to S2, respectively). A higher level of ambition in 2040 also requires industry to shift faster towards the manufacturing of net-zero technologies and the use of carbon capture, and to expand the associated supply chains that enable the decarbonisation of other sectors. Compared to S2, investments in 2031-2040 to decarbonise industry are 4% higher in S3, and 16% lower in S1. In services, the differences are +8% and -7%, respectively, and in the residential sector +5% and -5%, respectively. In agriculture, the difference between the scenarios is very small, at +0.4% and -1.2% relative to S2.

LIFE shows that demand-side action, including shifts to a more sharing economy, more circular use of materials or more sustainable mobility can reduce the need for investment across the entire period. The reduced energy demand results in lower investment requirements across the board. In aggregate, average annual investment needs (excluding transport) in 2031-2050 are almost EUR 50 billion or 7.1% lower with LIFE than under S3. They are about EUR 36 billion per annum (12%) lower on the supply side and about EUR 5 billion (15%) lower in industry.

Investment in transport ⁽⁷⁸⁾ is projected at about EUR 870 billion per annum (4.2% of GDP) in 2031-2050 and varies little across scenarios. About 80% of the average annual investment in 2031-2050 is projected in road transport, mainly to purchase private cars (about EUR 510 billion per annum and 60% of the total) ⁽⁷⁹⁾. Investment needs for recharging and refuelling infrastructure account for a small proportion of the total, at about EUR 15 billion per annum. Changes towards more sustainable mobility patterns (LIFE) reduce the average annual transport-related investments in 2031-2050 by around EUR 80 billion (9%).

These investment needs will be met by both private actors and the public sector. Private businesses are likely to be the main source of investment on the supply side and in industry. Public support via State aid has been instrumental in the past for the deployment of renewable energy generation. It will likely remain critical in the future deployment of innovative decarbonisation technologies in the energy system (e.g. renewable hydrogen) and industry (e.g. innovative production processes and carbon capture, storage, and use). Investment by SMEs largely depends on the sector where they operate (see Annex 4). Households will face large investment needs for the renovation of the building stock and the acquisition of zero tailpipe emission vehicles. How up-front investment costs for renovation and heating/cooling will be borne will depend on ownership structure (homeowners, tenant vs. landlord) and on the extent of public support.

The early push on investment under S3 enables the achievement of a higher mitigation target by 2040, with associated benefits in terms of a lower overall carbon budget, reduced fossil fuel imports and lower negative impacts of GHG emissions. In turn, the delay in investment effort under S1 comes at the cost of lower mitigation, higher fossil fuel imports and higher negative impacts from emissions.

The early push under S3 is most significant on the supply side, where the economic agents responsible for the investment consist mainly in private businesses with good access to finance, backed by collateral in terms of assets and predictable long-term revenue streams (Table 17). Industry would also need to anticipate investment under S3 to some extent, and it is likely to have solid access to finance. In the residential sector, where access to finance is likely more challenging for low- and middle-income households the need for an early push under S3 is less significant. Overall, average annual investment (including transport) under S3 is 4% higher than under S2 in 2031-2040. This amounts to 0.3% of GDP, most of which on the supply side.

⁽⁷⁸⁾ These figures represent the full acquisition cost of new vehicles, not only the incremental cost related to the decarbonisation of transport. In addition, it should be noted that investment in transport here reflect the expenditures on vehicles, rolling stock, aircraft and vessels plus recharging and refuelling infrastructure. They do not cover investments in infrastructure to support multimodal mobility and sustainable urban transport. They factor in a higher number of vehicles sold as well as any potential increase in the average size/class of vehicles.

⁽⁷⁹⁾ The figure factors in a higher number of vehicles sold as well as any potential increase in the average size/class of vehicles.

Table 17: investment profiles across options and financial feasibility (annual averages, 2031-2040)

	Billion EUR 2023		% change vs. S2		% GDP		Deviation vs. S2 (% GDP)	
	2011-2020	S2	S1	S3	2011-2020	S2	S1	S3
<u>Total</u>	<u>863</u>	<u>1505</u>	<u>-4.8%</u>	<u>+4.3%</u>	<u>5.8%</u>	<u>7.7%</u>	<u>-0.37%</u>	<u>+0.33%</u>
<u>Total excl. transport</u>	<u>248</u>	<u>644</u>	<u>-11.9%</u>	<u>+10.8%</u>	<u>1.7%</u>	<u>3.3%</u>	<u>-0.39%</u>	<u>+0.36%</u>
Supply	80	289	-18.4%	+18.0%	0.5%	1.5%	-0.27%	+0.27%
Industry	7	46	-15.7%	+4.4%	0.0%	0.2%	-0.04%	+0.01%
Residential	116	237	-5.1%	+4.7%	0.8%	1.2%	-0.06%	+0.06%
Services	29	53	-7.1%	+8.3%	0.2%	0.3%	-0.02%	0.02%
Agriculture	17	19	-1.2%	+0.4%	0.1%	0.1%	0.00%	0.00%
Transport	616	861	0.5%	-0.5%	4.2%	4.4%	+0.02%	-0.02%

Source: PRIMES.

A sensitivity analysis on investment costs has been done for electricity production from solar and wind energy, new fuels, and heat pumps, *i.e.* technologies at the core of the Commission proposal on a Net Zero Industry Act (NZIA) and that will be critical as enablers of the EU's decarbonisation objectives. Over the past decades, the cost of low carbon technologies has decreased sharply as a result of technological progress and learning-by-doing. However, as demand for renewable technologies and electrification - and for the raw materials needed for their production - are set to increase globally, these sectors could potentially be subject to price shocks or sustained price pressures. This would depend on the capacity of global markets to respond to that demand, on the ability of circular economy policies to create a resource base for "secondary" materials production in the EU, and on the capacity of the EU to create a domestic value chain for primary materials. A 20% increase in investment costs for the four NZIA-covered technologies would increase annual energy system investment needs (excluding transport) in 2031-2040 by 5.5%, 6.1% and 6.3%, respectively under S1, S2 and S3. However, such a cost increase would only affect newly installed capacity during the period of the price shock, and not the entire stock of assets. In this regard, a price shock on renewable technologies (or raw materials needed for their production) is fundamentally different from a price shock on fossil fuels.

Net-zero technologies are at the centre of strong geostrategic interests and at the core of the global technological race, as exemplified by the United States' Inflation Reduction Act and China's dominance in manufacturing of some cleantech. In this context, the Net-Zero Industry Act is part of the actions announced in the Green Deal Industrial Plan of February 2023, aiming at simplifying the regulatory framework and improving the investment environment for the Union's manufacturing capacity of technologies that are key to meet the Union's climate neutrality goals and energy targets. The investments needed to build EU-based manufacturing capacity for five key net-zero technologies (wind, solar PV, electrolyzers, batteries and heat pumps) are estimated at approximately billion EUR 23 for the decade 2031-2040. Two thirds of total investments are for battery manufacturing, one fifth to one quarter are for manufacturing of wind technologies, and electrolyzers, solar PV and heat pumps each represent between 2 and 6% of the total. This level of investment needs takes into account that investments in manufacturing capacity already take place by 2030.

6.4.3 Energy system costs and other mitigation costs

Energy system costs ⁽⁸⁰⁾ are one of the important factors driving the competitiveness of EU businesses. This Impact Assessment is based on model results, reflecting adopted legislation under the FF55 package (see Section 1.4.1), existing National Energy and Climate Plans ⁽⁸¹⁾ and understanding of the possible evolution of technologies and costs.

6.4.3.1 Energy system costs for the whole economy

The total energy system–costs - including capital costs and energy purchase costs for both the supply and demand sectors –⁽⁸²⁾⁽⁸³⁾ - that result from the modelling are projected to be only slightly higher for the more ambitious scenarios in 2031-2040. System costs are 1.5% higher under S3 than under S2, while they are only 2.1% lower under S1 than under S2. The moderate increase in system costs that parallels increases in mitigation targets in 2040 are driven by higher investment needs in 2031-2040, which translate into higher annual capital costs. A higher cost of energy purchases under S3 than under S2 also contributes to the increase in overall energy system costs.

When contrasted with the situation in 2011-2020, however, the shift in the composition of total energy system costs from energy purchases to capital costs is very clear under all three scenarios. Total energy system costs (including carbon revenues) in 2031-2040 range from 12.4% of GDP under S1 to 12.9% under S3. This is around the 2021-2030 average and represents a moderate increase from an average of 11.9% of GDP in 2011-2020. While energy purchases represented 9.2% of GDP in 2011-2020, they are projected to amount to 7.8% of GDP in 2031-2040 under S2. In contrast, capital costs are projected to increase from 2.7% of GDP in 2011-2020 to 4.9% in 2031-2040 (Table 18). The benefits of higher investment levels in terms of lower energy purchase are therefore very clear.

⁽⁸⁰⁾ While energy system modelling captures the energy system costs well, the costs associated with the transition are broader. Rapid structural change will lead to the devaluation of equipment and other assets in several industrial sectors, notably in fossil fuels extraction and processing.

⁽⁸¹⁾ “Current” at the time of publication, i.e. the NECPs submitted in 2020. Future climate and energy assessments will take into account the final NECPs updates (2024), including for nuclear capacity.

⁽⁸²⁾ The total energy system costs considered here includes capital costs (for energy supply installations such as power plants and energy infrastructure, as well as investment in buildings for energy efficiency related renovation, purchase of end-use equipment and appliances as well as energy related equipment for transport) and energy purchase costs. For transport, the “capital cost” covers only additional capital costs for improving energy efficiency or for using alternative fuels, including alternative fuels infrastructure.

⁽⁸³⁾ Capital cost is computed as the annualisation of overnight investment considering a weighted average cost of capital of 10%, which reflects both financing and opportunity cost.

Table 18: Energy system costs profiles across options (2031-2040, annual average)

	Billion EUR 2023		% change vs. S2		% GDP		Deviation vs. S2 (% GDP)	
	2011-2020	S2	S1	S3	2011-2020	S2	S1	S3
Total energy system costs	<u>1766</u>	<u>2472</u>	<u>-2.1%</u>	<u>+1.5%</u>	<u>11.9%</u>	<u>12.7%</u>	<u>-0.27%</u>	<u>+0.19%</u>
Industry*	270	410	-3.4%	+2.3%	1.8%	2.1%	-0.07%	+0.05%
Tertiary**	312	397	-0.5%	+0.5%	2.1%	2.0%	-0.01%	+0.01%
Residential	620	850	-1.4%	+1.0%	4.2%	4.4%	-0.06%	+0.04%
Low-income households	221	316	-1.5%	+1.0%	1.5%	1.6%	-0.02%	+0.02%
Transport	564	815	-3.1%	+2.0%	3.8%	4.2%	-0.13%	+0.08%
Road transport	467	485	-1.5%	+1.9%	3.2%	2.5%	-0.04%	+0.05%
Capital costs	<u>407</u>	<u>956</u>	<u>-1.8%</u>	<u>+1.7%</u>	<u>2.7%</u>	<u>4.9%</u>	<u>-0.09%</u>	<u>+0.08%</u>
Industry*	17	85	-3.2%	+1.6%	0.1%	0.4%	-0.01%	+0.01%
Tertiary**	51	137	-2.1%	+2.4%	0.3%	0.7%	-0.02%	+0.02%
Residential	251	490	-1.9%	+1.6%	1.7%	2.5%	-0.05%	+0.04%
Low-income households	78	176	-2.2%	+1.7%	0.5%	0.9%	-0.02%	+0.02%
Transport	87	243	-1.1%	+1.6%	0.6%	1.3%	-0.01%	+0.02%
Road transport	56	152	+0.9%	-1.3%	0.4%	0.8%	+0.01%	-0.01%
Energy purchases	<u>1359</u>	<u>1516</u>	<u>-2.3%</u>	<u>+1.3%</u>	<u>9.2%</u>	<u>7.8%</u>	<u>-0.18%</u>	<u>+0.10%</u>
Industry	253	325	-3.4%	+2.5%	1.7%	1.7%	-0.06%	+0.04%
Tertiary**	261	259	+0.3%	-0.5%	1.8%	1.3%	0.00%	-0.01%
Residential	369	360	-0.7%	+0.3%	2.5%	1.8%	-0.01%	+0.01%
Low-income households	143	140	-0.6%	+0.2%	1.0%	0.7%	-0.00%	+0.00%
Transport	476	572	-3.9%	+2.1%	3.2%	2.9%	-0.11%	+0.06%
Road transport	412	334	-2.5%	+3.4%	2.8%	1.7%	-0.04%	+0.06%

Note: *includes cost to abate industrial process CO₂ emissions. ** includes energy related costs in services and in agriculture.

Source: PRIMES.

Total energy system costs as a share of GDP are projected to gradually decrease under all three scenarios after 2040 as energy purchases continue to decline in relative terms, while capital costs remain broadly constant at around 4.8% of GDP. Total energy system costs are projected at around 11.3% of GDP in 2041-2050 under all three scenarios, lower than the level in 2011-2020. The LIFE setting shows that circular economy actions and more sustainable lifestyles can limit the costs associated with investments and fuel use by up to 0.2 percentage points in 2031-2040, and 0.5 percentage points in 2041-2050.

An important driver is the cost of net fossil fuels imports, which represented about 2.2% of GDP in 2010-2021 and 4.1% during the energy crisis in 2022⁽⁸⁴⁾. The EU's climate and energy policies by 2030 and the pathways to climate neutrality considerably reduce the exposure of the energy system to fossil fuel price shocks. As the energy system decarbonises, fossil fuel imports decrease over time⁽⁸⁵⁾ to 1.4% of GDP over 2031-2040 and down to 0.6% in 2041-2050, contributing directly to limiting the energy system cost

⁽⁸⁴⁾ Based on Eurostat's trade data for CN code 27, with the exclusion of codes 2712, 2714, 2715 and 2716.

⁽⁸⁵⁾ Despite assuming growing international fossil fuel prices over time – see Annex 6.

(Table 19). On the other hand, it increases the EU demand for raw materials and, possibly, the EU dependence on imports from other countries for low-carbon technologies.

Table 19: Average annual economy-wide energy system costs (billion EUR)

	2011-2020	2021-2030	2031-2040			2041-2050		
			S1	S2	S3	S1	S2	S3
Total energy system costs								
Billion EUR	1766	2130	2419	2472	2508	2508	2527	2530
% GDP	11.9%	12.5%	12.4%	12.7%	12.9%	11.2%	11.3%	11.3%
Fossil fuel imports								
Billion EUR	336	427	293	277	265	150	142	133
% GDP	2.3%	2.5%	1.51%	1.42%	1.36%	0.67%	0.63%	0.59%

Source: PRIMES.

The EU's future energy system will be characterised by a growing use of electricity, largely based on renewables. Electricity production costs are expected to be comparable across all scenarios in 2040. The cost structure will evolve towards a capital-based system, albeit at a different pace depending on the scenario: the share of fuels (fossil fuels, biomass, nuclear fuel) in total costs decreases to 22-13% depending on the level of decarbonisation and of associated remaining fossil fuels in 2040.

Table 20: Average electricity production cost

	2040				2050
EUR23/MWh	S1	S2	S3	Δ LIFE	(S3)
Average production cost, of which	97	96	94	-0.7%	87
Fuels (incl. taxes and ETS payments)	22%	16%	13%	-0.6%	13%
Capital cost	47%	51%	54%	+0.5%	53%
O&M cost	32%	33%	32%	+0.1%	34%

Source: PRIMES

6.4.3.2 Energy costs and prices for businesses

Energy system costs for the demand sectors (sectors others than those of energy or electricity production) are similar across scenarios for industry and tertiary sectors. As a share of gross value added and in comparison, with the level of the current decade, these costs are projected to decline over time for tertiary sectors, on account of lower energy purchases in relative terms.

As far as industry is concerned, the implementation of low-carbon processes, particularly carbon capture and storage, leads to higher capital-related costs for the scenarios with higher ambition. Capital-related costs under S3 are 1.6% higher than under S2 in 2031-2040 while energy purchases increase by 2.5%, in line with the level of decarbonisation and the role of e-fuels to substitute remaining fossil fuels. In turn, the lower ambition under S1 than S2 enables a reduction in capital costs and energy purchases of only about

3%. Overall, the limited increase in energy purchases across scenarios leads to a moderate increase in energy system costs as a share of gross value added in 2031-2040 compared to earlier periods, before a stabilisation thereafter.

In the tertiary sector, the increase in total energy system costs resulting from higher climate ambition is more limited (+0.5% in S3 compared to S2 and -0.5% in S1 compared to S2, for 2031-2040). Higher levels of investment in energy-efficient equipment and to renovate buildings result in lower energy purchases under S3 than under both S2 and S1. Capital-related costs in 2031-2040 are 2.4% higher under S3 than S2, but this is partly compensated by a reduction of 0.5% in energy purchases. Given that the largest part of companies in the tertiary sector are SMEs (62% of the gross value added of the sector, nearly 70% of employment by the sector) and that 65% of SMEs are in services, the effects on this sector are well representative of the impact on SMEs.

Table 21: Average annual energy system costs for businesses (billion EUR)

	2031-2040				2041-2050			
	S1	S2	S3	Δ LIFE	S1	S2	S3	Δ LIFE
<u>Industry & Tertiary</u>	<u>791</u>	<u>807</u>	<u>819</u>	<u>-20</u>	<u>881</u>	<u>885</u>	<u>886</u>	<u>-52</u>
Capital-related cost*	224	234	241	-7	277	281	285	-14
Energy purchases	567	574	578	-14	604	603	601	-38
<u>Industry</u>	<u>397</u>	<u>410</u>	<u>420</u>	<u>-16</u>	<u>462</u>	<u>467</u>	<u>470</u>	<u>-41</u>
Capital-related cost	83	85	87	-3	114	116	117	-9
Energy purchases	314	325	333	-13	348	350	352	-31
<u>Tertiary**</u>	<u>394</u>	<u>397</u>	<u>399</u>	<u>-4</u>	<u>419</u>	<u>418</u>	<u>417</u>	<u>-11</u>
Capital-related cost*	134	137	141	-3	150	151	153	-3
Energy purchases	260	259	258	-2	269	267	264	-8

*Note: * includes investment in energy efficient renovation of services buildings. ** includes energy-related cost in "services" and in agriculture. "ΔLIFE" compares the cost of the LIFE scenario to the S3 scenario, which both meet the same overall net GHG reductions by 2040.*

Source: PRIMES.

Table 22 shows the average electricity prices for industry and services in 2040 and 2050. They remain fairly stable in the long run with very similar patterns across scenarios, reflecting electricity production system costs shifting to lower operating costs and higher capital-related costs. Low carbon capacity progressively substitutes CO₂-emitting assets driving the system to a more capital-based structure which is less exposed to fossil fuel prices.

Table 22: Average final price of electricity for businesses

EUR23/MWh	2040	2050
Industry	130-131	131-133
Services	249	255

Note: The electricity prices shown here reflect the evolution of the average electricity production costs to supply these sectors (i.e., considering their load profile) as well as the taxes applied to the sectors.

Source: PRIMES.

Table 23 shows the share of energy related costs in total production costs for the different scenarios for all industries and differentiated between energy intensive and non-energy intensive industries (EIIs and non-EII) ⁽⁸⁶⁾. For the industrial sector as a whole, the difference across scenarios in 2031-2040 is limited, with higher climate ambition translating into only mildly higher energy related costs.

Table 23: Share of energy-related costs in total production costs in industry

		2031-2040				2041-2050	
		S1	S2	S3	ΔLIFE	S3	ΔLIFE
All	Energy related cost	3.8%	3.9%	4.0%	-0.15pp	4.0%	-0.34pp
	fuel expenses	3.0%	3.1%	3.2%	-0.12pp	3.0%	-0.26pp
	capital and other costs	0.8%	0.8%	0.8%	-0.03pp	0.9%	-0.08pp
EIIs	Energy related cost	10.2%	10.7%	11.0%	-0.55pp	11.5%	-1.31pp
	fuel expenses	7.9%	8.3%	8.5%	-0.44pp	8.6%	-1.01pp
	capital and other costs	2.3%	2.4%	2.5%	-0.11pp	2.9%	-0.30pp
non-EIIs	Energy related cost	1.63%	1.62%	1.63%	-0.02pp	1.48%	0.02pp
	fuel expenses	1.36%	1.35%	1.36%	-0.02pp	1.13%	-0.02pp
	capital and other costs	0.27%	0.27%	0.27%	0.00pp	0.35%	-0.01pp

Note: "ΔLIFE" compares the cost of the LIFE scenario to the S3 scenario, which both meet the same overall net GHG reductions by 2040.

Source: PRIMES.

There is a more marked difference across scenarios for EIIs. For these industries, which account for about 25% of total manufacturing value-added ⁽⁸⁷⁾, the share of energy-related costs in total production costs is 0.3 percentage points higher (corresponding to a 3% increase in energy system costs) in 2031-2040 in S3 than in S2. A lower level of ambition under S1 generates leads to a moderately lower energy system cost by 0.5 percentage points of total production costs compared to S2 (corresponding to a 4.4% decrease). The bulk of the difference comes from fuel expenses, while capital costs remain fairly similar across scenarios. Novel low-carbon technologies replace conventional processes, allowing a reduction in the purchase of fossil fuels, while, at the

⁽⁸⁶⁾ "EIIs" covers iron & steel, non-ferrous metals, chemicals, non-metallic minerals, paper & pulp.

⁽⁸⁷⁾ Estimate based on a [wide definition of the EII ecosystem](#), economy-wide gross value added and gross valued added in the manufacturing sector (NACE 2 code C)

same time, in scenarios with higher emission reductions by 2040, larger quantities of e-fuels are used. The EU put in place the Carbon Border Adjustment Mechanism (CBAM)⁽⁸⁸⁾ to avoid carbon leakage by ensuring that the carbon price of imports in key EIIIs is equivalent to that paid by producers in the EU.

In non-EIIs, which represent the majority of total manufacturing value-added and include many SMEs (see the SME test Annex), the share of energy-related costs in total production costs is much smaller and scenario S3 shows virtually no difference compared with S2 in 2031-2040, even though there is a 1% increase in energy system costs in absolute terms.

The LIFE setting shows how circular economy, material and energy efficiency actions contribute to limiting the share of energy related costs in EIIs. Among others, decrease of scrap export and increased recycling allows for a larger secondary production share, and significant savings in the more expensive e-fuels necessary for the decarbonisation of primary processes.

6.4.3.3 Costs related to mitigation of GHG emissions in the LULUCF sector and non-CO2 GHG emissions

Table 24 provides an overview of the average annual costs in the LULUCF sector and for non-CO2 emissions in the different scenarios. The costs are related to the implementation of abatement technologies or nature-based removal solutions. The technical available potential for nature-based removals and mitigation measures differs between the two decades, leading to varying annual costs across decades, as the entire potential up to the respective maximum carbon value is implemented.

Table 24: Costs related to mitigation of GHG emissions in the LULUCF sector and non-CO2 GHG emissions by decades

Average annual costs [EUR 2023 billion/year]	2031-2040			2041-2050			2031-2050		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Mitigation of LULUCF GHG emissions	1.1	2.5	2.5	1.6	2.8	2.8	1.3	2.7	2.7
Mitigation of non-CO2 GHG emissions	0.0	0.7	3.4	3.9	4.1	5.0	2.0	2.4	4.2
- of which in the agriculture sector	0.0	0.4	3.2	3.8	3.9	4.8	1.9	2.2	4.0

Source: GLOBIOM, GAINS.

S1 does not assume specific LULUCF and non-CO2 policies in 2040, showing smaller mitigation costs for the 2031-2040 period. Both sectors have to contribute to meeting climate neutrality in 2050 also in that scenario, which entails some mitigation action and associated costs in the last decade 2041-2050.

⁽⁸⁸⁾ CBAM covers cement, iron and steel, aluminium, fertilisers, as well as electricity and hydrogen.

For LULUCF, additional nature-based removals such as improved forest management, afforestation or rewetting are applied in S2 and S3 by 2040. The associated average annual cost in these scenarios amount to EUR 2.5 billion in 2031-2040 and EUR 2.8 billion in 2041-2050.

The average annual costs associated to mitigation of non-CO2 emissions over the 2031-2040 period are around EUR 0.7 billion per year in S2 and around EUR 3.4 billion per year in S3. Over the 2041-2050 period, the average annual costs are higher than in the previous decade: EUR 3.9 billion in S1, EUR 4.1 billion in S2, and EUR 5 billion in S3. Most of the annual mitigation costs take place in the agriculture sector, which represents the bulk of the unabated non-CO2 GHG emissions post-2030. The sectoral mitigation costs of the sector are reflected in the macro-economic analysis presented in section 6.4.1.

6.4.4 Social impacts and just transition

6.4.4.1 Fuel expenses, energy and transport poverty

Energy-related expenses represent a significant share of total expenditure for a large proportion of EU households, in particular middle- and low-income households. The recent increase in energy prices has had strong negative social impacts and increased the rates of energy (and transport) poverty. Assessing the implications of this initiative on energy system costs for households is therefore of critical importance.

The following assessment is based on modelling results, reflecting the current legislation, and understanding of the possible evolution of technologies and costs. This assessment will feed into the development of the future policy framework and support measures in the coming years to meet the 2040 target, which will determine the actual costs and how they impact individuals, regions, and society.

The cost structure is characterised by an increase of capital-related costs due to the purchase of more efficient appliances and the investment for enhancing the insulation of dwellings. This allows avoiding an increase in energy purchases despite the assumed increase in international fossil fuels prices over time, the impact of carbon pricing and the diffusion of new non-fossil fuels.

The relative importance of energy-related costs for households in private consumption is projected to decline in 2031-2040 compared to 2021-2030, due to the decreasing importance of fuel purchases in all scenarios. Early action in S3, driven by larger direct efficiency investments (see Section 6.4.2), also translates into a slightly higher share of energy-related costs in S3. It then represents 8.2% of private consumption as opposed to 8.0% in S1 and 8.1% in S2 (see Table 25). Energy purchases and electricity price are projected to be very similar across scenarios.

Table 25: Average annual energy system costs as % of private consumption and average final price of electricity for households in the residential sector

Average Annual Energy System Cost								
EU27 - Average across all income categories	2031-2040				2041-2050			
	S1	S2	S3	ΔLIFE	S1	S2	S3	ΔLIFE
Total (% of private consumption)	8.0%	8.1%	8.2%	-0.12pp	7.1%	7.1%	7.1%	-0.14pp
Capital related costs*	4.5%	4.6%	4.7%	-0.08pp	4.1%	4.1%	4.1%	-0.01pp
Energy purchases	3.4%	3.5%	3.5%	-0.04pp	3.0%	3.0%	3.0%	-0.13pp
EU27 - Low Income Categories	S1	S2	S3	ΔLIFE	S1	S2	S3	ΔLIFE
Total (% of private consumption)	14.0%	14.3%	14.4%	-0.20pp	12.0%	12.0%	12.1%	-0.25pp
Capital related costs	7.8%	7.9%	8.1%	-0.13pp	6.5%	6.5%	6.6%	-0.01pp
Energy purchases	6.3%	6.3%	6.3%	-0.07pp	5.5%	5.5%	5.4%	-0.25pp
Electricity Price (EUR/MWh)**								
Residential	288	288	288	-0	289	290	290	-0

Note: * includes purchase of appliances and cost of renovation. "ΔLIFE" compares the cost of the LIFE scenario to the S3 scenario, which both meet the same overall net GHG reductions by 2040. ** Average final price of electricity. The electricity price shown here reflects the evolution of the average electricity production cost to supply the sector (i.e., considering its load profile) as well as the taxes applied to the sector.

Source: PRIMES.

Modelling projections also show that capital related cost (including the purchase of appliances and cost of renovation) as a share of private consumption are higher for low-income households than for the average household (8.1% in low-income households compared to 4.7% on average over 2031-2040 in scenario S3, which is a relative increase with respect to S2 of 0.13 percentage points in low-income households and 0.07 percentage points on average). Low-income categories often live in relatively less well insulated homes, in most need of renovation. For low-income households, the capital-related costs as a share of private consumption are 0.2 percentage point higher in S3 than in S2 for 2031-2040. Specific social measures are needed to ensure a just and fair transition (see Annex 9).

Table 26: Average annual energy system costs of road transport (% of total private consumption), and average final price of electricity in private transport

Average Annual Energy System Cost								
EU27 - Average across all income categories	2031-2040				2041-2050			
	S1	S2	S3	ΔLIFE	S1	S2	S3	ΔLIFE
Total	3.7%	3.8%	3.8%	-0.19pp	2.3%	2.3%	2.3%	-0.23pp
Capital related costs*	1.3%	1.2%	1.2%	-0.04pp	1.1%	1.1%	1.1%	-0.10pp
Energy purchases	2.4%	2.5%	2.6%	-0.15pp	1.2%	1.2%	1.2%	-0.13pp
Electricity Price (EUR/MWh)**								
Private transport	223				223			

Note: "ΔLIFE" compares the cost of the LIFE scenario to the S3 scenario, which both meet the same overall net GHG reductions by 2040. * This covers only the additional capital costs for improving energy efficiency or for

*using alternative fuels. ** Average final price of electricity. The electricity price shown here reflects the evolution of the average electricity production cost to supply the sector (i.e., considering its load profile) as well as the taxes applied to the sector.*

Source: PRIMES.

Similarly, a higher degree of mitigation ambition is also linked to slightly higher total energy system costs in road transport⁸⁹, which represent 3.7%, 3.8% and 3.8% of private consumption respectively in S1, S2 and S3 (see Table 26) and correspond to a relative increase of 0.07 percentage points in S3 compared to S2 and a 0.10 percentage point decrease in S1. A limited decrease of capital costs from S1 to S3 is observed, and a moderate increase of energy purchase linked to a larger consumption of e-fuels in S3. The LIFE analysis shows that a more sustainable mobility can reduce energy purchases, by an order of magnitude of about 0.2 percentage points of private consumption in 2031-2041 and in 2041-2050.

The more ambitious the scenario, the quicker the dependence to fossil fuels is reduced, allowing households in Europe to be better protected from future fossil fuel price shocks.

6.4.4.2 Distribution

Section 6.4.4.1 assesses the impact of changes in energy and transport related expenses on households. Beyond this, impacts on relative prices throughout the economy are susceptible to affect households in differentiated manners. The JRC-GEM-E3 model and micro-data from the household budget survey were used to assess the potential impacts.⁹⁰ (A macro-economic model is better suited to capture the full effects and interactions across sectors that affect relative prices). Changes in relative prices are projected to differ relatively little across scenarios, though the relative price of housing is likely to be higher under S2 and S3 than under S1, as higher levels of renovation increase costs for homeowners and renters alike (see Annex 8 for details). Similarly, energy purchases for transport by households are projected to increase with a higher level of mitigation in 2040.

Linking these estimated changes in relative prices to micro-data from the household budget survey, the JRC estimated distributional impacts per expenditure and income decile. This shows that lower income households will be more affected than higher income households, as measured in terms of compensating variation, i.e. the monetary transfer that would be necessary to maintain the same level of utility as under the past set of relative prices. Assuming that none of the additional revenues from ETS are redistributed to households to temper impacts, the welfare impact of S2 would amount to less than -0.5% (% of total expenditure) for the lowest expenditure deciles, and about -

⁸⁹ The details of the total transport expenditures of households (including total capital costs) are provided in Annex 8.

⁹⁰ The analysis benefited from inputs from two joint projects between Directorate-General Employment, Social Affairs and Inclusion (DG EMPL) and the Joint Research Centre (JRC) of the European Commission: “Assessing and monitoring employment and distributional impacts of the Green Deal (GD-AMEDI)” and “Assessing distributional impacts of geopolitical developments and their direct and indirect socio-economic implications, and socio-economic stress tests for future energy price scenarios (AMEDI+)”. See <https://ec.europa.eu/social/main.jsp?langId=en&catId=1588>.

0.3% for the highest expenditure decile. The effects would be larger under S3 at about -1.2% and -0.8%, respectively. Redistributing some of the additional carbon revenues at national or EU level would sharply reduce this negative impact on the lower expenditure deciles.

6.4.4.3 Employment

The aggregate employment impacts of S2 and S3 differ only slightly from S1, which already factors in the transformation of the EU economy to climate neutrality by 2050, with a lower 2040 target. The labour market and social implications of the transition itself, however, will be concentrated in some specific sectors. It will entail opportunities but also challenges, particularly in terms of skills availability and reallocation of the labour force across sectors and occupations. This analysis focuses on the implications of the transition for the most affected sectors more than on the comparison of impacts across scenarios. In parallel to decarbonisation, other factors will also impact the labour market: ageing of the population, decline in the working age population and other trends fully independent from climate policy, including technological changes and the uptake of artificial intelligence.

Modelling under JRC-GEM-E3 projects that recent trends in sectoral employment (increase in the share of services in employment and decrease in the share of industry and manufacturing), are set to continue across the different scenarios, which display very similar patterns by 2040 (Table 27). The flipside of the increase in the share of service sector jobs is a gradual decrease in the share of employment in energy intensive industries, consumer goods industries and transport equipment. The share of employment in other equipment goods, however, is projected to remain stable as the transition should increase EU and global demand for the type of equipment needed for decarbonisation. While output in energy intensive industries, consumer goods industries and transport equipment are projected to grow significantly between 2015 and 2040, they will be outpaced by overall GDP growth. However, in the context of a declining aggregate level of employment, driven by a shrinking labour force, these sectors' share of employment (and absolute employment) are projected to decline over the coming decades.

Employment in fossil fuel industries is expected to be at negligible levels in 2040 and 2050. In contrast, market and non-market services together represent more than 60% of total employment. Given the downward trend in employment in sectors where men are more represented alongside an upward trend in services, the transition is expected to have a limited or positive impact on women's employment. Annex 8 further assesses the implications of the transition for the labour market and skills requirements by considering the potential opportunities arising from investment needs. Employment opportunities should be particularly significant in areas related to the renovation of the building stock, the transition to decarbonised sources of heating and cooling (heat pumps) and the electrification of the economy, including the large-scale installation of renewable sources of electricity.

Table 27: Sectoral employment, share in total employment (%)

	2020	2030	2040			2050
			S1	S2	S3	S3
Fossil fuel industries	0.13%	0.11%	0.07%	0.06%	0.05%	0.05%
Energy intensive industries	6.7%	6.5%	6.2%	6.1%	6.2%	5.9%
Transport equipment	2.1%	2.0%	1.9%	1.9%	1.9%	1.8%
Other equipment goods	6.3%	6.1%	6.1%	6.1%	6.1%	6.1%
Consumer goods industries	4.4%	4.2%	4.1%	4.1%	4.0%	3.9%
Transport	3.6%	3.9%	3.7%	3.7%	3.7%	3.7%
Construction	7.8%	7.6%	7.6%	7.7%	7.7%	7.7%
Market services	34.0%	34.6%	35.0%	34.9%	34.9%	35.3%
Non-market services	26.6%	27.1%	27.3%	27.3%	27.3%	27.5%
Agriculture	3.5%	3.3%	3.1%	3.1%	3.1%	2.8%
Forestry	0.4%	0.3%	0.4%	0.5%	0.5%	0.4%
Other	4.4%	4.3%	4.5%	4.6%	4.6%	5.0%

Note: In this table, “transport” does not include storage.

Source: JRC-GEM-E3 model.

Further, major opportunities for employment creation should arise from the development of manufacturing capacity for green technologies, mainly solar photovoltaic and solar thermal, wind power generation, battery and storage facilities, heat pumps, electrolyzers and fuel cells, sustainable biogas and biomethane, carbon capture and storage and grid technologies. Boosting the EU manufacturing capacity in these sectors is at the core of the Net Zero Industry Act proposal, and it will necessitate corresponding efforts to ensure that the skills needs are developed among the EU’s labour force. The transition will require accompanying policies at the regional and sectoral levels to ensure that reskilling and retraining opportunities are available for workers who need them.

6.4.4.4 Regional impacts

The transition to a low-carbon economy will have heterogenous impacts on regions within the EU. The decarbonisation of production capacities, the transformation of the energy system, the need to develop an industrial carbon management system and the evolution of the land sector will all affect regions differently.

Regions with a relatively high share of employment in sectors most impacted by the transition are more exposed to the transition (see details in Annex 8). This includes the regions with a high share of employment in sectors that are being phased out in several countries (mining of coal, lignite and oil shale; extraction of crude petroleum, natural gas and peat; refining of petroleum products), in energy intensive sectors, as these will have to produce the same goods differently (manufacturing of chemicals and chemical products, manufacturing of other non-metallic mineral products, manufacturing of basic metals), and in sectors that will have to produce different goods (manufacturing of motor

vehicles, trailers and semi-trailers) ⁽⁹¹⁾. In 2020, only two EU regions (NUTS-2 level) had employment shares of more than 1% of direct employment in coal and lignite mining, crude petroleum, and natural gas extraction, with potential wider local impacts due to indirect employment. The employment and social consequences of the decline in extraction activities need to be mitigated, in line with the European Green Deal's objective of leaving no region behind (see Annex 9). When considering energy intensive industries or industries that will have to produce different goods (e.g. automobile sector), more regions will be affected. In these regions and territories, the employees from these sectors will have specific reskilling needs. In regions where the automobile sector represents a high share of the economic activity, the move to the manufacturing of electricity vehicles requires companies in the supply chain to adjust their business models. The transition will be faster in S3 than in S2 and faster in S2 than in S1. Regions that are particularly impacted by the transition need to be accompanied and supported (see examples of EU and national measures and programmes in Annex 9).

All scenarios require a decrease of fossil fuels and a strong growth of renewable energy for electricity production. This will entail different opportunities and challenges for regions: reconversion of fossil fuel producing regions, opportunities to develop local resources and create jobs where the renewable energy potential is the largest, and infrastructure development challenges to connect electricity producing centres with consuming centres. These opportunities and challenges will be more acute in S3, which has the largest increase of electricity production needs, 6% higher than in S2, while S1 is 7% lower than S2. The development of an industrial carbon management system will require the development of a full supply chain and of the necessary infrastructure to link CO₂ emitting energy supply and industrial sites to carbon storage or usage sites (notably to produce e-fuels). The territories with strong presence of energy intensive industries (e.g., cement production, chemicals industries, etc) will have to anticipate and develop the corresponding capacities. The scenarios show a very different picture in 2040: while projections for S1 are around 80 MtCO₂ of capture, S2 exceeds 200 MtCO₂ and S3 gets close to 350 MtCO₂, where virtually all regions hosting CO₂ emitting industrial process sites would be concerned.

The need to maintain and enhance LULUCF net removals and to curb GHG emissions from the agriculture sector will mostly affect rural regions. Territories where agriculture plays a major role and where associated emissions are currently the highest will have to achieve a larger deployment of technologies and practices to reduce GHG emissions in S2 or S3 than in S1. A shift in society towards a healthier and more sustainable food system, as in LIFE, means a higher uptake of more extensive farming practices with opportunities to generate revenues from nature-based removals activities.

Innovation capacity, the level of instruction and the quality of infrastructure contribute to the preparedness of regions for the transition. Annex 9 provides examples of EU and national measures and programmes that can support regions for the transition. The EU's cohesion policy plays an important role.

⁽⁹¹⁾ See also OECD (2023), *Regional Industrial Transitions to Climate Neutrality*, OECD Regional Development Studies, OECD Publishing, Paris.

7 HOW DO THE TARGET OPTIONS COMPARE?

The different target options are compared based on the results of the analysis of the different representative scenarios shown in section 6. The target Option 2 serves as the “baseline” target level (see section 5.1).

7.1 Effectiveness

7.1.1 Specific objectives

The effectiveness of the different target options is assessed against the different specific objectives defined in section 4.

The capacity to secure the delivery of climate neutrality by 2050 (specific objective SO1) is measured in terms of overall and sectoral progress of required GHG reductions between 2030 and 2050 achieved by 2040 for the different target options. Option 1 covers only half the necessary overall reductions throughout the period, with sectoral progress ranging from 9% to 68% only. Compared to the baseline Option 2, Option 1 delays to the last decade significant sectoral reductions, including in the hard-to-abate sectors, and the development of carbon removals (see sections 6.1.1 and 6.1.2), putting at risk the achievement of climate neutrality by 2050. Conversely, Option 3 anticipates the importance to implement reductions in all sectors and to deploy carbon removals, with 77% of the overall needed reductions over 2030-2050 achieved by 2040, ranging from 58% to 93% across sectors, thus securing a higher capacity to deliver climate neutrality by 2050 than Option 2.

In terms of climate performance and importance to minimise the GHG budget (SO2) to contribute to the global Paris Agreement temperature goals, Option 3 leads to a lower GHG budget over 2030-2050 of at most 16 GtCO₂-eq (11% lower than option 2), against 18 GtCO₂-eq for option 2, and 21 GtCO₂-eq for option 1 (17% higher than option 2).

Table 28: Effectiveness: Delivering climate neutrality and GHG budget

Specific objective		Assessment criteria		Option 1	Option 2	Option 3
SO1	Delivering climate neutrality	GHGs reductions achieved in 2040 as a % of needed over 2031-2050	Total net GHGs	50% (-15 pp vs Option 2)	65%	77% (+ 12 pp vs Option 2)
			Sectors* (min / max)	9% / 68%	55% / 88%	58% / 93%
SO2	Minimising GHG budget	Cumulative GHG emissions over 2030-2050 (GtCO ₂ -eq)		21 (+17% vs Option 2)	18	16 (-11% vs Option 2)

Note: *Sectors described in section 6.1.1. **Assuming net zero being reached in 2050 and linear interpolation of net GHGs between 2030 and 2040 and between 2040 and 2050.

In terms of just transition (SO3), the difference in energy costs for households is limited compared to Option 2. Option 1 is lower by 1.4% in the residential sector (1.5% for low-income households) and by 1.5% in road transport. Energy costs for households under Option 3 are 1% higher in the residential sector (also for low-income households) and 1.9% higher in road transport.

The effect of competitiveness (SO4) is measured by the overall energy system cost, the economic output (total GDP and Energy intensive industries) and by the shares on global trade. Overall, the difference between options is limited on all these criteria, and even more so between option 3 and the baseline target option 2.

The overall energy system cost over 2031-2040 is 1.5% higher in option 3 than in option 2, while it is 2.1% lower in option 1 (Table 29).

For industry, total energy system costs in 2031-2040 are 2.3% higher in option 3 than in option 2, and 3.4% lower in option 1 (see Annex 8). For the tertiary sector, they are 0.5% higher in option 3 and 0.5% lower in option 1. For the time period 2041-2050, these differences are smaller and even reverse: for industry, total energy system costs are then 0.6% higher in option 3 than in option 2, and 1.1% lower in option 1. For the tertiary sector, they are 0.3% lower in option 3 and 0.2 higher in option 1. For energy intensive industries, the share of energy-related costs in total production costs vary between 10.2% in option 1 and 11% in option 3 for the time period 2031-2040.

This translates into very limited difference in terms of overall macro-economic impact, with option 3 showing a very minor negative deviation in GDP of -0.2% compared with option 2, and option 1 showing a slight positive deviation of 0.5% compared to option 2. By 2050, there is no difference in GDP levels across scenarios as the impacts are transitory.

The options also differ little in terms of economic output of key EU sectors. For example, for energy intensive industries, it is projected to be 0.2% lower under option 3 than option 2, and 1.4% higher under option 1. As also highlighted by certain stakeholders, what matters more for these industries and other export-oriented sectors than the EU target per se, is the extent to which the industrial sector decarbonises in the rest of the world, both in terms of processes and power supply. In the context of higher mitigation ambition in the rest of the world, output under option 1 is 2.3% lower than under option 2. In option 3, it is almost at the same level as in option 2. This is due to first-mover advantages that benefit EU industries.

Finally, the EU share in global exports varies little across options, with long-term trends dominated by other factors such as regional trade dynamics and trade agreements, or the declining relative share of the EU's population and GDP globally. Higher ambition under Option 3 generates a marginal 0.1 percentage point decrease in the EU's share in global exports compared to Option 2, with Option 1 yielding only a 0.2 percentage point increase.

Section 7.1.2 discusses the financial feasibility for the different actors.

Table 29: Just transition and Competitiveness

Specific objective		Assessment criteria			Option 1 vs 2	Option 3 vs 2
SO3	Just transition	Cost for households (2031-2040)	Residential	Average	-1.4%	+1.0%
				Low income	-1.5%	+1.0%
			Road transport	Average	-1.5%	+1.9%
SO4	Competitiveness	Total system cost (annual average 2031-2040)			-2.1%	+1.5%
		Economic output* (2040)	GDP		+0.5%	-0.2%
			Ells		+1.4%	-0.2%
		EU shares in global exports (% of world trade, 2040)			+0.2 pp	-0.1 pp

Note: *Considering fragmented climate action in the rest of the world.

In terms of deployment of technologies (SO5), option 3 already deploys more than half (54%) of the investment needs to get to climate neutrality by 2050 by 2040, against 48% in Option 2. With only 43% of the investment needs by 2040, Option 1 delays the technological effort towards the last decade (Table 30).

Option 3 leads to the deployment by 2040 of almost two thirds of the renewable electricity capacity compatible with climate neutrality by 2050 (against 56% for option 2), more than half the needed renewable hydrogen production capacity (41% for option 2) and almost three-fourths of the needed carbon capture capacity (against about half for option 2). Conversely, Option 1 delays the deployment of these key technologies to the last decade 2041-2050 (less than half of the renewable capacity installation needs, only about a third of the needed hydrogen production capacity and less than 20% of the carbon capture capacity by 2050 are installed by 2040), thus putting the achievement of climate neutrality by 2050 at risk.

Section 7.1.2 discusses the technological feasibility for the different actors.

In terms of security of energy supply (SO6), in 2040 Option 3 has a lower dependence on fossil fuel imports than Option 2 (26% versus 29%). Option 1 still has a dependence on fossil fuels of 34%. This translates into lower fossil fuel import costs for the EU of about EUR 12 billion (annual average over 2031-2040) in Option 3 compared to Option 2, while Option 1 shows about EUR 16 billion higher costs.

Option 3 shows higher deployment of new technologies, which will lead to a higher consumption of rare and raw materials. However, the nature of these materials allows to a stock to be built up, making the system more resilient than with the combustion of fossil fuel. Moreover, it creates a resource base that can be recycled and reused, which is not possible for fossil fuels. The coherence section (7.3) discusses the interplay with the security of raw materials supply.

Table 30: Effectiveness: Deployment of technologies and security of energy supply

Specific objective		Assessment criteria		Option 1	Option 2	Option 3
SO5	Deployment of technologies	Investment	Progress achieved in 2040 (% 2031-2050)	43%	48%	54%
		RES deployment	Progress achieved in 2040 (% 2031-2050)	47%	56%	64%
		H2 production	Progress achieved in 2040 (% 2050)	32%	41%	54%
		Carbon capture	Progress achieved in 2040 (% 2050)	19%	49%	76%
Specific objective		Assessment criteria		Option 1 vs 2	Option 2	Option 3 vs 2
SO6	Security of energy supply	Energy dependence (2040) (Fossil fuels imports / GAE)		+5pp	29%	-3pp
		Fossil fuel imports costs (2040) (bn EUR 2023)		+6%	277	-4%

Regarding environmental effectiveness (SO7), Option 3 is very similar to Option 2 on all accounts, while Option 1 shows a slightly lower use of bioenergy by 2040 compared to Option 2. The differences in terms of biodiversity impact are expected to remain very limited across all target options (see sections 6.3.3) - the coherence section (7.3) discusses the risks of trade-offs associated to bioenergy use. Finally, the three target options also yield strong and very similar benefits in terms of improved air quality for ecosystems and health (see sections 6.3.3 and 6.3.2).

Table 31: Environmental effectiveness

Specific objective		Assessment criteria	Option 1 vs 2	Option 2	Option 3 vs 2
SO7	Environmental effectiveness	Gross available energy from biomass (EJ)	-1.0	8.8	+0
		Biodiversity	Differences smaller than 0.2% on biodiversity indicators		
		Air quality	Very limited differences across target options, which all show benefits for ecosystems and health compared to current		

7.1.2 Financial and technological feasibility

Financial feasibility

The up-front investment needs and the associated capital costs are the two key indicators of financial feasibility. Most of the early push in investment in 2031-2040 under S3 compared to S2 or S1 that lower the risk of missing 2050 climate objective takes place on the energy supply side, where investors are mainly large private and/or public utilities with good access to finance due to secure and relatively predictable revenue streams. The increase compared to historical investments and the difference across options is much less significant in industry, and takes place in sectors where large companies dominate and where access to long-term finance is likely to be good as well, especially considering a context where industrial policy might be strengthened to maintain a globally competitive industrial base in EU. For buildings the level of investment differs little across options, though the push for gains in energy efficiency will require an increase in the investment to GDP ratio of about 0.4 percentage points in 2031-2040 compared to the level in 2011-2020. A wide range of actors, from individual homeowners to real-estate investors or public authorities (social housing), will be responsible for these investments, with different abilities to access low-cost finance.

Table 32 shows that the annual energy system investment needs (excluding transport) are projected to increase under S2 to 3.3% of GDP in 2031-2040, compared to 1.7% in 2011-2020 (Table 32). Average energy system investment in 2011-2020 was historically low, however, and the increase in the investment to GDP ratio is well within the variability experienced over the past decades. A higher level of climate ambition under S3 in 2040 leads to non-negligible, though macro-economically limited, increases in investment needs (excl. transport) during the first decade, i.e., an increase of 0.4 percentage points compared to S2, while S1 leads to a similar decrease of 0.4 percentage points compared to S2. Over the whole period 2031-2050, the three scenarios require a similar level of investment (excluding transport) of 3.2% of GDP.

Table 32: Average annual investment needs in 2031-2040 (% of GDP and deviation vs. S2)

	% GDP		Deviation vs. S2 (% GDP)	
	2011-2020	S2	S1	S3
<u>Investment needs</u>				
<u>Total</u>	<u>5.8%</u>	<u>7.7%</u>	<u>-0.37%</u>	<u>0.33%</u>
<u>Total excluding transport</u>	<u>1.7%</u>	<u>3.3%</u>	<u>-0.39%</u>	<u>0.36%</u>
Supply	0.5%	1.5%	-0.27%	0.27%
Industry	0.0%	0.2%	-0.04%	0.01%
Residential	0.8%	1.2%	-0.06%	0.06%
Services	0.2%	0.3%	-0.02%	0.02%
Agriculture	0.1%	0.1%	0.00%	0.00%
Transport	4.2%	4.4%	0.02%	-0.02%

Source: PRIMES.

The supply side accounts for the largest differences between the scenarios (+/- 0.27 percentage point of GDP lower or higher than S2 for S1 and S3, respectively). While SMEs and households will play a role in the deployment of renewables, the vast majority of investment on the supply side will be carried out by large private and/or public utilities. The latter have good access to finance on favourable terms, including because their financial flows are relatively secure and predictable, which makes them good candidates to access long-term finance from players like insurance companies or pension funds. The development of green finance instruments will nevertheless be important to ensure that funding is indeed available. In industry, large businesses will bear a significant share of the increase in investment needs. They are likely to have good access to long-term finance and other supports to enhance their competitiveness, and the difference in investment needs across options is quite limited, at +0.05 percentage points of GDP between S1 and S3.

After energy supply, the residential sector is the sector where investment needs increase the most across options (+/- 0.06 percentage point of GDP lower or higher for S1 and S3, respectively). While the range between S1 and S3 is relatively limited at 0.12 percentage points of GDP, it comes on top of a 0.4 percentage point increase between the average for 2011-2020 and the average under scenario 2 for 2031-2040. The feasibility of the increase in renovation investments will hinge upon a range of factors that go well beyond financial issues, some of which are independent from the level of climate ambition, for example, the level of awareness or information on renovation options among households,

knowledge about and confidence in contractors. In terms of financial feasibility, the situation will also differ widely according to household type and income level, and whether renovations are driven by individual homeowners or larger companies or public authorities owning real estate assets. In any case, a strong enabling framework will be needed to ensure access to finance at affordable costs for homeowners, or direct support from public budgets.

Table 33: Average annual investment needs (excluding transport) and capital costs (billion EUR 2023 and deviation from S2)

	S2			S1 vs. S2 (bn EUR)			S3 vs. S2 (bn EUR)		
	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050
Up-front investment									
Supply	289	328	308	-53	+49	-2	+52	-46	+3
Demand	355	357	356	-23	+20	-2	+18	-19	-1
Industry	46	24	35	-7	+7	0	+2	-2	0
Residential	237	242	239	-12	+8	-2	+11	-12	0
Services	53	73	63	-4	+5	+1	+4	-6	-1
Agriculture	19	19	19	0	0	0	0	0	0
Total	644	685	664	-76	+69	-4	+69	-66	+2
Annual capital costs *									
Industry	85	116	101	-3	-2	-2	+1	+1	+1
Residential	137	151	144	-3	-1	-2	+3	+2	+2
Tertiary	490	507	499	-9	-5	-7	+8	+4	+6
	S2			S1 vs. S2 (%)			S3 vs. S2 (%)		
	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050	2031-2040	2041-2050	2031-2050
Up-front investment									
Supply	289	328	308	-18%	+15%	-1%	+18%	-14%	+1%
Demand	355	357	356	-7%	+6%	0%	+5%	-5%	0%
Industry	46	24	35	-16%	+28%	0%	+4%	-7%	+1%
Residential	237	242	239	-5%	+3%	-1%	+5%	-5%	0%
Services	53	73	63	-7%	+6%	+1%	+8%	-8%	-1%
Agriculture	19	19	19	-1%	+2%	+1%	0%	-1%	0%
Total	644	685	664	-12%	+10%	-1%	+11%	-10%	0%
Annual capital costs *									
Industry	85	116	101	-3%	-2%	-2%	+2%	+1%	+1%
Residential	137	151	144	-2%	-1%	-1%	+2%	+1%	+2%
Tertiary	490	507	499	-2%	-1%	-1%	+2%	+1%	+1%

* includes financing and opportunity costs.

Source: PRIMES.

This impact assessment considers a target at EU level only and therefore does not assess specific aspects at the level of Member States. National budgets will nevertheless need to contribute to the investment needs either via direct public sector investment, or via support for private investment, subject to the State aid rules where applicable, e.g., to support renovation in the residential sector as described above or to support industrial decarbonisation. The extent to which the public sector will support the transition will vary widely across Member States, depending on national policy choices. The extent to which Member States have fiscal space to fund the transition also varies significantly, depending on their current level of indebtedness and the level of indebtedness that they will have by the start of the next decade. Such factors will impact, among others, their room for manoeuvre under the EU fiscal rules that will prevail at the time and their financing costs on the financial markets. None of this can be predicted at this stage, and this goes well beyond the scope of this impact assessment.

Finally, the difference in investment needs across options in the tertiary sectors and transport sectors are negligible and do not raise issues in terms of the comparison in the financial feasibility across scenarios.

Technological feasibility

All the target options remain within the technology feasibility indicators thresholds used by the ESABCC: primary energy biomass of 20 EJ/year in 2050, a maximum amount of carbon capture of 500 Mt CO₂/year, hydrogen production capacity of 150 GW in 2030 and a 20% decline of final energy demand between 2020 and 2030. They also remain lower than the technological deployment challenges identified by the ESABCC for wind and solar installed capacities in 2030, (respectively 900 and 623 GW) ⁽⁹²⁾, which considered the implication of conservative potential estimates.

Reducing energy and industry CO₂

Any of the options considered will require increasing the rate of deployment of mature technologies such as wind and solar power. Already by 2030, the deployment of wind and solar will increase considerably compared to both the historical average and the highest historical level of deployment reached in 2022 (see Section 1.2.2 of Annex 8). Option 1 leads to a lower level of effort between 2031 and 2040 compared to the 2021–2030 decade but, to reach carbon neutrality by 2050, it requires after 2040 by far the highest growth of wind and solar across all options and periods, with an average annual installation rate over the decade 2041-2050 more than twice the level achieved in 2022. This trend (a reduction in ambition followed by a very steep acceleration) appears counterintuitive and might put the climate neutrality target at risk. Option 3 anticipates decarbonisation of the power sector in the years 2031-2040 with lower effort required up to 2050. The trajectory of Option 3 is safer as it leaves more flexibility in the last years to cope with delays and unexpected developments. Option 2 lies in between Option 1 and Option 3. The growth of wind and solar power is also described in position papers collected during the public consultation, where the deployment rate for these two

⁽⁹²⁾ ESABCC report Table 5 and Table 6.

technologies is projected to increase several times in the 2020-2040 period. Each of the options considered will increase the need for critical raw materials. In the 2031–2040-decade, Option 3 will require more raw materials than the other options considered. However, the increase in global supply for raw materials such as Cobalt, Copper and Lithium is expected to be considerably larger than the amount needed for the energy transition in the EU ⁽⁹³⁾.

A clear distinctive feature of the target options is the importance of **novel technologies** to reduce CO₂ emissions in energy, transport and industry such as CCS, BECCS, DAC, production of hydrogen by electrolysis and e-fuels and low-carbon processes for energy-intensive industries. The maturity of technologies is an important driver of the projected portfolio of net-zero technologies. In recent years, innovation resulted in significant improvements of the technology readiness. For the main bulk of net-zero technologies needed to reach the 2040 targets, the Technology Readiness Level (TRL) is already at least 8 (out of 9) which means that they are in an advanced deployment stage ⁽⁹⁴⁾. DAC (TRL of 7) and BECCS (TRL of 5.5) are less mature today, and need to be further developed over the coming years, as highlighted by stakeholders during the public consultation. Subsequently, these two technologies will come into play only between 2030 and 2040.

Target Option 3 goes in hand with a stronger deployment of these technologies over 2031-2040 compared to Target Option 2, while Option 1 largely delays these developments to the last decade 2041-2050. For example, carbon capture is projected to amount in 2040 to close to 350 MtCO₂ (including 155 MtCO₂ for DAC and BECCS) in Option 3, against only 86 MtCO₂ (16 MtCO₂ for DAC and BECCS) in Option 1, while a total of about 450 MtCO₂ is projected to be needed to reach climate neutrality in 2050. More details on the deployment of carbon capture technologies and their implication can be found on the Industrial Carbon Management Communication.

The use of these novel technologies will affect total electricity production needs and entail the development of hydrogen and carbon removal infrastructure. The implications across the energy system thus go beyond what is captured by cost estimates alone, including on availability of these technologies for large-scale industrial projects, public acceptance of CCS or large amounts of renewables, availability of raw materials or geological storage sites. Finally, a slower deployment of novel technologies would increase the recourse to other (mature) technologies, including for instance biomass (see section 7.3). These different aspects are more relevant for Option 3 by 2040, which will require an adequate policy framework to secure the needed technological uptake while limiting trade-offs and addressing public acceptance. Conversely, delaying these deployments to the last decade, Option 1 also delays the design and implementation of the action and measures and thus risks missing the climate neutrality objective.

⁽⁹³⁾ See for instance the expectations on future supply in: IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, Paris <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>

⁽⁹⁴⁾ The TRL evaluation is based on the EU's Clean Energy Technology Observatory (CETO).

Non-CO2 and LULUCF

All technologies to mitigate non-CO2 GHG emissions considered in the analysis already exist and they are available for implementation, although in some cases there is ongoing research to improve them. There is, however, some uncertainty regarding the mitigation effectiveness and costs of some technologies that have not yet been applied on a large scale (for instance, feed additives and precision farming). Nature-based solutions that can increase the LULUCF net removals (e.g. forest management, rewetting, afforestation, agroforestry, soil carbon management) are all at a fully developed technological stage. Future evolution of the LULUCF net removals bears still some uncertainty due to natural impacts such as droughts, high variation between regions and vegetation, and variation on the implementation level (e.g. forest management or agroforestry).

7.2 Efficiency

The assessment of the efficiency of the target options through a comparison of their overall mitigation costs and a monetisation of their environmental benefits, shown in Table 34. This table is computed based on the cost analysis in section 6.4.

Table 34. Comparison of the monetised costs and benefits across the different target options

Average annual cost (bn EUR2023/year)	Comparison to Target 2					
	2031-2040		2041-2050		2031-2050	
	Target 1	Target 3	Target 1	Target 3	Target 1	Target 3
MITIGATION COSTS (see Table 19 and Table 23 in section 6.4.3)						
Energy system cost <i>(% of energy system cost)</i>	-53 -2.1%	+36 +1.5%	-19 -0.8%	+3 +0.1%	-36 -1.5%	+20 +0.8%
Non-CO2 and LULUCF costs	-2	+3	-1	+1	-2	+2
Total GHG mitigation cost	-55	+39	-20	+4	-38	+21
ENVIRONMENTAL BENEFITS (see Table 11 and Table 12 in section 6.3)						
Climate change ⁽¹⁾	<i>Lower</i>	0 +1	0 +1	0 +1	0 +1	0 +1
	<i>Higher</i>	0 +2	0 +2	0 +2	0 +2	0 +2
Air pollution ⁽²⁾	<i>Lower</i>	-26 +21	-31 +25	-29 +23	-29 +23	-29 +23
	<i>Higher</i>	-49 +40	-58 +46	-53 +43	-53 +43	-53 +43
Climate change + Air pollution	<i>Lower</i>	0 +1	0 +1	0 +1	0 +1	0 +1
	<i>Higher</i>	0 +2	0 +2	0 +2	0 +2	0 +2
NET BENEFITS (Environmental benefits - Mitigation costs)						
« Lower » valuation of externalities	+29	-18	-11	+21	+9	+3
« Higher » valuation of externalities	+6	+1	-38	+42	-15	+22

Note: ⁽¹⁾ Calculations based on the Handbook on the external costs of transport (Version 2019 – 1.1) following the avoidance cost approach. The cost of carbon is interpolated from values of the Handbook. The “lower valuation” uses the “central” value of the handbook EUR 155 per tonne of CO2 in 2031-2040 and EUR 224 per tonne in 2041-2050. The “higher” valuation uses the “high” value of the handbook of EUR 291 per tonne in 2031-2040 and EUR 416 per tonne in 2041-2050 in EUR 2023. ⁽²⁾ The valuation methodology is similar to that used in the Third Clean Air Outlook: the “lower” number uses the Value of a Life Year (VOLY) approach, while the “higher” value uses the Value of Statistical Life (VSL) approach.

Target Options 1 and 3 show a limited deviation of mitigation cost compared to target 2 by 2040, with annual mitigation cost being respectively EUR 56 billion lower and 36 billion higher. The difference in mitigation cost is largely dominated by the energy system cost, which is -2.1% lower for Option 1 than for Option 2, and +1.5% higher for

Option 3. Over the entire period 2031-2050, the difference is even smaller (-1.4% and +0.8%, respectively).

The difference of monetised environmental costs across options are of the same order of magnitude as the difference in mitigation costs. In the 2031–2040 decade, Option 1 shows net benefits compared to Option 2, driven by lower mitigation costs. However, in the second decade 2041-2050 target Option 3 clearly outperforms Option 2 and Option 1, leading to net benefits over the entire period 2031-2050 compared to the “baseline” option 2 with the two valuations of climate change externalities. It must be noted that the methodology used for the monetisation of the external costs of climate change is subject to discussions and that there is a high level of uncertainty associated with such estimates and their use. Some studies conclude that the costs used are (significantly) underestimated.

7.3 Coherence

The assessment of the target options looks at the coherence and risks of trade-offs in terms of environmental impact, strategic autonomy notably with respect to raw materials and manufacturing needs.

Environmental risks

The analysis shows that all the target options in 2040 remain close or below the environmental risk levels identified in the ESABCC report ⁽⁹⁵⁾, namely carbon capture (425 Mt CO₂ annually), the LULUCF net removals (400 Mt CO₂ annually) and “gross available energy” from biomass (9 EJ annually). However, Option 3 relies on a higher level of industrial carbon removals and of e-fuels in 2040 than the other options: a limited deployment of these technologies may be compensated by a higher recourse to biomass-based solutions (BECCS, liquid biofuels). Depending on the size of these additional volumes, this in turn may negatively affect the LULUCF net removals or biodiversity, making this option more at risk of environmental trade-offs. This risk is also highlighted in some position papers published by stakeholders, which support an ambitious climate target together with other environmental priority goals. The adoption of more sustainable lifestyles as in the LIFE analysis limits the environmental risks of higher demand for bioenergy feedstocks observed in Option 3, due to a lower need for industrial carbon removals and e-fuels, while simultaneously delivering strong land-use related environmental co-benefits.

Strategic autonomy

⁹⁵⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405, Table 6. Carbon capture use and storage (CCUS) includes fossil fuels, bioenergy, industry or direct air carbon capture (DACC). The level of the LULUCF net removals is currently declining and may further decline due to climate change. Therefore the risk level was set at 400 Mt CO₂ annually, meaning that scenarios should not rely on even higher carbon removal levels. Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

Specific Objective 6 (in Effectiveness) shows that target Option 3 has the highest security of energy supply with the lowest dependence on external supply of fossil fuels, notably oil and natural gas.

However, the resilience of future energy systems will also be measured notably by a secure access to the technologies that will power those systems. Demand for raw materials (including critical raw materials) and the domestic manufacturing needs (Cfr. NZIA) to build these capacities will be proportional to the deployment of technologies such as renewables and storage, which is lower in Option 1 than in Option 2 in 2040 (renewables capacity is 8% lower) and higher in Option 3 (renewables capacity is 6% higher). The three target options all display a similar pattern of growing needs of raw materials in the coming decades in line with global trends ⁽⁹⁶⁾, which highlights, in line with the opinion of several stakeholders, the importance of securing supply chains and anticipating the creation of a resource base within the EU economy in view of developing secondary supply.

A more sustainable economy

The analysis done with the LIFE case highlights the important contribution resource efficiency can make to meeting climate objectives, while reducing the effort required in key sectors. It shows that strong synergies are possible between a more efficient use of resources in the economy and GHG mitigation objectives. The greater the reductions in 2040, the more valuable these synergies will be. This view is also shared by stakeholders, which are in favour of better implementation of resource efficiency strategies in climate action.

LIFE also shows that an increased uptake of demand-side options and more sustainable lifestyles would reduce the need to deploy the most novel abatement technologies such as carbon capture and hydrogen technologies and lower the amount of green electricity required. More generally, LIFE improves energy efficiency and significantly reduces the need for electricity consumption, installed renewable capacity, and storage, while providing opportunities in the land sector. It makes the pathways less dependent on novel technologies, while still reaching the highest target levels and the corresponding net GHG budget.

7.4 Subsidiarity

Climate change is a trans-boundary problem. For trans-boundary problems, individual action is unlikely to lead to optimal outcomes. Instead, coordinated EU action can effectively supplement and reinforce national and local action. Coordination at the European level enhances the effectiveness of climate action. This is particularly true in view of meeting the EU climate neutrality objective by 2050 and is valid for all 2040 climate target options assessed in this impact assessment.

⁽⁹⁶⁾ IEA (2023). “Net Zero Roadmap. A Global Pathway to Keep the 1.5°C Goal in Reach”

7.5 Proportionality

The different target options differ substantially in terms of level of progress to the climate neutrality and in terms of cumulative GHG emissions (the “GHG budget”), with Option 3 outperforming the other two target Options. This option secures best the deployment of the needed technologies to meet climate neutrality by 2050. Its additional mitigation cost to bring the EU towards climate neutrality remains limited compared to the baseline Option 2 (+1.5% over 2031-2040, +0.8% over the entire period 2031-2050). The cost-benefit analysis shows a positive outcome for Option 3 compared to Option 2, including with a conservative valuation of the cost of climate change, while Option 1 shows a more uncertain outcome dependent on the valuation.

Target Option 3 is thus assessed to be the most proportional to the objective of this initiative, namely bringing the EU economy to climate neutrality by 2050 and for the EU to contribute to the global climate action in view of meeting the Paris Agreement temperature goals of limiting the temperature increase to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels.

The post-2030 climate, energy and wider policy framework will need to ensure that the social and industrial policies and support required is in place to deliver the clean technologies needed by 2040, including for carbon management.

7.6 Summary

Table 35 presents a summary of the comparison of the different options to the “baseline” Option 2. The assessment is done in the absence of the future policy framework post-2030, which will need to be designed to ensure a just transition and coherence with other policies.

Table 35: Summary of the comparison of options

	Opt.1 vs Opt. 2	Opt. 3 vs Opt. 2	Source	Scoring methodology
Effectiveness				
S01 Delivering climate neutrality	- - -	+++	Table 27, section 7.1.1.	Quantitative comparison: “=” means a deviation up to 1%, “+” or “-” a deviation up to 3%, “++” or “--” a deviation up to 10%, “+++” or “---” a deviation higher than 10%
S02 Minimising GHG budget	- - -	+++	Table 27, section 7.1.1.	
S03 Just transition	+	-	Table 28, section 7.1.1.	
S04 Competitiveness*, cost GDP, trade	+ =	- =	Table 28, section 7.1.1.	
S05 Deployment of technologies	- -	++	Table 29, section 7.1.1.	
S06 Security of energy supply	- -	++	Table 29, section 7.1.1.	
S07 Environmental effectiveness	=	=	Table 30, section 7.1.1.	
Financial feasibility (annual capital cost)	+	-	Table 32, section 7.1.1.	
Technological feasibility, 2031-2040 2041-2050	+ -	- +	Based on section 7.1.2	Qualitative comparison*
Efficiency				
Lower valuation of externalities	+	=	Table 33 in section 7.2.	Quantitative comparison: “=” means a deviation of annual net benefit up to 5 bn EUR
Higher valuation of externalities	- -	+++		“+” or “-” net benefit up to 10 bn EUR “++” or “--” net benefit up to 20 bn EUR “+++” or “---” net benefit above 20 bn EUR
Coherence				
Environmental risks (land use)	+	-	Based on section 7.3	Qualitative comparison*
Strategic autonomy (excl. security of energy supply)	+	-		Qualitative comparison*
Subsidiarity	=	=	Based on section 7.4	
Proportionality	-	+	Based on section 7.5	Qualitative comparison*

*Note: *Qualitative comparison: “+” means that the Option performs better than Option 2, “-” means that the Option performs worse than Option 2, “=” means that the Option performs as Option 2.*

8 PREFERRED OPTION AND ITS IMPACTS

Target Option 3 with a range of 90-95% is the preferred option. This range is consistent with that recommended by the ESABCC and ensures the lowest GHG budget of all options. It provides the best balance between climate ambition and contribution to a fair share of the global carbon budget to meet the Paris Agreement temperature goals on the one hand, and feasibility on the other. 72% of the individuals and 66% of the organisations who responded to the public consultation consider that an ambitious climate target by 2040 will ensure that the EU does its part in protecting the planet and fulfilling its duty towards future generations. Several position papers analysed during the public consultation also call for an ambitious climate target, with some stakeholders explicitly targeting ranges at 90% or above.

Target Option 3 is **the most effective** in terms of bringing the EU to climate neutrality by 2050. With the lowest GHG budget, it also provides the strongest leadership from the EU and the most credible push to the EU's partners worldwide on the need and opportunities for accelerating climate action. Stakeholders largely agree on the positive influence that an ambitious EU climate target can trigger at global level. By encouraging early action, Target Option 3 is expected to have the **most impact on reducing global emissions**, and on increasing the prospect of keeping 1.5 degrees warming within reach, so as to limit the worst climate impacts and disruptions to all economies, including the risk of reaching irreversible climate tipping points.

Target Option 3 is also the **most effective in ensuring the EU's security of energy supply and strategic autonomy**, with an energy import dependency ratio 3 percentage points lower than the "baseline" Option 2 and a reduction in fossil fuel imports of 4%. It is also the option that best protects the EU against the negative socio-economic impacts of potential fossil fuel price shocks in future.

In terms of **financial feasibility**, all target options require a similar increase in average annual energy system investment over the period 2031-2050 and imply a moderate increase in energy system costs as a share of GDP compared to the average for 2011-2020. Target Option 3 entails a moderate early push in investment in 2031-2040 compared to the "baseline" Option 2, mostly on the energy supply side, where investors have good access to finance due to secure and relatively predictable revenue streams. The anticipation of investment under Target Option 3 is very limited in industry and in the residential sector.

Ensuring a just transition requires an even greater focus for Target Option 3 than for less ambitious target options, as the transition is somewhat accelerated. However, the **increase in costs for households compared to the "baseline" Option 2 is small, and this assessment does not account for any policy measures and redistributive instruments that can be expected to address this impact**; for example, the assessment of impacts does not include the use of carbon revenues to support households.

In terms of the **competitiveness**, Target Option 3 will lead to a greater impact for fossil fuel sectors, and a small negative impact on the output of energy intensive sectors compared to the "baseline" Option 2. However, the higher ambition of Option 3 can further showcase the EU's climate leadership. Target Option 3 will also lead to earlier

investments in novel technologies, an important opportunity to develop the expertise and skills in the EU to supply the equipment and infrastructure that will be needed worldwide over decades to come for carbon dioxide removals to ensure global carbon neutrality. By supporting a higher development of low-carbon technologies, Option 3 would thus increase the positioning of the EU in the global race to clean technologies and solutions. Finally, in addition, the increased energy independence mentioned below is a strong advantage for the competitiveness of the EU industry, in reducing its exposure to the international markets volatility.

Target Option 3 is also **the most efficient** to meet climate neutrality by 2050, showing the **highest net benefits in terms of avoided climate change and air pollution compared to the mitigation cost**. It shows slightly higher mitigation cost overall (+1.5% over 2031-2040 compared to the “baseline” Option 2, but only +0.8% over 2041-2050), which differs across sectors: while the cost increase in industry and transport are close to 2%, they are limited in services and the residential sector to 1% and 0.5%, respectively. Most SMEs are in sectors for which the impacts are very limited.

A greater push will also be required under Target Option 3 to ensure the availability of novel technologies such as carbon capture, including for DACC and BECCS, or e-fuels, which will need the setting up a dedicated policy. The implications above and other impacts or **trade-offs** identified, for example for avoiding new dependencies on imports of critical raw materials or pressure on biodiversity from the use of biomass associated with a more ambitious climate target option, can and must continue to be addressed and mitigated through dedicated policy measures, as part of the design of the future climate and energy policy framework, and wider enabling framework (e.g. financing, land-use and biodiversity, supply of critical raw materials, competitiveness).

Finally, the Impact Assessment further shows the potential for demand-side actions, such as behavioural changes in food, circularity and mobility (as in LIFE) to complement the energy and industrial transition (as shown in the scenarios) and to reduce the costs to society of reaching the 2040 target, lowering energy system costs, the need for investment in (novel) technologies, and environmental risks (e.g. of higher demand for bioenergy). However, lifestyle choices depend to a large extent on personal choice and positive incentives.

9 HOW WILL ACTUAL IMPACTS BE MONITORED AND EVALUATED?

The key EU legislation for planning, monitoring and reporting of progress towards the EU’s climate targets and its international commitments under the Paris Agreement is the Regulation on the **Governance of the Energy Union and Climate Action** (‘Governance Regulation’) ⁽⁹⁷⁾.

The Governance Regulation requires EU Member States to communicate and implement integrated **National Energy and Climate Plans (NECPs)** and to regularly report on

⁽⁹⁷⁾ In accordance with Article 45 of the Governance Regulation, the Commission should review the Regulation with six months of each global stocktake. The evaluation of the Governance Regulation is planned in Q1 2024.

their progress in implementing them. It lays out the detailed reporting obligations on GHG emissions, policies and measures, projections, adaptation actions and support provided to developing countries. Every two years, Member States need to take stock of the progress achieved towards the objectives, targets and contributions set out in their NECPs, which are updated to reflect the countries' contributions to the EU climate and energy objectives ⁽⁹⁸⁾⁽⁹⁹⁾.

With the adoption of the **European Climate Law** in July 2021, the Commission should also provide an assessment of the progress made by all Member States towards the EU 2050 climate-neutrality objective ⁽¹⁰⁰⁾. The first Climate Law assessment was undertaken in October 2023, together with the assessment of progress provided for under the Governance Regulation. The Climate Law assessment is to be carried out every five years, aligned with the global stocktake under the Paris Agreement. The Climate Law provides that the Commission base its assessment on an indicative, linear trajectory, which sets out the pathway for the reduction of net emissions at Union level, linking the Union 2030 climate target, **the Union 2040 climate target, when adopted**, and the 2050 EU climate-neutrality objective. The assessment of progress includes data derived from the European Earth Observation Programme Copernicus.

Under the annual **State of the Energy Union Report** ⁽¹⁰¹⁾, the Commission adopts the EU **Climate Action Progress Report** where it reports each year on EU-wide climate progress and delivers on obligations set out in the Governance Regulation, including to assess progress with the EU's climate targets. The Climate Action Progress Report is an opportunity to inform a wide audience about recent developments in EU climate action.

⁽⁹⁸⁾ Based on guidance to MS issued by the European Commission issues, like the one for the updated NECPs 2021-2030 in view of contributing to “fit-for-55” objectives.

⁽⁹⁹⁾ Final NECPs, in view of meeting the “fit-for 55” objectives, are due in June 2024.

⁽¹⁰⁰⁾ The European Climate Law also requires the Commission to assess the collective progress made by all Member States on adaptation, the consistency of Union and national measures with climate neutrality and with progress on adaptation.

⁽¹⁰¹⁾ Under Article 29 of the Governance Regulation, where the Commission has to assess progress at Union and Member State level towards meeting the objectives of the Energy Union.

Annex 1: Procedural information

1. LEAD DG, DECIDE PLANNING/COMWORKPROGRAMME REFERENCES

The lead DG is DG CLIMA, Unit A2: Foresight, Economic Analysis & Modelling. The co-lead DG is DG ENER.

DECIDE reference number is: PLAN/2023/220.

It shows in the Commission Work Programme 2024 as item 2 in Annex I.

2. ORGANISATION AND TIMING

The impact assessment started in 2023, with the call for evidence published on 31 March 2023.

The impact assessment on the EU 2040 climate target was coordinated by an Inter-Service Group (ISG).

The Inter-Service Steering Group met 3 times: on 20 January 2023, 30 June 2023 and 18 September 2023. It was consulted throughout the different steps of the impact assessment process, notably on all the stakeholder consultation material and on the draft Impact Assessment.

The Commission Services participating in the ISG were: Secretariat-General, SJ, DG AGRI, DG BUDG, DG CNECT, DG COMM, DG COMP, DG DEFIS, DG ECFIN, DG EMPL, DG ENV, ESTAT, DG GROW, DG INTPA, JRC, DG MOVE, DG NEAR, DG RECOVER, DG REFORM, DG REGIO, DG SANTE, DG RTD, DG TAXUD, DG TRADE. The EEAS was also consulted.

3. CONSULTATION OF THE RSB

An upstream meeting between the lead DGs and the RSB took place on 24 April 2023.

The draft report was submitted to the RSB on 16 October 2023 and was discussed by the RSB on 15 November 2023.

On 17 November 2023, the RSB issued a negative opinion. A revised Impact Assessment has been submitted on 6th December 2023, fully addressing the recommendations provided by the Board in its first opinion.

On 22 December 2023, the RSB issued a second, positive opinion with reservations.

Table 36 and Table 37 show the RSB findings and the changes made to respond to the first and the second opinion respectively, which have been shared with the Inter-Service group.

Table 36: How the RSB findings of the 1st opinion have been addressed

Findings	How findings were addressed
(1) The problem, its drivers and its potential consequences are not clearly identified. The report does not adequately define the specific objectives and criteria based on which the performance of alternative 2040 target options would be assessed in line with the requirements of the EU Climate Law.	Following the recommendation by the RSB, the problem definition (section 2) has been simplified and aligned with the legal obligation stemming from the European Climate Law. The specific objectives (section 4) have been better defined, based on the elements under its article 4(5) for the Commission to take into consideration when proposing the 2040 target. The intervention logic has been streamlined. A set of criteria is used to compare the performance of the target options in terms of effectiveness according to these different specific objectives (section 7).
(2) The description of the dynamic baseline is underdeveloped and not sufficiently clear. The report fails to establish an appropriate benchmark for comparison. The rationale behind, the content of and the interaction between the options and the scenarios lack clarity. The report does not bring out clearly enough all available target and pathway choices and the trade-offs between them.	A more detailed section was added on what would happen to the net GHGs emissions by 2040 with a continuation of the current policy framework (section 5.1). On that basis the report establishes a clear “baseline” target level (section 5.1) against which the other target options are compared in terms of effectiveness, efficiency, coherence and trade-offs (in section 7). The relationship with the linear trajectory set out in Article 8 of the European Climate Law is described in the text. The choice of the target options is informed by the analysis by the ESABCC and other scientific publications on the EU 2040 target and their description reflects the responses of stakeholders to the public consultation (section 5.2). The methodology to calculate the cumulative GHG emissions over 2030-2050 (the “GHG budget”) for each target option is described (section 5.2). Finally, the description of the target options and the relation to their representative scenarios have been simplified (sections 5.2 and 5.3), which allows a clearer comparison of the target options and the trade-offs between them (section 7). The scenarios are described in terms of very broad sectoral mitigation mix (section 5.3, which is completed by Annex 6). The detailed analysis (section 6, Annex 8) provides the details on the reductions of GHG per sector and the associated technology deployment, investment needs and costs for the scenarios associated to the target option. The LIFE scenario has been clarified as a “sensitivity” case to societal assumptions, whose conclusions can apply to the different target options. The assumptions for each sector under LIFE are drawn from and benchmarked to external studies, and are referenced in a new table in Annex 6 (section 3) and in the sector-specific sections of

	Annex 8
(3) The level of uncertainty of the modelling, including in terms of the remaining CO2 budget, and the robustness of the results is not clearly identified and analysed.	To complement the more detailed description of the analytical framework that can be found in Annex 6, Annex 1 section 4 on “evidence, sources and quality” provides a description of the different economic models used for this impact assessment and the underlying key assumptions. The impact assessment is backed by a detailed analysis (Annex 8) that makes use of a multi-model approach that provides a cross-model comparison for a number of indicators to cross-validate the results of the analysis. A summary comparison across models for selected key indicators on energy and CO2 as well as on macro-economic modelling has also been added to Annex 1 section 4. The convergence of results shows that the conclusions are robust and not biased by the internal logic and parameters of each model. Finally, the different sensitivity analyses undertaken are now presented in a clearer manner. This includes the sensitivity analysis to test how different costs for key energy technologies affect total investment costs, the LIFE variant to show the impact of a more sustainable materials and production, mobility, and food system, as well as an additional variant to analyse the effect on the energy mix of the recent review of the nuclear legislation in some Member States.
(4) The costs and benefits of each option are not clearly presented. The report is neither clear on the total costs and benefits due to frontloading investments in the 2031- 2040 period nor on the related financial and technological feasibility.	The presentation of costs and benefits of each option and how they compare has been clarified and extended in section 6. A new section (6.3.1) on the cost of the climate change externality has been added, which allows to compare the benefits of a lower 2030-2050 GHG budget (option 3) compared to a higher GHG budget (option 1) and compared to the “baseline”. This complements the monetisation of the environmental benefits related to air quality improvement on health (section 6.3.2). These costs and benefits inform the comparison of target options in the new sections related to effectiveness along the different specific objectives, financial feasibility (including considering the financing cost associated to the investment needs) and overall efficiency (section 7). The assessment of competitiveness is also clearer, with some more detail on SME impacts. Further details are added in the main report on the views expressed by stakeholders in the public consultation. On technological feasibility, a new section has also been introduced (in section 7) that compares with the ESABCC analysis and assesses the Technology Readiness Levels

	(TRL) of technologies needed to reach the 2040 targets. As a result, the IA now presents the technological feasibility of the options. A new variant has also been added to illustrate the changes to the energy mix of the recent nuclear plans in some Member States (section 6.2).
(5) Options are not adequately compared as regards effectiveness, efficiency, coherence and proportionality. The choice of the preferred option is not sufficiently justified.	Criteria for the assessment of options (based on the European Climate Law article 4 (5)) have been defined to allow a clearer description of comparative impacts of the target options in terms of efficiency, coherence and proportionality. In addition, new sections have been introduced that look in detail at how the options compare according to each of these dimensions. The effectiveness assessment is done for each specific objective through specific quantitative indicators and is complemented by an analysis of the financial feasibility and the technological feasibility (see point above). Efficiency is assessed through the comparison of mitigation costs with benefits in terms of saved externalities, notably related to GHG emissions. Coherence is assessed in terms of environmental trade-offs and strategic autonomy. Proportionality compares the net benefits of each 2040 target option to achieve climate neutrality by 2050 and puts this in perspective with the limited mitigation cost difference and the possible trade-offs. This comprehensive comparison of the different target options motivates the choice of the preferred target option.

Table 37: How the RSB findings of the 2nd opinion have been addressed

Findings	How findings were addressed
(1) The report is not clear on how sustainable lifestyle changes are reflected in the dynamic baseline scenario. The policy choices regarding the inclusion of sustainable lifestyle changes (via the LIFE variant) are not brought out clearly and their interaction with the three scenarios is neither comprehensively assessed nor compared.	The 2040 target IA compares different 2040 target levels under a set of common key assumptions related to socio-economics and technology costs and performance. It does not aim at assessing policy choices that could influence such assumptions. However, as complementary dimension, the IA provides a sensitivity analysis on different socio-economic developments, including lifestyle choices, via the “LIFE” variant. Following the feedback by the RSB, the report makes clearer the role of this variant. The variant is built to meet the target option 3, and thus by design reaches in 2040 the same overall net GHGs

	reductions levels as the core scenario S3. The assumptions used are described in detail in Annex 6 (section 3.1.5) and further in the sectoral sections of Annex 8 (in section 1). This variant leads to a different sectoral composition of the abatement of net GHGs, as well as different costs in relation with mitigation of CO2 emissions from fossil fuel combustion and industrial processes. The conclusions of this sensitivity analysis are not exclusive to target option 3 and can be applied to all target options.
(2) The scoring of options is not convincingly demonstrated, the key trade-offs between options not clearly presented and the choice of the preferred option not sufficiently justified.	The methodology behind the scoring of options has been clarified, demonstrating its link with the full analysis in terms of effectiveness, efficiency, coherence, subsidiarity, and proportionality. For each of these aspects, the data sources (in case of quantitative comparison), the relevant sections for the analysis (in case of qualitative comparison) and the detailed scoring methodology, have been included in the summary table (Table 35). The comparison of the options has been further detailed in Section 7, including elements that guide the reader in the understanding of the key trade-off between the options. In particular, the key trade-off between fast technological deployment (and associated challenges) to secure climate neutrality and delayed action that would put at risk the net-zero target have been explained in section 7.1. Additional arguments in support of the preferred option in line with the extended analysis of section 7 and relevant views of stakeholders collected during the public consultation have been introduced in section 8.
(3) The report is not sufficiently clear about the risks related to financial and technological feasibility.	More detailed elements have been included in the financial and technological feasibility section (section 7.1.2). The financial feasibility analysis makes clearer the comparison across options in terms of investment needs and derived annualized capital cost, for energy supply, industry and households. The technological feasibility section adds an analysis on capacity deployment needs and more elements on raw materials needs to the Technology Readiness Level assessment.

4. EVIDENCE, SOURCES AND QUALITY

The impact assessment relies on a wide range of state-of-the art and proven modelling tools that ensure the quality of the analysis. The models have been used by the European Commission ⁽¹⁰²⁾, Member States and a variety of stakeholders in the past decades to assess the impact of climate and energy policies. The models are continuously improved with cutting edge features and periodically peer-reviewed ⁽¹⁰³⁾ by the scientific community. The models have also been used as basis for numerous publications in scientific peer-reviewed journals and conferences ⁽¹⁰⁴⁾. They are managed by teams of highly experienced staff who have been working alongside the European Commission for many years in policy analysis, and therefore understand the scientific, technical and policy requirements to carry out modelling exercises. Their methodological underpinnings are explained in detailed descriptions available publicly for peer review, for instance in the Modelling Inventory and Knowledge Management System of the European Commission (MIDAS)⁽¹⁰⁵⁾.

The underlying exogenous assumptions and the modelling scenarios are shared across models. Exogenous assumptions on population and GDP projections are based on the work of Eurostat (population projections) ⁽¹⁰⁶⁾ and DG ECFIN (Ageing Report) ⁽¹⁰⁷⁾. The methodology underpinning these projections are subject to regular review among Member States. Assumptions on technological costs and abatement costs are based on recent scientific literature review carried out by external consultants in collaboration with

⁽¹⁰²⁾ For instance, the main modelling suite of Impact Assessment was used for the Commission's proposals for the Long-Term Strategy (COM (2018) 773), the 2030 Climate Target Plan (SWD (2020) 176 final), and the Fit for 55 package (COM (2021) 550 final).

⁽¹⁰³⁾ See POTEnCIA peer-review in SORIA RAMIREZ A., POTEnCIA technical peer-review – Related documents, European Commission, Seville, 2017, JRC108360, and METIS peer-review in Ahlgren, E.O., et al. (2020). The METIS model review, EUR 30388 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-22744-1, doi:10.2760/28916, JRC118638.

⁽¹⁰⁴⁾ Description and selected publication for the models used in the impact assessment:

PRIMES <https://e3modelling.com/publications/>,

POTEnCIA https://joint-research-centre.ec.europa.eu/potencia/potencia-publications_en,

EU-TIMES https://www.i2am-paris.eu/detailed_model_doc/eu_times,

POLES <https://www.enerdata.net/solutions/poles-model.html>

METIS: <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-metis/references/>

AMADEUS <https://www.engie.com/decarbonation-scenario-engie>

GLOBIOM <https://iiasa.github.io/GLOBIOM/index.html>

CAPRI https://www.capri-model.org/doku.php?id=capri:capri_pub

JRC-FSCM <https://data.europa.eu/doi/10.2760/244051>

GAINS http://gains.iiasa.ac.at/models/gains_peer_reviewed.html

JRC-GEM-E3 https://joint-research-centre.ec.europa.eu/gem-e3/gem-e3-publications_en

E3ME <https://www.e3me.com/how/papers/>

NEMESIS <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-nemesis/references/>

QUEST (E-QUEST) https://economy-finance.ec.europa.eu/economic-research-and-databases/economic-research/macroeconomic-models/quest-macroeconomic-model_en

⁽¹⁰⁵⁾ MIDAS: <https://web.jrc.ec.europa.eu/policy-model-inventory/>

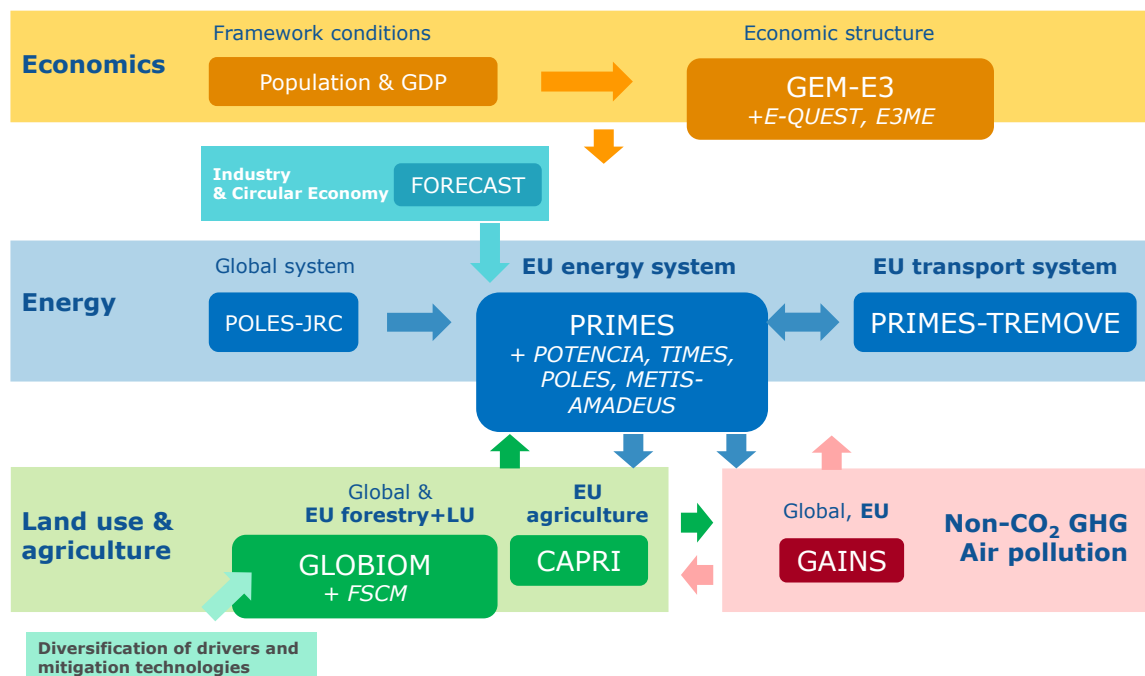
⁽¹⁰⁶⁾ EUROPOP2019 (proj_19n) and short-term update of the projected population (2022-2032) (proj_stp22), which was the latest available projection at the time the key assumptions were adopted as a framework for all models used in the impact assessment.

⁽¹⁰⁷⁾ DG ECFIN. [Autumn 2022 Economic Forecast: The EU economy at a turning point.](#)

the JRC and were validated by a dedicated stakeholders consultation prior to the modelling exercise. In particular, a stakeholder workshop on technology assumptions on land-sector-related and non-CO₂ GHG emissions took place with national authorities, researchers and businesses in October 2022 and energy- and mobility-related techno-economic assumptions were discussed with several stakeholders in February 2022, and subsequently updated in February 2023.

The models are interconnected in multiple ways, as represented in Figure 5. For the energy system and the macro-economic analysis of this impact assessment, multiple independent models have been used in parallel to evaluate and assure the robustness of the results. The PRIMES model is the main energy system modelling tool for this impact assessment. The robustness of the results was assessed by comparing results from other energy system models, mainly the JRC's POTEnCIA and POLES, METIS-AMADEUS and TIMES. The GLOBIOM/G4M model suite (called "GLOBIOM" in this impact assessment) was used to cover all LULUCF-related GHG emissions in this impact assessment, and the results were tested with the JRC forest sector carbon model (FSCM). The CAPRI model was used to assess impacts from agricultural, trade and environmental policies on agriculture as well as biodiversity aspects linked to agriculture. The GAINS model was used as the main modelling tool to estimate air pollutant emissions and their impacts on human health and the environment, as well as non-CO₂ GHG emissions. Three macro-economic models with distinct methodological underpinnings were used to assess the socio-economic impact of the target options and assess the robustness of the key findings. The JRC's GEM-E3 was used as the core model and is a recursive dynamic computable general equilibrium model, and DG ECFIN's E-QUEST and the Cambridge Econometrics' E3ME macro-econometric models complemented the analysis.

Figure 5: Modelling tools used for the impact assessment



The results of the independent modelling analyses are cross-checked across models, indicating a level of uncertainty for the different figures, and validating the robustness of

the conclusion. While high-level results across models are well aligned (see Annex 8), uncertainty increases for more disaggregated results. Detailed modelling results are highly dependent on the design of the energy and climate policy framework (which is not the subject of this Impact Assessment) and the improvement and deployment of different technologies. The dependence of projections on the choice of model can be estimated comparing values obtained from models using the same assumptions and closely calibrated to the same statistical data: this is the case for the PRIMES and POTEnCIA energy models and for the JRC-GEM-E3, E3ME and E-QUEST macro-economic models.

Table 38 shows a summary of the cross-model uncertainty levels for the key high-level indicators of this Impact Assessment. Projections for the main emissions and energy indicators are closely aligned in PRIMES and POTEnCIA models (with deviations of few percentage points in 2040).

Table 38: Uncertainty level for key high-level energy and CO2 indicators.

Indicators	Uncertainty level		
	S1	S2	S3
2030-2050			
EU CO2 budget 2030-2050 (energy & industry CO2)	9%	1%	2%
2040			
Net Energy & industry CO2	8%	4%	8%
GAE	0%	3%	4%
FEC	4%	3%	3%
Share of RES in GFEC	6%	2%	1%

Note: Uncertainty level is defined as the dispersion between the max and min value obtained across models (max/min-1).

Table 39 shows a summary of the impacts on GDP, private consumption and investment for S1 and S3 (in percentage change vs. S2) for the JRC-GEM-E3, E3ME and E-QUEST models. All three models concur that the macro-economic differences across the three representative scenarios are very limited to less than 1%.

Table 39: Impacts on key macro-economic variables across models (% change vs. S2, 2040)

	S1 (fragmented action)			S3 (fragmented action)		
	JRC-GEM-E3	E3ME	E-QUEST	JRC-GEM-E3	E3ME	E-QUEST
GDP	0.5%	0.0%	0.4%	-0.2%	0.0%	-0.8%
Private consumption	0.7%	0.3%	0.3%	-0.5%	-0.2%	-0.5%

Source: JRC-GEM-E3, E3ME, E-QUEST.

Annex 6 provides a more detailed description of the modelling tools and the way they interact in the impact assessment. It also provides a detailed description of the modelling scenarios underpinning the target options, including assumptions, drivers, and rationale.

Furthermore, Annex 7 provides the analysis of the cost of climate inaction based on a review of the literature and dedicated macro-economic modelling carried out for this impact assessment with the NEMESIS macro-econometric model. The NEMESIS model has been designed by an EU consortium to assess socio-economic impacts of research and innovation policies and used in several peer-reviewed publications ⁽¹⁰⁸⁾.

Annex 8 provides the detailed analysis of the sectoral transformations towards different 2040 target levels and to climate neutrality by 2050, and a cross-model comparison for a number of additional indicators. A comprehensive literature review, including the advice by the European Scientific Advisory Board on Climate Change ⁽¹⁰⁹⁾, complements throughout the documents the use of economic modelling.

⁽¹⁰⁸⁾ NEMESIS, Selected publications: <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-nemesis/references/>

⁽¹⁰⁹⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405.

Annex 2: Stakeholder consultation (Synopsis report)

Synopsis report on the stakeholder activities for setting an EU climate target for 2040

1. INTRODUCTION

In the framework of proposing an intermediate climate target for 2040 within the European Climate Law, the European Commission conducted consultation activities aimed at gathering views of different identified stakeholders: citizens, public authorities, businesses, etc. The current synopsis report is a summary of the results of the consultation activities. These will inform the impact assessment prepared by the EC.

The consultation activities included the following elements:

- **Public consultation (questionnaire and position papers):** A public consultation was conducted over a 12-week period from the 31/03/2023 until the 23/06 2023. It included a questionnaire and the option to submit position papers. The questionnaire comprised of a general section (17 questions) and an expert section (18 questions). The general section was targeted at a wider group of stakeholders while the expert section was more technical and involved questions about specific policy domains relevant for the target setting. The consultation incorporated mainly closed questions (32) but also few open questions.
- **Call for evidence:** In addition to the public consultation, stakeholders had the opportunity to share general remarks and feedback on the policy initiative through a call for evidence. They had the opportunity to upload position papers which were analysed together with the position papers received in the public consultation.
- **Targeted stakeholder event:** A hybrid stakeholder event was hosted by the EC in Brussels. Participants were informed about the policy initiative for setting the EU climate target for 2040 and invited to share their views.

The current synopsis report is prepared by a contractor ⁽¹¹⁰⁾.

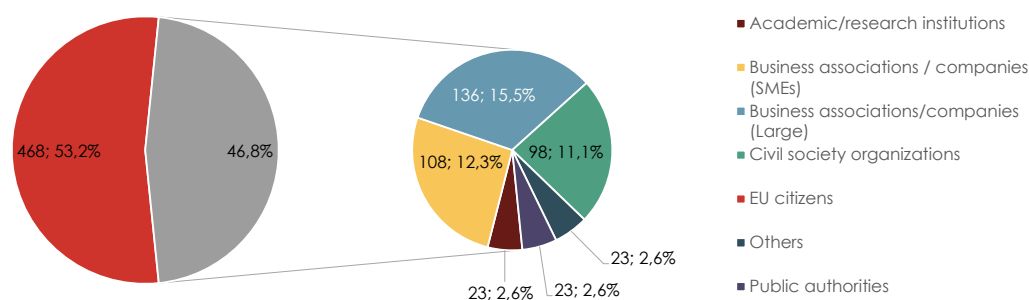
2. ANALYSIS OF PUBLIC CONSULTATION QUESTIONNAIRE

2.1. Overview of responses

In total, 903 responses to the public consultation were received. Among these, 23 (2.5%) responses were classified as part of a single campaign from private individuals in Slovakia (see Section 2.2). In addition, one response was identified as a duplicate, so that a total of 879 responses were included in the analysis. Out of these, 480 (54.6%) (EU citizen: 468, non-EU citizen: 12) were provided by private individuals, and 399 (45.4%) by organisations.

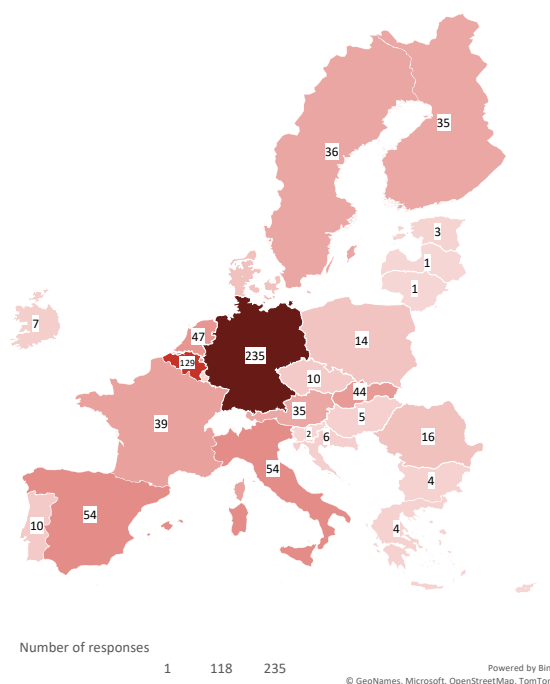
⁽¹¹⁰⁾ Technopolis Group in association with COWI A/S and Eunomia.

Figure 6: Responses by stakeholder group



Note: n = 879 (Number of responses to the public consultation questionnaire) ⁽¹¹¹⁾

Figure 7: Geographical distribution of responses by EU Member States



Note: n = 811 (Number of responses from EU27 Member States. The responses from Slovakia which are classified as a campaign are not included here. An additional 68 responses were received from non-EU countries.)

Most organisational responses came from companies and business associations: Small and medium-sized enterprises (SMEs) and business associations representing SMEs (108, 12.3%) or large companies (>250 employees) and associations representing them (136, 15.5%). An additional 98 (11.1%) responses came from civil society organisations. ⁽¹¹²⁾ Furthermore, 23 (2.6%) responses were received from

⁽¹¹¹⁾ The responses from Slovakia which are classified as a campaign are not included here. See Section on campaign identification for an overview of the campaign.

⁽¹¹²⁾ Clusters the responses from NGOs (68), environmental groups (20), trade unions (9), and one consumer organisation (1).

academic/research institutions and an equal number of 23 (2.6%) responses from public authorities. Also, 23 (2.6%) responses were classified as “Other”. ⁽¹¹³⁾

The frequency of responses varied greatly between EU Member States (see Figure 7). The largest number of responses came from Germany (235, 26.7%), followed by Belgium (129, 14.7%) (also representing EU-level stakeholders).

2.2. Methodological approach and campaign identification

The data from closed questions was processed and cleaned to facilitate descriptive analysis and representation. Results are consistently presented as absolute numbers and percentage values. The latter indicate the proportion of responses within each respective stakeholder group. For Likert-scale questions, the share of (dis)agreement is supplemented by an average for all responses.

The methodology used for analysing open-text questions involved several steps. After eliminating invalid responses and identifying coordinated ones, a semi-automated thematic analysis was conducted, and themes were identified without preconceived notions.

Views from the public consultation are not statistically representative.

The strategy chosen to identify coordinated responses relied on clustering of closed question responses and a semi-automated analysis of similarities in open-text answers. The analysis of open-text answers led to the discovery of a distinct group of 23 (2.5%) responses from EU citizens from Slovakia, which were classified as a campaign, and analysed separately. The responses in the campaign showed the same narrative of urging political leaders to use sustainable transportation (Q11, open-text). Regarding climate ambition for 2040, most responses indicated that the EU should make its ambition dependent on other countries’ climate ambition (19, 83%). Overall, the answers in the campaign could be characterised as expressing climate-sceptical beliefs and attitudes.

2.3. Results from the general section of the questionnaire

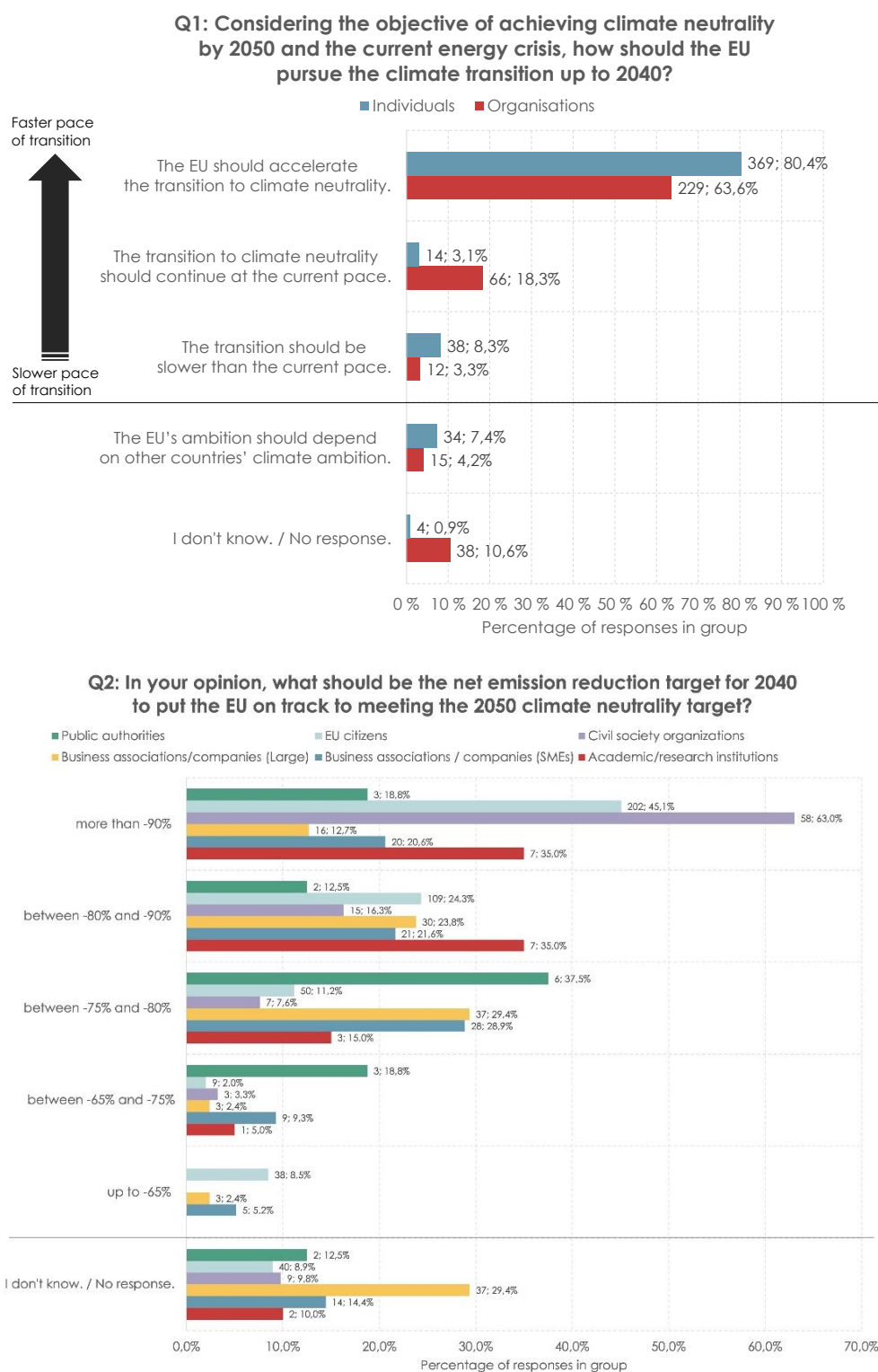
Overall opinion on the EU’s climate ambition for 2040

Overall, the responses to the level of ambition strongly endorse setting an ambitious EU climate target for 2040. A majority (598, 73%) of respondents (Individuals: 369, 80.4%; Organisations: 229, 63.6%) indicated that they want the EU to accelerate the transition to climate neutrality. Civil society organisations (84, 91.2%) and academic/research institutions (17, 85.0%) showed the highest levels of support, but also about half of SMEs (51, 52.6%) and large business associations or companies (60, 47.6%) favoured an acceleration of the transition. Regarding a specific net emission reduction target for 2040, more than half of the respondents supported a target of more

⁽¹¹³⁾ Includes the responses from non-EU citizens (12).

than -80% by 2040 (504, 61.5%). Again, more individuals (322, 70.2%) required a target of more than -80% than organisations (182, 50.5%). Stakeholder groups showed variation in ambition levels. A large majority of civil society organisations supported a net emission reduction target of more than -80%” (73, 79,3%), followed by academic/research institutions (14, 70,0%). Among business associations and companies, the responses dispersed more: 42,3% (41) of SMEs and linked associations advocated for more than -80 %, while among the group of large business and business associations 36.5% (46) advocated for more than -80%. Amon public authorities 31.3% (5) advocated for more than -80% reduction.

Figure 8: Responses on the pace of the climate transition (Q1) and the level of ambition (Q2)

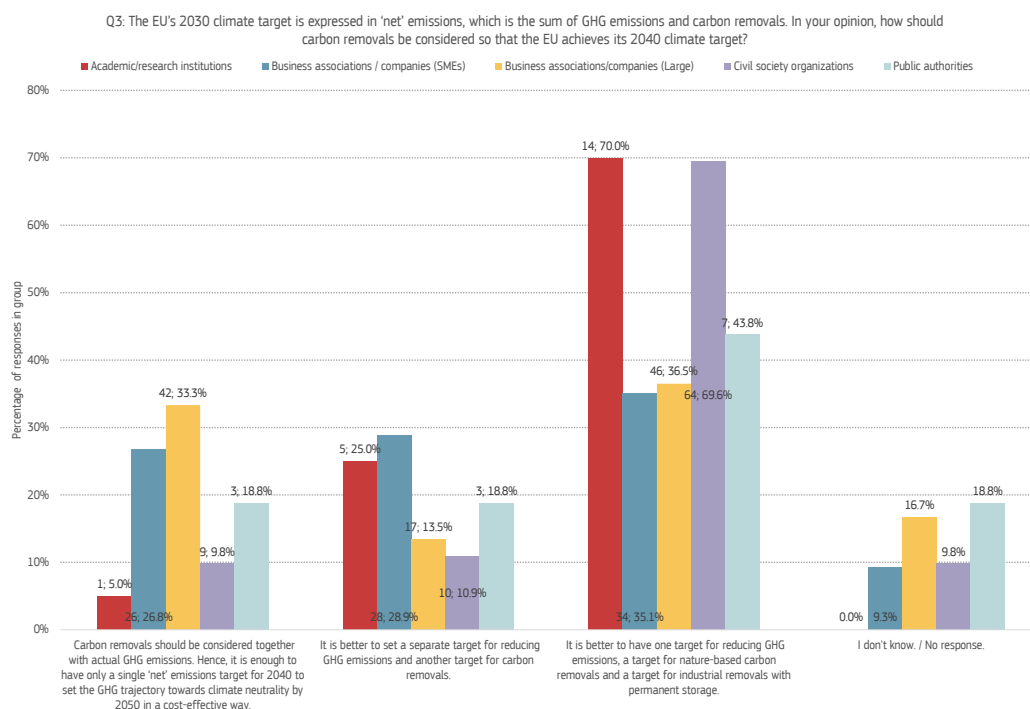


Note: n = 819 (Responses to the general section of the public consultation questionnaire)

In relation to the role of carbon removals in the EU's 2040 climate target, both individuals (272, 59.3%) and organisations (171, 47.5%;) favoured separate targets for

GHG emission reductions, nature-based carbon removals and industrial removals with permanent storage. Especially, civil society organisations (64, 69.6%) and academic/research institutions (14, 70.0%) believed that three separate targets are the best solution while public authorities (7, 43.8%) SMEs (34, 35.1%) and large business associations/companies (46, 36.5%) were less inclined to this option (see Figure 9).

Figure 9: Responses on the set up for the EU 2040 climate target



Respondents viewed most opportunities and challenges associated with ambitious EU climate targets as very relevant, mainly collective well-being (555, 67.8%) and taking responsibility for the planet and future generations (571, 69.7%). The most important challenges were ensuring a socially just transition for everybody (Avg.: 4.34, 52% rating 5), ensuring public support for climate ambition supported by EU policy (Avg.: 4.29, 56% rating 5) and improving energy efficiency (Avg.: 4.27, 56% rating 5). For SMEs associations/ companies, large business associations/ companies and for public authorities the most promising potentials were all related to economic factors, such as green jobs (58.8%, 57.1% and 75.0%), economic signals (57.7%, 73.0% and 75.0%) and energy security (55.7%, 58.7% and 81.3%).

The question of whether issues of gender should be of concern for climate policy created a stark divide, with most respondents being either strongly in favour (181, 22.1%) or strongly against it (162, 19.8%).

Contribution of individual sectors to the EU's climate ambition

Overall, a large majority of the respondents claimed that all sectors can and should do more to reduce emissions. The three most favoured sectors to increase their efforts were “Aviation & maritime transport” (Avg.: 4.42, 57% rating 5), “Road transport (passenger and freight transport)” (Avg.: 4.39, 59% rating 5) and “Industrial processes & waste” (Avg.: 4.25, 48% rating 5). “Production of electricity and district heating” was the sector that was expected to reach climate neutrality first, (442, 54%) and “Aviation & maritime transport” to be the last (393, 48%).

Personal contribution to protect the climate

Overall, respondents depicted a great awareness for climate change impacts and a willingness to make behavioural changes. (89% rating 4 and 5, Avg.: 4.66). They also declared to be ready to change their behaviour to reduce their carbon footprint (82% ratings 4 and 5, Avg.: 4.36).

The impacts of the climate crisis

Overall, respondents indicated that they are aware and concerned about the negative impacts of the climate crisis. At the same time, they point out that relevant actors must do more to prepare cities and countries for these impacts. “Loss of biodiversity and natural habitats” was of greatest concern for the respondents (Individuals: 355, 77.3%; Organisations 151, 41.9%; Total: 506, 61.6%). Additionally, in the open question on possible impacts of the climate crisis the themes climate refugees and migration; social and political conflicts; and health impact were mentioned most frequently.

On the societal level, natural disasters (338; 73.6%), negative impacts on food production (315; 68.6%) and migration or refugee movements (307; 66.9%) were most frequently selected by individuals as the most relevant climate-change related impacts.

Dealing with climate change-induced natural hazards, individuals indicated the highest level of fear for local vulnerability regarding heatwaves (322; 70.2%), droughts (310; 67.5%) and lack of water (306; 66.7%). Organisations feared the same hazards.

2.4. Results from the expert section of the questionnaire

General policy framework

Overall, respondents indicate that there is strong support for an extension of the scope of EU emissions trading to all fossil fuel uses and to cover non-CO₂ GHG emissions. For the other climate policy instruments, the results are less conclusive. Respondents most strongly agreed that all fossil fuel uses (Avg.: 4.27, 48% rating 5) as well as non-CO₂ GHG emissions (Avg.: 4.09, 46% rating 5) should be covered by EU emissions trading.

Regarding the future role of the Carbon Boundary Adjustment Mechanism (CBAM) and its scope, the strongest support is for the option that sectors with the highest absolute

emissions should be prioritised for inclusion (Avg.: 3.90, 28% rating 5): transportation (appeared in 29 out of 151 responses), chemicals and polymers (24); and agriculture (20).

There are no significant majority opinions regarding the future development of the ESR. Especially large companies or business associations representing large companies favoured the idea that national targets should only cover emissions not covered by an ETS (37% rating 5), whereas they strongly disagreed with the idea that national targets should cover all GHG emissions from all sectors (7% rating 5).

Mitigation of GHG emissions from the land sector and policy options

In general, stakeholders demand more ambitious regulations to mitigate the GHG emissions in the land sector. They also indicate that if a carbon price were to be set for agricultural emissions, it should preferably be set for industry actors and then passed-on along the value chain - food companies and producers of fertilisers. Most respondents agreed that there is a need for regulatory approaches such as ambitious sectorial standards to drive the transition of the agricultural sector (Avg.: 4.23, 37% rating 5) and that focusing on aspects such as better information is not enough (Avg.: 1.75, 5% rating 5).

The role of carbon removals

Stakeholders' view on the general role of carbon removals was divided, with EU citizens and civil society organisations (52, 61.9%), in contrast to other stakeholder groups, arguing for a limited role of removals. EU citizens also argue for a stronger reliance on nature-based removals, while SMEs display a preference for a stronger reliance on industrial removals. Academic/ research institutions (10, 52.6%), public authorities (11, 61.1%) and SMEs (60, 62.5%) as well as large business associations/ companies (94, 72.9%) have a higher share of responses in favour of an important role of carbon removals. In contrast, civil society organisations (52, 61.9%) together with EU citizens (110, 50.2%), mostly prefer to limit the role of carbon removals.

Technologies

Overall, stakeholders identified technology costs as the most important barrier for the deployment of CCS. At the same time renewable energy sources are seen as the most relevant energy technology for the transition supplemented by energy efficiency, storage technologies, demand management, and innovation. T

Furthermore, the respondents rated that the most relevant technologies are wind, solar and hydropower. Energy efficiency and storage technologies are also considered as highly relevant. The open question confirmed the prominence of renewable energy with the addition of hydrogen (19 out of 156 responses) and nuclear power (15).

Engagement and social impacts

In general, stakeholders perceived the local and regional implementation of the European Green Deal as insufficient. They emphasised the importance of a just transition and agreed that the transition will affect and alter multiple sectors, including the energy, transport and agriculture sectors.

With regards to sectoral impacts of the transition, respondents specifically agreed that action to reskill and upskill the workforce due to structural shifts is required (Avg.: 4.45, 46% ranking 5) and that the green transition represents an opportunity for SMEs (Avg.: 4.14, 34% ranking 5).

Adapting to climate change

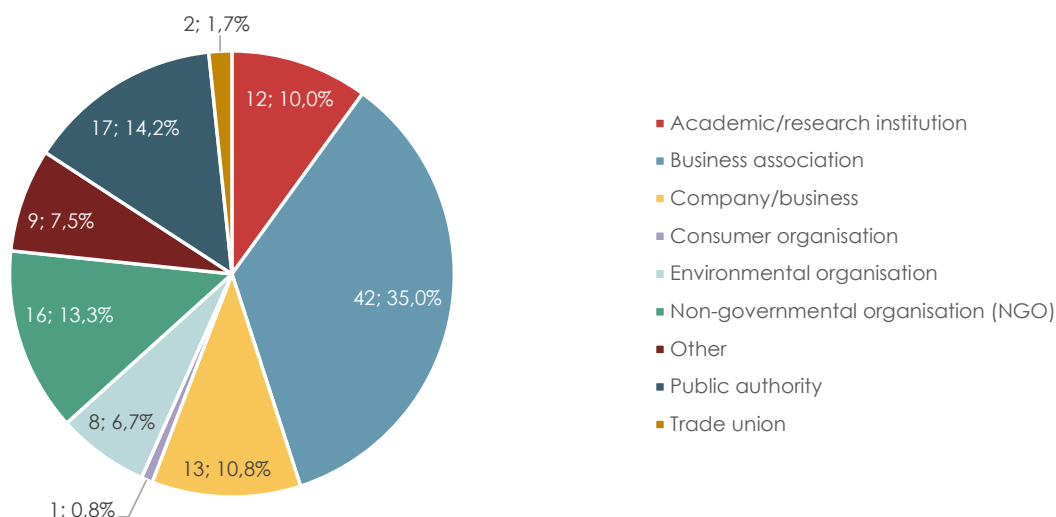
Overall, stakeholders agree that current EU regulations and policy are sufficient to guarantee the security of the mitigation efforts. Only 5.3% (31) of the respondents did agree that current EU regulations and policy are sufficient to guarantee the security of the mitigation efforts in face of climate impacts. The most favoured response was that the EU should draft new legislation to improve the climate resilience of mitigation efforts (167, 28.8%).

3. ANALYSIS OF POSITION PAPERS

3.1. Overview of position papers

A total of 237 position papers were received from the public consultation, and 146 through the call for evidence (63 were submitted to both). Out of these, two papers from national governments and one from the United Nations were submitted outside the formal consultation context. In addition, a couple of additional papers were identified through desk-research. Based on a preliminary review and a selection (removal of duplicates, relevance, type of stakeholder, previous contribution to IIA), 120 papers were thoroughly analysed.

Figure 10: Position papers by stakeholder group



Note: n = 120 (Number of position papers for in-depth analysis)

3.2. Methodological approach

The objective of the analysis was to identify the main views expressed in the position papers. A preliminary screening of all papers was conducted to identify the main characteristics and core idea of the papers. After selection, an in-depth review of all papers was conducted to identify the statements relevant for the analysis and the topics to which they belong. They were then associated with a unique identifier and basic information on the respondents which was subsequently used as variables for the analysis: stakeholder groups, country, sector etc. The main trends observed through this thematic analysis then explained and described.

3.3. Focus on position papers received from public authorities

Position papers received through the public consultation include contributions from the national governments of Denmark, Estonia, Poland, and Sweden. On a regional and local level, additional contributions from the Bavarian State Parliament, the Bavarian Ministry for the Environment and Consumer Protection, the Government of Flanders, the Cities of Amsterdam and Gothenburg were also received as part of the public consultation. On an international level, the United Nations also provided a contribution. Further relevant position papers from public authorities were identified based on desk research and provided by the EC. ⁽¹¹⁴⁾

The contributions by public authorities include recommendations and positions regarding the level of ambition and process for setting the EU climate target for 2040 and input on

⁽¹¹⁴⁾ These included position papers by the Dutch Ministry of Infrastructure and Water Management, the Irish Environmental Protection Agency, the German Environment Agency, the European Central Bank, and the Autonomous province Bolzano.

how this relates to national and regional progress of the transition and (sectoral/national) decarbonisation scenarios.

Most public authorities welcome the process of setting an EU-wide climate target for 2040. The Danish Ministry of Climate, Energy and Utilities, the Bavarian State Parliament, the United Nations, and the Autonomous province Bolzano call for an acceleration of the transition. The Danish Ministry of Climate, Energy and Utilities additionally advocates for setting an additional interim target for 2035, which would be aligned with the five-year timeframe for Nationally Determined Contributions (NDCs).

Contrarily, the Polish Ministry of Climate and Environment and the Government of Flanders express the view that the target setting for 2040 should be postponed as it is still too uncertain to predict the impact of an EU-wide climate target for 2040 and that the implementation of measures to achieve the 2030 climate targets should remain the primary objective.

4. ANALYSIS OF THE CALL FOR EVIDENCE

In addition to the public consultation, respondents were able to share feedback through a call for evidence. In total, 579 feedbacks were received. After the removal of 13 duplicate answers 566 unique feedbacks remained. Most comments originated from Slovakia (126, 22.3%), Germany (100, 17.7%), Belgium (60, 10.6%), and Finland (50, 8.8%). Furthermore, a total of 146 position papers were collected, which were analysed together with the position papers obtained in the public consultation (see Section 3).

356 comments (62.9%) were received from **EU citizens**. Most opinions supported stringent GHG emission reduction targets by 2040, acknowledging that climate change is a serious threat to the EU. More radical opinions insisted on reaching climate neutrality by 2040. The second group of opinions came from climate change sceptics, insisting that climate change is not anthropogenic, and that climate action is a waste of resources. Most of opinions showed similarities with the campaign of Slovakian private individuals identified in the responses to the public consultation questionnaire.

98 submissions (17.3%) were made by **business associations** (55, 9.7%) and **companies** (43, 7.6%). Overall, companies and business associations were in favour of setting ambitious yet realistic 2040 GHG emission reduction targets based on the best available science.

55 submissions (9.7%) were made by CSOs, including NGOs (43, 7.6%), environmental organizations (9, 1.6%), trade unions (2, 0.4%), and one consumer organization (0.2%). The key messages from this stakeholder group underscored the importance to meet the requirements set by the Paris Agreement, generally, advocating for a more ambitious “net zero” transition.

14 submissions (2.5%) were made by **academic and research institutions**. The key messages from these responses related to the prevalent demand that the EU should integrate the latest scientific evidence when formulating the emission targets for the 2030-2040 period. Another important aspect was the EU's historical responsibility when it comes to carbon emissions.

Seven submissions (1.2%) were made by **public authorities**. The key messages from these responses related to the need for investments concerning the green transition for aspects such as green technologies and re-skilling. In this context, the submissions of public authorities highlighted the EU's crucial role as a supporting force that can facilitate the transition of other countries and thereby contribute to its global responsibility.

A further 36 responses (6.4%) came from **non-EU citizens** (4, 0.7%) or from stakeholders who classified themselves as "Other" (32, 5.7%). The topics of these responses largely mirrored the topics of the other stakeholder groups. Especially those stakeholder types that related strongly to their respective type.

4.1. Results from the analysis of position papers

The 2040 target and associated opportunities, challenges and enabling factors

Regarding the level of ambition for the net emission reduction target for 2040, 41 papers (34 % of the total) provided an opinion. Most papers (32) advocate for an acceleration of the transition and five prefer its current speed.

Many contributions favour a realistic transition pathway for industry, by undertaking a critical review of the practical feasibility of an ambitious 2040 target including impacts on competitiveness; the impact on energy prices; and the cost-effectiveness of a more ambitious target.

57 papers (48%) expressed an opinion about the opportunities related to higher climate ambition. More than a third of the papers consider that a higher climate ambition would benefit EU's economic competitiveness; the creation of new jobs; EU global leadership; innovation fostering or well-being. At the same time, most papers mention that the EU is facing multiple, technological, financial, social, regulatory and political challenges.

Only few papers discussed the impact of climate policies on SMEs, not expecting negative impacts provided that the administrative burden does not increase, and that support, and resources are provided to cope with the needed transition (fair transition).

The contribution of Individual sectors to the EU's climate ambition

Around 70 position papers (58% of all answers) provided opinions on the prioritisation of sectors and the following sectors were identified as priority for GHG emission reduction: transport (24), agriculture and forestry (14). Buildings (11) and industry (10).

The role of policy instruments

- EU Emission Trading System (EU ETS)

63 papers (53%) commented on the role of the ETS post-2030. An overwhelming majority considered the EU ETS as an instrument playing a key role in the mitigation of EU emissions. However, an evolution of the tool in relation to the 2040 target is needed.

The most widely discussed topic was the sectoral coverage, with a suggestion to extend to all, or to a restricted number of additional sectors. The interaction with other policies and instruments (ESR, LULUCF, CBAM) was addressed, with concerns expressed about

the risk of double-coverage, relation between ETS- and CBAM-prices and scope coverage.

Most stakeholders supported an integration of carbon removal in the ETS.

The third most discussed topic concerned the international integration and potential linkages to other countries/regions.

- Carbon Border Adjustment Mechanism (CBAM)

39 papers (33%) provided elements on the role of CBAM. Most papers indicated that CBAM plays an essential role to avoid carbon leakage and to support carbon market internationalisation. However, more than a third considered that its efficiency is yet to be demonstrated.

22 papers discuss CBAM extension, with contradicting views. While two thirds of the papers considered that CBAM should be extended (to sector at most risk of carbon leakage, to cover the export part of the EU production, to integrate downstream sectors or cover all sectors covered by free allowances under the ETS), one third considered that a CBAM extension should be carefully considered.

- Effort Sharing Regulation (ESR)

23 papers (19%) expressed an opinion on the role of ESR. A bit less than half the papers expressed the need to adjust the ESR, notably given the broadening scope of the ETS.

Mitigation of GHG emissions from the land sector and policy options

44 of the analysed papers (37%) commented on options to tackle agricultural emissions including sustainable farming/carbon farming (9) followed by dietary changes (7) and agriculture carbon removal role (7). Other options mentioned frequently were some form of market incentives and the non-inclusion of the agricultural sector in LULUCF.

The role of carbon removals

73 papers (61%) commented on the role of carbon removals to reach 2040 climate neutrality goals. Most papers acknowledged carbon removals as an important means, yet reservations and concerns were shared in 15 position papers, emphasising they should not be a substitute and offset for GHG emission reduction and should only be considered as a second-best option.

Carbon capture and storage/use

34 papers (28%) commented specifically on the role of different carbon capture and storage technologies. About half the papers, from business associations, public authorities and academia, encouraged the uptake of carbon capture and storage technologies, without assigning priority to one specific technology type.

Energy technologies

72 papers (60%) discussed the most relevant technologies for supporting the energy transition as well as opportunities and barriers of their uptake. 33 position papers (28%)

argued for enhancing the utilization of renewable energies and increasing their share in energy consumption. Moreover, 15 papers (13%) supported applying energy efficiency principles and taking into consideration the beneficial interaction between renewables, increased energy efficiency and GHG targets.

Engagement and social impacts

57 position papers (48%) discuss the social impact of future climate change policies. 28 (23%) make a comment on the need for a socially or economically just transition, where vulnerable groups, communities and Member States are protected from climate risks and poverty.

5. ANALYSIS OF THE STAKEHOLDER EVENT

On 9 June 2023, an all-day stakeholder event was held to gather further feedback and insights on the view of the EU's 2040 climate targets. It was attended in person by 34 stakeholder representatives, including ten from the energy sector, six from industry, six from think tanks, and six from NGOs, as well as representatives from transport, agriculture, SMEs, trade unions, and cities. In addition, a further 48 participants followed the meeting online.

The contents of the event are summarised in the following:

Climate impacts and cost of inaction: Stakeholders were convinced that natural hazards and biotic risks will impact the forestry, agriculture, and other land-use sectors, as well as renewables and waste management/recycling. They emphasised that cities and industries will be affected by employment and work-related risks. In this context, the communication of mitigation and adaptation measures should be linked with other environmental benefits to give a positive narrative, as well as to stress the costs of inaction.

Fair transition, employment, and social aspects: Stakeholders highlighted the skills gap regarding the required technologies and demographic factors as aspects that should be considered. It was stressed that financial support will be needed for green infrastructure (especially for smaller cities), as well as targeted support for lower/middle income groups for the switch of technologies (e.g., upfront costs of heat pumps and electric vehicles).

Energy – including storage, grids, and renewables: Stakeholders believed that aspects such as energy efficiency and contributions to energy security are key in the energy transition. There was disagreement on the role of hydrogen and e-fuels.

Carbon removals/storage: Participants demanded a clear differentiation between emission reductions and carbon removals, suggesting separate targets. The focus should be on emission reductions, with carbon removals reserved only for residual hard-to-abate emissions. In addition, two targets are also needed within the context of carbon removals: one for nature-based removals, and one for technological removal/storage.

Economic effects, competitiveness, industry, and SMEs: Most stakeholders approved the positive effects of having long-term targets and a more stable and predictable legal and regulatory framework is required for investments. More support for industry, such as Carbon Contracts for Differences (CCfD) will be needed for the transition. Additional claims included that the EU industry needs capital investment and reliable/available renewables as well as breakthrough technologies for key industries and lead markets for green technologies.

Agriculture, food security and land sectors (LULUCF, forests, biodiversity, and biomass): Agriculture stakeholders called for intensified food production within GHG boundaries. Forestry stakeholders emphasised the important role of wood-based raw materials and products, whereas civil society organizations called for agriculture to avoid energy crops and questioned the role of wood-based products.

International aspects, and non-EU climate action: Stakeholders emphasised that the EU should align with the UNFCCC 5-year policy cycles, such as setting a 2035 target. Additional claims included: assessing the EU's carbon footprint and the global contribution of EU-based companies in terms of behaviour and policies outside of Europe, as well as embedding carbon in trade flows.

Behavioural change and lifestyles: Stakeholders proposed to frame the green transition as “our well-being and lifestyles will be damaged if we fail to limit global warming to 1.5°C”. The focus should be on sufficiency principles, active mobility, new production models, and consumption-related emissions, as well as the green infrastructure and support for upfront costs that are needed to enable individual climate-friendly choices.

6. OTHER CONTRIBUTIONS

In 2023, the European Scientific Advisory Board on Climate Change (ESABCC) published an advice on the 2040 climate target and GHG budget ⁽¹¹⁵⁾. The ESABCC's advice is reflected throughout the Impact Assessment and comparisons with the ESABCC's analysis are made where appropriate.

The outcomes of Horizon 2020 and Horizon Europe projects related to climate science and mitigation pathways provided important contribution and evidence base for this Impact Assessment.

⁽¹¹⁵⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405.

Annex 3: Who is affected and how?

1. Practical implications of the initiative

The scope of the current initiative focuses on the ambition level of a 2040 GHG target only. The accompanying post-2030 policy implementation framework will be designed and proposed in a later stage. As such, in absence of this post-2030 policy implementation framework, it is not possible yet to calculate the administrative costs, regulatory fees and charges, and enforcements costs for businesses and citizens. All these elements of the ‘one in, one out’ approach will depend on the changes in the implementation of the post-2030 policy implementation framework, in comparison with the current 2030 policy framework.

The implementation of the current 2030 policy framework is supported by the 30% minimum climate mainstreaming in the MFF, and the 37% minimum climate requirement of the Recovery and Resilience Facility (RRF).

The preferred option for this initiative corresponds to a target range of 90-95% emission reduction compared to 1990.

2. Summary of costs and benefits

I. Overview of Benefits (total for all provisions) – Preferred Option		
Description	Amount	Comments
Direct benefits		
Avoided costs of climate change (section 6.3.1).	In option 3, in comparison with option 2, the average annual benefit from climate change mitigation is between EUR 20 and 38 billion for the time period 2031-2040, by EUR 24 and 44 billion for 2041-2050 and by EUR 22 and 42 billion over the entire period 2031-2050.	Avoiding costs of climate change is a general benefit for the whole society, including population, businesses, the public budget, and for nature and ecosystems. Such costs are generally thought to be underestimated, given the difficulty in predicting the impacts of climate change. This is specifically a benefit for all companies in sectors that are dependent on meteorological conditions and natural ecosystems (agriculture, fishery, etc). This is a benefit for companies as it reduces the risk of natural disasters

		and associated consequences on economic activities. This is particularly true for SMEs which tend to have low insurance coverage for risks associated with extreme weather events. This is beneficial for public budgets as it reduces the risk that public money is needed to compensate losses associated with extreme weather events (for example losses in agriculture due to droughts). Finally, all citizens, whether workers in exposed sectors, inhabitants of potentially exposed accommodations, owners of exposed properties, or taxpayers benefit in consequences of the points mentioned above.
Higher energy independence and reduction of the risks associated with fossil fuel price shocks (see section 6.4.3.1)	In comparison with option 2, option 3 implies average annual savings of €22 billion for 2031-2040 due to reduced fossil fuel import. In 2041-2050, the annual savings amount to EUR 9 billion.	This is a benefit for the whole economy, large companies as well as SMEs, and, in fine, for the public budget as well. The higher energy independence reduces the risk of fossil fuel price shocks for companies, SMEs and all citizens. For all, it provides larger certainty to have access to energy at an affordable price.
Indirect benefits		
Reduction of air pollution and reduction of the associated premature mortality and morbidity (see Section 6.3.2)	Annually, the average benefit from air pollution reduction is between EUR 1 to 2 billion in option 3 compared to option 2 (in 2031-2040, as well as in 2041-2050).	This is a benefit for the whole EU population and for the public budget as a consequence of reduced health expenses. The health of all citizens benefits from reduced air pollution. This reduces health expenses, whether they are borne by public authorities or by private insurance companies. In turn, this benefits taxpayers and allows the public budget to be used for other needs.

II. Overview of costs – Preferred option							
		Citizens/Consumers		Businesses		Administrations	
		One-off	Recurrent	One-off	Recurrent	One-off	Recurrent
Action (a)	Direct adjustment costs		The figures for energy system costs provided below are annual averages. More details can be found in section 6. 4.3. of this document and in Section 2.3 of Annex 8. For the residential sector, the total energy system costs in 2031-2040 are EUR 9 billion (1%) higher in option 3 than in option 2. For 2041-2050, they are EUR 2 billion (0.2%) higher in option 3 than in option 2. The capital costs¹¹⁶ are EUR 8 billion (1.6%) more in option 3 than in option 2 for 2031-2040 and EUR 4 billion (0.7%) more for 2041-2050. Energy purchases are EUR 1 billion higher in option 3 than in option 2 for 2031-2040 but EUR 2 billion lower for 2041-2050.		The figures for energy system costs provided below are annual averages. More details can be found in section 6. 4.3. of this document and in Section 2.3 of Annex 8. For industry the capital costs are EUR 2 billion (2%) higher in 2031-2040 in option 3 compared to option 2 and EUR 1 billion (less than 1%) higher in 2041-2050. Energy purchases are EUR 8 billion (2%) more in option 3 compared to option 2 for 2031-2040. They are EUR 2 billion (0.5%) more for 2041-2050. For the tertiary sector, capital costs are EUR 4 billion (3%) more in option 3 than in option 2 for the time period 2031-2040. They are EUR 2 billion (1%) higher for the time period 2041-2050. Energy purchases are EUR 1 billion (0.4%) smaller in option 3 than in option 2 for 2031-2040. They are EUR 1 billion (0.4%) smaller for 2041-2050.	<i>Will depend on the future post-2030 policy framework. It will also depend on the share of the costs for households and companies that can be borne by public funding. This partly depends on the national legislations (for example national or regional funding for improving energy efficiency in the residential sector).</i>	
		Energy systems costs for transport are borne partly by households, partly by businesses and public administrations. The corresponding capital costs are EUR 4 billion (1.6%) higher in					

¹¹⁶ Capital costs includes financing and opportunity cost for private actors through the application of a WACC at 10% in the annualization of overnight investment costs.

		2031-2040 for option 3 compared to option 2, and EUR 6 billion (2%) higher in 2041-2050. Energy purchases for transport are EUR 12 billion (2%) higher in 2031-2040 but EUR 7 billion (1.4 %) lower in 2041-2050.					
	Direct administrative costs	Will depend on the future post-2030 policy framework					
	Direct regulatory fees and charges	Will depend on the future post-2030 policy framework					
	Direct enforcement costs	Will depend on the future post-2030 policy framework					
	Indirect costs						
Costs related to the 'one in, one out' approach							
Total	Direct and indirect adjustment costs	The figures for energy system costs provided below are annual averages. More details can be found in section 6.4.3. of this document and in Section 2.3 of Annex 8. For the residential sector, the total energy system costs in 2031-2040 are EUR 9 billion (1%) higher in option 3 than in option 2. For 2041-2050, they are EUR 2 billion (0.2%) higher in option 3 than in option 2. The capital costs¹¹⁷ are EUR 8 billion (1.6%) more in option 3 than in option 2 for 2031-2040 and EUR 4 billion (0.7%) more for 2041-2050. Energy purchases are EUR 1 billion higher in option 3 than in option 2 for 2031-2040 but EUR 2 billion	The figures for energy system costs provided below are annual averages. More details can be found in section 6.4.3. of this document and in Section 2.3 of Annex 8. For industry the capital costs are EUR 2 billion (2%) higher in 2031-2040 in option 3 compared to option 2 and EUR 1 billion (less than 1%) higher in 2041-2050. Energy purchases are EUR 8 billion (2%) more in option 3 compared to option 2 for 2031-2040. They are EUR 2 billion (0.5%) more for 2041-2050. For the tertiary sector, capital costs are EUR 4 billion (3%) more in option 3 than in option 2 for the time period 2031-2040. They are EUR 2				

¹¹⁷ Capital costs includes financing and opportunity cost for private actors through the application of a WACC at 10% in the annualization of overnight investment costs.

		lower for 2041-2050.	billion (1%) higher for the time period 2041-2050. Energy purchases are EUR 1 billion (0.4%) smaller in option 3 than in option 2 for 2031-2040. They are EUR 1 billion (0.4%) smaller for 2041-2050.		
		Energy systems costs for transport are borne partly by households, partly by businesses and public administrations. The corresponding capital costs are EUR 4 billion (1.6%) higher in 2031-2040 for option 3 compared to option 2, and EUR 6 billion (2%) higher in 2041-2050. Energy purchases for transport are EUR 12 billion (2%) higher in 2031-2040 but EUR 7 billion (1.4 %) lower in 2041-2050.			
	Administrative costs (for offsetting)	Will depend on the future post-2030 policy framework			

^[1] Capital costs includes financing and opportunity cost for private actors through the application of a WACC at 10% in the annualization of overnight investment costs.

3. Relevant sustainable development goals

The initiative aims to assess the climate target for 2040, so goes beyond the time horizon of the UN sustainable development goals (SDG) for 2030. Nevertheless, it relates to a number of these goals and, by setting a clear direction beyond 2030, and will also contribute positively to these objectives by 2030 by providing long-term certainty for policy and investment decisions. The analysis also shows that there can be strong positive effects from some SDGs that play a role in reaching the 2040 climate target.

III. Overview of relevant Sustainable Development Goals		
Relevant SDG	Expected progress towards the Goal	Comments
SDG 3 – Good health and well being	Strong synergies in terms of air quality in all target options in EU and in countries that follow the EU lead and take more ambitious climate action.	

SDG 7 Affordable and clean energy	Clean and decarbonised energy is a key component of all target options. It shields consumer from shocks on the fossil fuel markets.	
SDG 8 Decent jobs and economic growth	The different 2040 target options display very limited difference in terms of overall macro-economic impact. They will contribute to mitigating the impacts of climate change, including for workers and on the economy. New markets and jobs to substitute fossil fuel-dependent economic activities and new opportunities in clean, technology manufacturing and deployment, land-use sector, service sector.	Skilling needs for new products and services in a low carbon economy. The new target and future framework are an opportunity to address labour market inequalities.
SDG 9 Industry, innovation and infrastructure	Reaching climate neutrality by 2050 represents an industrial and infrastructure challenge that will spur innovation. The most ambitious option (Option 3) builds on a larger deployment of low carbon solutions already by 2040, while the least ambitious one (Option 1) rather delays it during the last decade.	
SDG 13 Climate action	All target options are compatible with meeting climate neutrality by 2050.	However, the least ambitious target options rely heavily on deployment on novel technologies during last decade 2041-2050, which puts the climate neutrality target at risk.
SDG 15 Life on land / SDG 14 Life below water	Mitigate the adverse impacts of climate change on land, oceans and biodiversity.	Limited direct impact of climate action. The most ambitious climate target is at risk of trade-offs on land use due to potential bioenergy needs.
SDG 17 Partnerships for the goals	The preferred target option of 90-95% is much more likely to contribute positively to international climate action effort.	

ANNEX 4: SME TEST

Note: the “analytical framework” Annex appears as Annex 6, just ahead of the detailed analysis shown in Annex 7 (Cost of inaction) and Annex 8 (Detailed quantitative analysis of GHG pathways to climate neutrality).

Step 1/4: Identification of affected businesses

All segments of the EU economy are and will be affected by climate change, although some sectors are more exposed than others, notably agriculture, tourism, fisheries and forestry. SMEs have a more limited financial capacity and lower resources to adapt to climate change ⁽¹¹⁸⁾.

To contribute to limiting climate change globally through the implementation of the objective of climate neutrality by 2050, this initiative aims at assessing a 2040 EU-wide climate target covering the whole economy. It is thus relevant for all businesses and sectors since it will set the pace of the transition to 2050. The climate target is expressed as a reduction of net GHG emissions compared to 1990. It will directly affect GHG emitting sectors and those involved in the removal of CO₂ from the atmosphere through natural or industrial means, but also, indirectly, other sectors consuming energy or providing goods and services to deliver a competitive and climate neutral EU economy by 2050.

This initiative does not specifically target or have specific provisions for SMEs. The objective of the current assessment is to compare various GHG ambition levels for 2040 to define the path between the established 2030 and 2050 objectives. This initiative and assessment come without the design of a new 2040 policy framework, which is expected in a later stage. The impact on SMEs depends on the sectors in which they operate. According to the 2022 Flash Eurobarometer “SMEs, green markets and resource efficiency” ⁽¹¹⁹⁾, about one in three (32%) SMEs in the EU offer green products or services, with a further 11% planning to do so in the next two years. For the largest share (43%) of SMEs selling green products and services, these products and services make up not more than 10% of their most recent annual turnover. About one in five (21%) reply that green products and services represent between 11% and 50% of their annual turnover and a slightly higher proportion (23%) answer that the sale of such products and services makes up more than 50% of their turnover. Just under 40% of SMEs surveyed have at least one full-time employee working in a green job some or all of the time: 33% say there are between one and five ‘green’ employees in their SME and 5% report that their number is higher than five.

According to this survey, most SMEs are taking measures to be more resource efficient. At the same time, the actual investment by SMEs in resource efficiency remains low. 35% of SMEs surveyed invested 1% or more of their turnover in this area in the two years before the survey. Saving energy is the second most common resource efficiency

⁽¹¹⁸⁾ Enabling business mitigation and adaptation to climate change Green policies and the role of Employer and Business Membership Organization. International Labour Organization. December 2022

⁽¹¹⁹⁾ Flash Eurobarometer 498 – SMEs, green markets and resource efficiency, March 2022.

action undertaken by SMEs. More than three-quarters (77%) of SMEs plan to implement additional measures to improve resource efficiency in their company. The most common resource efficiency action planned for the two years following the survey is saving energy (53%). A vast majority of SMEs (72%) do not (yet) have a concrete strategy in place to reduce their carbon footprint and become climate neutral; about a quarter of these SMEs reply they are planning to define one. One in five SMEs already have a concrete strategy in place to reduce their carbon footprint and 4% say they are already climate neutral. The most common actions undertaken to become carbon neutral (among SMEs with a carbon reduction strategy) include adopting or purchasing new technological solutions (49%).

To identify affected businesses,

Table 40 presents the share of each sector in the total number of SMEs and the share of employment by SMEs in each. About 66% of all SMEs are active in services. In this sector, many businesses will not be affected in any significant manner by the transition, while others may gain from business opportunities stemming from the need for innovative low carbon solutions. Agriculture represents almost a fourth of small and medium businesses and is a sector exposed to climate change. Given its hard-to-abate GHG emissions and its potential role to enhance LULUCF carbon removals, this sector is also very relevant for the transition. SMEs are also very present in construction, a sector that plays a major role to decarbonise the EU's building stock. Finally, SMEs are less present in other key sectors for the transition and where the assessment shows differences across target options in terms of deployment of new technologies and investment needs: electricity and clean fuels production, energy intensive industries and carbon capture and storage technologies.

Table 40: Indicators of SME activity by sector (2019)

	SME shares in the economy (% of total)		Sectoral split of SMEs (% of economy-wide SMEs)		
	Share in GVA	Share in employment	Number of companies	GVA	Employment
Fossil fuels	7.0%	6.6%	0.0%	0.1%	0.0%
Other mining and extraction	53.1%	59.2%	0.1%	0.3%	0.2%
Energy intensive industries	29.1%	34.4%	0.6%	2.9%	2.0%
Manuf. transport equipment (incl. parts and accessories)	7.9%	14.1%	0.1%	0.6%	0.6%
Manuf. electrical equipment and other machinery	32.0%	35.4%	0.5%	3.1%	2.0%
Other manufacturing	44.4%	65.0%	7.5%	14.3%	15.9%
Electricity, gas, steam and air conditioning supply	22.3%	29.0%	0.7%	1.4%	0.5%
Construction and architecture services	77.8%	89.1%	19.0%	16.4%	17.5%
Transport and storage	49.0%	43.6%	5.4%	5.2%	4.9%
Services	62.7%	69.5%	65.7%	54.3%	55.5%
Water, treatment and waste	46.7%	45.3%	0.3%	1.3%	0.9%
Total	52.9%	64.4%	100.0%	100.0%	100.0%
<u>Memo:</u>			Million	Billion	Million
All sectors above	52.9%	64.4%	23.1	3332	76.3
Agriculture	66.7%	95.6%	8.7	128	8.3

Source: Eurostat Structural Business Statistics; Farm Indicator by Legal Status of the Holding; and Detailed Breakdown of Main GDP Aggregates ⁽¹²⁰⁾.

⁽¹²⁰⁾ The data is calculated from the Structural Business Statistics (SBS), except for agriculture, which is not included in the dataset. For SBS sectors, the table is based on an aggregation of sectors by size class for special aggregates of activities (NACE 2). Fossil fuel sectors (B05, B06, C19); other mining and extraction activities (B07, B08, B09); energy intensive industries (C17, C20, C21, C23, C24); manufacturing of transport equipment (C29, C30); manufacturing of electrical equipment and other machinery (C27, C28); other manufacturing (all other C codes); electricity, gas, steam and air conditioning supply (D35); construction and architecture services (F41, F42, F43, M71); transport and storage (H49 to H53); services (all codes not listed in other sectors); water, treatment and waste (E36 to E39). The data for agriculture is not directly comparable and therefore provided separately. All farms under the holding of natural persons are considered SMEs, while all others are considered as not being SMEs. The gross valued added of SMEs in agriculture (and its share in total agricultural GVA) is estimated based on the percentage of hectares exploited by holdings under the ownership of natural persons, using total gross value added in

Step 2/4: Consultation of SME Stakeholders

The consultation of SME stakeholders includes the public consultation for this initiative, with the possibility to reply to a public questionnaire and to submit position papers, and a stakeholder event. The 2022 Flash Eurobarometer “SMEs, green markets and resource efficiency” also provides more general insights from SMEs.

The public consultation for the initiative was held from 31 March to 23 June 2023. The information about the public consultation was disseminated via 28 social media posts on the channels of the Commission (Twitter, Facebook, LinkedIn, Instagram). It was communicated to several Directorate Generals (DGs) of the Commission, Permanent Representations and stakeholders, some of which shared the information further to their own networks. The consultation was promoted in two intranet articles and multiple newsletters of the Directorate General for Climate Action (“Climate Pact” and “DG CLIMA monthly”) and other DGs.

The questionnaire includes 13 general questions (e.g. on the level of ambition for the EU) and 18 more specific questions (e.g. on the role of carbon removal), including question 33 which covers the sectoral implications for SMEs. SMEs and representative organisations represent 12% of the responses to the public questionnaire. The diversity of SMEs (micro, small and medium-size enterprises) is represented, for example via the contribution of organisations such as SMEunited or Bundesverband Erneuerbare Energie e.V. (BEE). Respondent SMEs support for the different 2040 target levels assessed is split between reductions of 75%-80% (29%), 80%-90% (22%) and above 90% (20%). They consider that the green transition represents an opportunity for them (with a mark of 4.2/5), and agree with the following statements (sorted by decreasing support):

- The likely structural shift and changing skill requirements in the economy towards a green and circular economy will require EU action to reskill and upskill the workforce (4.4/5).
- The EU transition to a net-zero economy impacts differently the competitiveness of SMEs from those of large companies (4.1/5).
- The impact on competitiveness of micro-companies is likely to differ from the impact on small and medium-sized ones (4.0/5).
- After 2030, there will be a greater need to support SMEs to cope with the adaptation and costs associated with the green transition (3.9/5).

Only few position papers discuss the impact of climate policies on SMEs. These do not expect negative impacts provided that the administrative burden does not increase for SMEs, and that support and resources are provided to cope with the needed transition.

agriculture (NACE code A01) as reporting in the national accounts. Similarly, SME employment in agriculture (and its share in total agricultural employment) is estimated based on the percentage of farms under the ownership of natural persons. SBS-based data is for 2019 to avoid the distortions due to the COVID pandemic. Figures for agriculture are for 2020 due to data availability.

Indications of possible support and resources are given in the paragraph 4/4 – Minimising negative impacts on SMEs (see below).

A stakeholder consultation event was held on 9 June 2023. 66 organisations were invited, including SMEs representatives (e.g. the European association of craft, small and medium-sized enterprises - SMEunited, or European Entrepreneurs - Confédération Européenne des Associations de Petites et Moyennes Entreprises - CEA-PME) or associations representing sector specific businesses including SMEs, for example the Committee of Professional Agricultural Organisations (COPA-COPEGA) or the Confederation of European Forest Owners (CEPF).

More generally, the 2022 Flash Eurobarometer evaluated the level of resource efficiency actions and the state of the green market among Europe's SMEs. Among SMEs taking resource efficiency actions, 31% say that their production costs have increased, 26% that there has been no change in their production costs and 31% that there has been a decrease of their production costs over the two years before the survey as a result of the resource efficiency actions. Among SMEs that take resource efficiency actions, 64% rely on their own financial resources and 54% on their own technical expertise in their efforts to be more resource efficient. About a quarter of SMEs (24%) rely on external support. More than a third (36%) of SMEs relying on external support in their efforts to be more resource efficient say they receive public funding, such as grants, guarantees or loans. Over a quarter (28%) receive private funding from a bank, investment company or venture capital fund. More than one third of SMEs (36%) think that grants or subsidies would help their company the most to be more resource efficient.

The SMEs inputs from the public consultation and stakeholder event have been taken into consideration in this impact assessment, its in-depth analysis (see, for example, the competitiveness aspects in Section 8) and enabling framework annexes.

Step 3/4: Assessment of the impact on SMEs

The initiative does not set out measures that require specific compliance efforts from SMEs. Relevant impacts of this initiative on SMEs include the benefit from mitigating climate change (avoided cost of climate inaction and extreme climate-related events), investment needs and potential changes in energy prices, and change in specific markets. The understanding of the impacts on SMEs is important in view of better defining the enabling framework that will allow supporting and accompanying the transition for these actors.

First, contributing to mitigating climate change implies a benefit for SMEs. Small companies have started to experience the impact of climate change on their operation, as reported by the European Investment Bank in its 2022 overview on SMEs. Collier and Ragin⁽¹²¹⁾ indicate that the higher frequency of extreme events due to climate change will imply higher costs for small businesses. In the worst cases of climate related extreme

⁽¹²¹⁾ Collier B. and M. Rajin, "As climate risk grows, so will costs for small businesses". Harvard Business Review, August 2022.

events, exposed SMEs could lose up to 100% of their productive capacities. 38% of SMEs declare not to be covered for the risk of physical loss or damage from a natural disaster and 56% declare not to be covered for the risk of stopping business activities due to disaster related damage ⁽¹²²⁾. In such circumstance, contributing to mitigating climate change is beneficial for all. According to the International Labour Organization, SMEs are less equipped than large companies to plan and invest in adaptation measures ⁽¹²³⁾. A more ambitious 2040 target is more likely to lead to limiting climate change than a lower one.

Another benefit of the transition to a climate neutral EU economy is a reduction of the exposure of SMEs to fossil fuel price shocks, which can propagate through the entire energy system and all energy vectors. Due to the war in Ukraine, energy and their volatility have increased (180% increase in the gas price in the first two weeks of the war, reaching an all-time high of 320 €/MWh on 26 August 2022, while the average price was around 16, 47 and 123 €/MWh in 2015-2020, 2021 and 2022 respectively) ⁽¹²⁴⁾ ⁽¹²⁵⁾. Improving energy efficiency and independence from fossil fuel reduces the risk of such costs for SMEs. Simulations done with the JRC GEM-E3 model show that the economic impact of fossil fuel price shocks is smaller if the ambition for 2040 is larger.

In terms of cost of energy, the different target options display fairly similar impacts for most sectors relevant for SMEs (see Sections 2.2 and 2.3 in Annex 8). SMEs are expected to face very similar energy prices (including electricity prices) across target options. However, the most ambitious target entails a stronger reliance on new fuels, which are currently little deployed (for instance hydrogen to heat at high temperature) and which can concern large but also some smaller industrial actors (for instance the ceramic industry, where most manufacturers are SMEs).

Investments for electrification and energy efficiency improvement are required across all options, with a slightly higher level for the highest level of ambition than for the lower level. As presented in Table 40, around 66% of SMEs are active in services. For the majority of these SMEs, the impact of the transition is likely to be limited and the difference between options is small. For services sectors, average annual investment needs for all companies, including large businesses, range between EUR 49 billion (lower level of ambition) and EUR 57 billion (higher level of ambition) in 2031-2040. This is equivalent to a range of €800 to 940 per employee, keeping in mind that about 30 percent of employees in services work in large enterprises. On average over 2031-2050, investment requirements are very similar.

The impact of the three possible options on SMEs is rather dependant on the sectors. To some degree, the impact of the transition on SMEs depends on the ambition of the 2040

⁽¹²²⁾ Flash Eurobarometer, SME insurance trends, European Insurance and Occupational Pensions Authority, 2022.

⁽¹²³⁾ Enabling business mitigation and adaptation to climate change Green policies and the role of Employer and Business Membership Organization. International Labour Organization. December 2022

⁽¹²⁴⁾ Adolfsen J. F., F. Kuik, E. M. Lis and T. Schuler, The impact of the war in Ukraine on euro area energy markets". ECB Economic Bulletin, Issue 4/2022.

⁽¹²⁵⁾ Dutch Title Transfer Facility prices, Internal analysis based on S&P Global Platts.

target, in particular in the sectors that will need to contribute more or in which specific technologies will need to be applied more extensively. But the final impact will largely depend on the future design of policies and measures to be determined in the years to come in view of meeting the 2040 target.

Most SMEs are in sectors where the energy system costs for option 3 are limited in comparison with option 2 (see Table 41 below).

Table 41: Energy system costs for 2031-2040 and sectoral distribution of SMEs

	Sectoral split of SMEs (number of companies)	Sectoral split of SMEs (GVA)	Aggregate sector in the macro-economic analysis	Energy system costs for 2031-2040 (% change compared to option 2)
Services	65.7%	54.3%	Tertiary	+0.5%
Construction and architecture services	-19.0%	16.4%		
Water, treatment and waste	0.3%	1.3%		
Manuf. transport equipment (incl. parts and accessories)	0.1%	0.6%	Non-EIIs	+0.8%
Manuf. electrical equipment and other machinery	0.5%	3.1%		
Other manufacturing	7.5%	14.3%		
Electricity, gas, steam and air conditioning supply	0.7%	1.4%		
Transport and storage	5.4%	5.2%	Transport	+2%
Energy intensive industries	0.6%	2.9%	EIIS	+2.8%
Fossil fuels	0.0%	0.1%		
Other mining and extraction	0.1%	0.3%		

Note: the sectoral disaggregation used by the Structural Business Statistics does not exactly match the sectoral disaggregation used in PRIMES. The correspondence is indicative.

For the tertiary sector (services represent more than 65% of SMEs), the average investment needs over 2031-2050 are the same across options. It is their distribution over the two subperiods (2031-2040 and 2041-2050) which varies across options. The capital costs for the transition are higher in the most ambitious options (nearly +5% in option 3 compared to option 1 for 2031-2040 vs +2% in option 2 compared to option 1) but this is partly compensated by larger savings in energy purchases (nearly -1% in option 3 compared to option 1 vs -0,5% in option 2 compared to option 1).

For the construction sector (19% of SMEs in construction and architecture services), the transition is an opportunity as it requires the renovation of the building stock to improve energy efficiency. The need for renovation is high across options, but it is front-loaded with the most ambitious target (10% larger investment needs for 2031-2040 in option 3 compared to option 1, but equally smaller needs for 2041-2050). To avoid shortages, the transition will require to anticipate the needs with regards to skills and supply in general.

For the transport sector (5% of SMEs are in the transport and storage sector), the investment needs are comparable across options (see Section 6 of the main report). The most ambitious option implies a larger use of e-fuels and biofuels. The use of new energy carriers requires new types of engines and new activities (e.g. for their installation/maintenance). At the same time, new infrastructures need to be developed

(for example, charging stations for electric vehicles). The reduced use of conventional vehicles with internal combustion engines ⁽¹²⁶⁾ implies a reduction in corresponding activities, but, at the same time, new jobs are created for the supply, installation and maintenance of the new equipment and infrastructure, as well as for the development of new mobility services (e.g. shared cars).

In the manufacturing sectors that are not energy intensive (7.5% of SMEs in the manufacturing other than transport or electrical equipment), SMEs are most likely to decarbonise their production processes mainly via electrification and improvements in energy efficiency. For the sectors that are not energy-intensive, the options differ little in terms of investment needs in 2031-2050 at an average of around EUR 10 billion per annum, but options 3 and 2 imply a quicker transition than option 1. The risks associated with energy costs are limited even if they are higher with the most ambitious target (see Annex 8). The latter indeed relies more on relatively more expensive fuels. The transition brings opportunities in the markets for low-carbon technologies – for instance, in ocean energy ⁽¹²⁷⁾ or sustainable advanced biofuels ⁽¹²⁸⁾.

In the sectors that are most exposed to the transition (fossil fuel, other mining and extraction, energy intensive industries, electricity, gas and steam), SMEs only represent a very small share of the activity (less than 1.5% of SMEs). In these sectors, SMEs will have to adjust their activities. To give an example, the ceramic industry will have to rely on new fuels to heat at high temperature. Specific support programmes and measures exist to ensure a just and fair transition (see Annex 9).

Finally, the agriculture sector (23% of SMEs) is strongly exposed to climate change. The reduction of emissions implies opportunities and challenges. The intermediate and most ambitious options lead to strong GHG reductions in agriculture and a generalised uptake of new technologies. Agriculture is mildly affected by a higher level of ambition, with output 1% lower under S3 than under S2, which is itself 2% lower than under S1. In contrast, output in the forestry sector in 2040 is significantly higher under the higher ambition scenarios than under S1 as a result of the increased demand for biomass. By 2050, the differences are much less significant as biomass uses tend to converge across scenarios. The need to develop carbon removals is a source of opportunities and new revenues in the bioeconomy. The move to a more sustainable food system would contribute positively to the transition towards climate neutrality.

To conclude, the impact of the three possible options on SMEs is rather dependant on the sectors. In the sectors that are most exposed to the transition, SMEs have to anticipate

⁽¹²⁶⁾ Less than 0.07% of SMEs in the EU are in the manufacturing of motor vehicles, trailers and semi-trailers; less than 0.06% are in the manufacturing of other transport equipment (Eurostat Structural Business Statistics). Around 3.4% are in the wholesale and retail trade and repair of motor vehicles and motorcycles. Other sectors involved in the supply chain of the automobile sector may be not impacted by the transition (e.g. textile manufacturing), negatively impacted (e.g. the manufacturing of compounds used in fossil fuel engines) or positively impacted (e.g. the manufacturing of batteries).

⁽¹²⁷⁾ Ocean Energy – Technology Development Report. Low-carbon Energy Observatory, Joint Research Center, European Commission. EUR 30509 EN. 2020

⁽¹²⁸⁾ Sustainable Advanced Biofuels– Technology Development Report. Low-carbon Energy Observatory, Joint Research Centre, European Commission. EUR 30502 EN. 2020

and adjust. This can be a challenge but also yield opportunities in terms of new markets for smaller businesses which tend to be more agile in developing innovative solutions. Across all target options, opportunities arise for green solutions and technical support including digitalisation, circular economy, and sustainable products. While the decarbonisation requires investments, it benefits SMEs by mitigating the risks associated with climate change and reducing the exposure of SMEs to fossil fuel price shocks.

Step 4/4: Minimising negative impacts on SMEs

The decarbonisation contributes to minimising climate change and hence to minimising the negative impact of climate change on SMEs.

Regarding the transition to a climate neutral economy, as the emission objectives for 2030 and 2050 have already been set, the options for intermediary ambition levels in 2040 are relatively close to one another. The analysis shows that there is limited difference between the target options assessed in terms of overall macro-economic impacts and costs for the sectors with more SMEs. While the decarbonisation of the EU economy will entail changes in business activities, it is also a source of opportunities given the role they play in innovation.

As the impact of the transition is strongly dependent on the sector in which SMEs operate, minimising the impact of the transition is achieved not only via programmes for SMEs but also by sector-specific measures. The EU has already put in place a number of measures and programmes dedicated to SMEs as well as those that are specifically targeted to sectors and regions exposed to the climate transition. As an example, the European programme for small and medium-sized enterprises (COSME) contributed to the climate mainstreaming objectives from 2014 to 2020. It included, among others, the Equity Facility for Growth (EFG) and the Enterprise Europe Network (EEN) which provides advice and support to SMEs. Based on the experience with COSME, other comparable programmes could be developed in the future. The European Investment Bank develops financing instruments that are particularly targeted to SMEs. The recent SME Relief Package (129) is expected to support SMEs in the transition to a low-carbon economy. Rules to ensure small businesses are paid in due time help them invest and innovate in sustainability and hire more employees. The Recovery and Resilience Facility makes unprecedented levels of funding available for greening, digitalisation, and upskilling in SMEs. It includes €44 billion of measures to support SMEs directly in 22 national plans. SMEs can benefit from broader measures worth €109 billion, such as loans or equity support open to all companies. InvestEU will help SMEs access loans and equity. It aims to mobilise over €370 billion in investment. This builds on the success of the European Fund for Strategic Investments where over 1.4 million SMEs benefitted from investment projects. It will also include guarantees for Solvency Support to tackle solvency risks. This will attract additional private investments to help SMEs scale-up and grow.

(129) COM(2023) 535 final

The actual impacts on SMEs will largely depend on the future design of policies and measures to be determined in the years to come in view of meeting the 2040 target once it has been agreed. These future policies, including enabling measures, need to take account of SME's ability to engage in climate action, from their ability to adapt to the impacts of climate change and invest in resilience, to their access to skills and finance for the investments needed to reduce their own emissions or to bring new technologies and solutions to market.

ANNEX 5: COMPETITIVENESS CHECK

This annex describes the competitiveness check of the preferred option (Option 3) of a target range of 90-95% reduction compared to 1990.

In terms of **cost and price competitiveness**, capital related costs for industry are 2% higher in Option 3 than in Option 2 for the time period 2031-2040. The difference between these two options falls to less than 1% for the time period 2041-2050. For the tertiary sector, capital related costs are 2.9% higher in 2031-2040 and 1.3% higher in 2041-2050. Energy expenditures for industry are 2.5% higher in Option 3 than in Option 2 in 2031-2040 and around 0.5% higher in 2041-2050. For the tertiary sector, energy expenditures are 0.3 lower in option 3 than in Option 2 in 2031-2040 and around 1% lower in 2041-2050. For energy intensive industries, this actually implies that the share of capital related costs in total production costs in 2031-2040 is only 0.1 percentage point higher in Option 3 than in Option 2 while the share of fuel expenses in total production costs is only 0.2 percentage point higher. In aggregate, total energy system costs are 1.5% higher in Option 3 than in the “baseline” Option 2, partly due to higher financing costs. This difference corresponds to 0.19% of GDP. However this has a very limited impact on the EU share in global exports (see following paragraph). The price of electricity is very close in all the options considered. LIFE could reduce the total investment needs by 8%.

Regarding **international competitiveness**, earlier investment allows companies to position themselves earlier in the competition in low-carbon technologies. 52% of the organisations who responded to the public questionnaire agree that an ambitious target for 2040 will improve the competitiveness of the European economy and give EU industry a first-mover advantage on global markets. The EU share in global exports is comparable across options, with a difference of less than 0.1 percentage point between Option 3 and Option 2. The level of ambition in mitigation policies in the rest of the world actually has a higher impact on it: a higher level of global climate mitigation effort is susceptible to increase market shares for EU companies. In a setting where the rest of the world acts in line with the 1.5°C objective (global action setting), the EU share in global exports is 16.6% for Option 3, compared to 16.1% in the case of a more fragmented climate action (see Section 6.4.1). At the sector level, the differences between options are also very small. What matters more is international action. For example, for energy intensive industries, the EU share in global exports in 2040 is 17.1% for both Options 2 and 3 in a fragmented action setting, but 17.6% in a global action setting). For markets services, the EU share in global exports in 2040 is 22.7% in Option 3 compared to 22.8% in Option 2 in a fragmented action setting. It is 21.7% for both Options 2 and 3 in a global action setting. Option 3 for the EU is more likely to trigger more ambitious climate action in the rest of the world than the other target options. With more ambition domestically, the EU is in a stronger position to convince countries in the rest of the world to increase ambition of their own Nationally Determined Contributions within the UNFCCC. By showing that the transition is feasible at an acceptable cost, it can be an example to inspire from for climate policy development. By developing technologies to decarbonise the economy, it can also facilitate decarbonisation in other countries. Finally, it is also the option which reduces most the exposure to fossil fuel price shocks like the one induced by the war in Ukraine.

All options will have a positive impact on the **capacity to innovate** by triggering the development of new markets for products and services compatible with the 2050 climate neutrality objective. Option 3 accelerates this pull further already in 2031-2040 compared to the other options.

With regards to **SME competitiveness**, the preferred option shows no significantly higher energy-related cost for most sectors relevant for SMEs than the other options (see Annex 4). The impact depends on the sectors (see Annex 8). While the decarbonisation requires investments, it benefits SMEs by mitigating the risks associated with climate change and by providing an economic framework which is more resilient to potential energy price shocks.

Table 42: Overview of impact on competitiveness

Dimensions of Competitiveness	Impact of the initiative (++ / + / 0 / - / -- / n.a.)	References to sub-sections of the main report or annexes
Cost and price competitiveness	[0] Investment needs for 2031-2050 are very close across options. The preferred option implies more investment in 2031-2040 and less in 2041-2050 in comparison with Option 2. The difference in total energy system costs between options 3 and 2 corresponds to less than 0.2% of GDP.	Sections 6.4.2 and 6.4.3 Annex 8 Sections 2.2 and 2.3
International competitiveness	[0] The EU share in global exports is comparable across options, with a difference of around 0.1 percentage point between options 3 and 2. However, the preferred option is more likely to induce more ambitious mitigation action in the rest of the world, which, in turn, would have a positive impact on the EU share of global exports. The preferred option allows an earlier positioning of EU companies in the growing global market for innovative, low carbon technologies, clean products and services. The preferred option reduces exposure to fossil fuel import costs the quickest.	Section 6.4.1
Capacity to innovate	[++] The preferred option will spur innovation in a number of sectors by 2040 to deliver the reductions of net GHGs, including in energy, industry or the land sector.	Sections 6.1 and 6.2 Annex 8 Section 1
SME competitiveness	[0] The investment needs will depend on the sector. The preferred option shows no significantly higher energy-related cost than option 2 for most sectors relevant for SMEs.	Annex 4 Annex 8 Section 2.3

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PART 2/5

COMMISSION STAFF WORKING DOCUMENT

IMPACT ASSESSMENT REPORT

Part 2

Accompanying the document

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS**

**Securing our future
Europe's 2040 climate target and path to climate neutrality by 2050 building a
sustainable, just and prosperous society**

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Annex 6: Analytical methods

1 COST OF CLIMATE CHANGE

1.1 Literature Review

The analysis on the cost of climate change is based on a review of scientific literature, including the reports by authoritative bodies, such as IPCC and WMO. The results from the JRC PESETA IV study ⁽¹⁾, investigating the effects of climate change impacts on the EU at sectorial level, as well as how impacts can be reduced with mitigation and adaptation policies, and from the EU Horizon 2020 COACCH (CO-designing the Assessment of Climate CHange costs) ⁽²⁾ project, assessing the risks and costs of climate change in Europe, are also included.

The Annex 7 summarizes the current literature on the state of the climate globally, and the impacts and risks of climate change, including on climate tipping points and on ecosystems and biodiversity. Impacts on selected most vulnerable regions (Africa, Small Islands and Asia) are described. This is followed by a focus on the European Union, with a review of the literature on the observed and projected impacts of climate change on health, water scarcity, flood risks, infrastructure, and on the land system.

Economic valuation of the cost of climate change is presented by first providing a brief overview of the literature on the evidence of economic damages from past climate events globally and in the EU, followed by the presentation of findings from studies estimating damages from climate change under different warming scenarios. The limitations of economic valuation with economic models are also explored.

Future emissions, climate change and related risks and impacts as well as adaptation and mitigation options are explored in different modelled scenarios, which describe how the future may develop. Those scenarios are based on a range of assumptions, including socio-economic variables and mitigation. The Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) uses a core set of five illustrative Shared-Socio-economic Pathways (SSP) scenarios, that span a wide range of societal and climatic futures. They correspond to Representative Concentration Pathway (RCP) levels for radiative forcing at the year 2100 as follows: RCP1.9, RCP2.6 (both SSP1 – ‘green growth’), RCP4.5 (SSP2 – ‘middle of the road’), RCP7.0 (SSP3 – ‘regional rivalry’) and RCP8.5 (SSP5 ‘fossil fueled development’). The PESETA IV study assesses sectorial climate change impacts in scenarios where mitigation and adaptation action take place and warming is limited to 1.5°C and 2°C, and a scenario without climate policy actions, and impacts are assessed at 3°C global warming. The COACCH project uses nine different combinations of climate change and socio-economic scenarios, based on four SSPs (SSP1, SSP2, SSP3 and SSP4) and four RCPs (RCP2.6, RCP4.5, RCP6.0 and RCP8.5). The evaluation of the macro-economic costs of a range of climate hazards, done for this impact assessment using NEMESIS, considered two damage scenarios: IPCC’s SSP1-1.9 (RCP1.9), and a SSP3-7.0 (RCP7.0) scenario.

⁽¹⁾ Feyen L., Ciscar J.C., Gosling S., Ibarreta D., Soria A. (editors) (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. EUR 30180EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18123-1, doi:10.2760/171121, JRC119178.

⁽²⁾ [COACCH – CO-designing the Assessment of Climate CHange costs](#), accessed 20.7.2023

1.2 Tools for complementary analysis

In complement to the comprehensive literature review and existing studies on climate change impacts and costs mentioned above, the impact assessment makes use more specifically of two models: NEMESIS for an economic analysis and GLOBIOM for impacts on the LULUCF sector. A description of these two models is provided in the Modelling Inventory and Knowledge Management System of the European Commission MIDAS ⁽³⁾.

1.2.1 Economic analysis

An evaluation of the macro-economic costs of a range of climate hazards was carried out for this impact assessment, using the NEMESIS macro-econometric model. The NEMESIS model (New Econometric Model of Evaluation by Sectoral Interdependency and Supply) is a sectoral detailed macroeconomic model for the European Union devoted to study issues that link economic development, competitiveness, employment, and public accounts to economic policies, and notably all structural policies involving long term effects. The essential purpose of the model is to provide a consolidated framework to realise “business as usual” (BAU) scenarios (or other alternative scenarios), up to 30 to 40 years, and to assess the socioeconomic impact of the implementation of all additional policies not already implemented in the BAU.

NEMESIS includes a detailed energy-environment module that allows the model to deal with climate mitigation policies, at EU and EU-national level. In this Impact Assessment, NEMESIS is used to assess the macro-economic impacts of climate-related weather events and climate change in general. The analysis follows an approach similar to the one of the JRC PESETA IV study mentioned in the literature review.

1.2.2 Analysing land and forestry.

The GLOBIOM model was used to project impacts of climate change and natural disturbances on the LULUCF sector by different Representative Concentration Pathways (RCP 2.6 and 7.0). CMIP6 climate data, four General Circulation Models along with predicted changes in climate variables from RPCs were used as an input to 3PGmix for forestry to analyse biophysical impacts on crop and forest productivities. These impacts were then integrated into the GLOBIOM and G4M model to assess the changes in the LULUCF sector.

The model projects regional impacts by different tree species and different types of natural disturbances. This involves assessing the effect of climatic trends on temperature and precipitation, using process-based models to estimate the effect of resulting temperature and precipitation on productivity, and using equilibrium models to estimate the impacts and adaptations on the agricultural market and the environment.

⁽³⁾ MIDAS: <https://web.jrc.ec.europa.eu/policy-model-inventory/>

2 ANALYSIS OF FUTURE GHG EMISSIONS

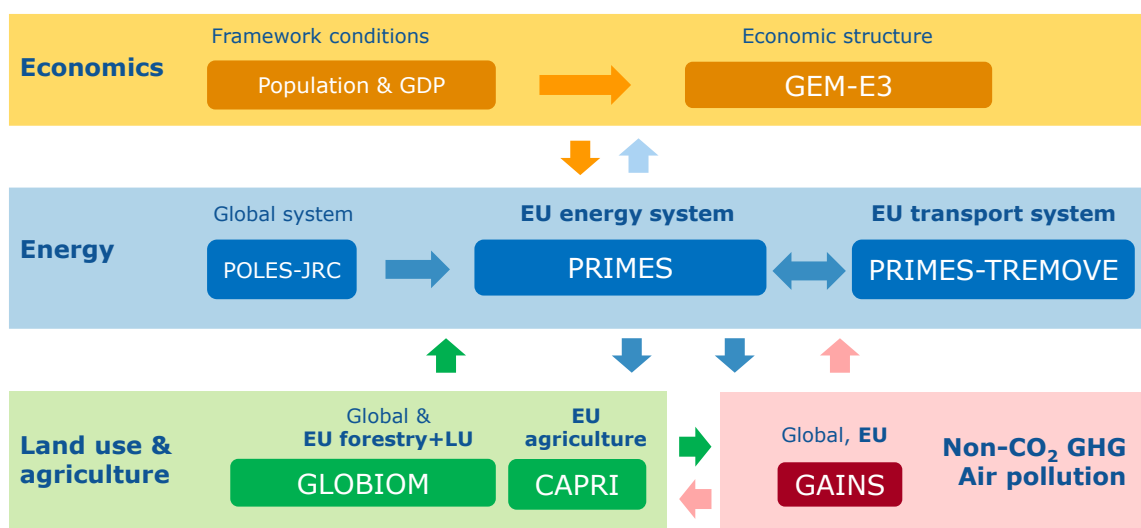
2.1 Models ⁽⁴⁾

The projections for this Impact Assessment are performed with the help of state-of-the-art, computational models for energy and GHG system analysis, which follow an approach based on micro-economics, solve a price-driven market equilibrium, and integrate engineering and economic representations for all sectors. The models use peer-reviewed assumptions and detailed and up-to-date databases to produce projections per sector and per country. Calibration ensures continuity between historical data and projections.

2.1.1 Main modelling suite for GHG emissions

The main modelling suite (Figure 1) is common to the one used for the Commission's proposal for Long Term Strategy ⁽⁵⁾, the 2030 Climate Target Plan ⁽⁶⁾, and the EU Reference Scenario 2020 ⁽⁷⁾ as well as for the most recent modelling exercises supporting the Fit for 55 ⁽⁸⁾ and the REPowerEU ⁽⁹⁾ policy frameworks.

Figure 1: Main modelling suite used for GHG projections.



The modelling capacity consists of a series of interlinked models well known to the modelling community ⁽¹⁰⁾. These are continuously improved with cutting edge features and are managed

⁽⁴⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

⁽⁵⁾ In-depth analysis in support of the commission communication COM (2018) 773

⁽⁶⁾ SWD (2020) 176 final

⁽⁷⁾ European Commission, *EU reference scenario 2020: energy, transport and GHG emissions: trends to 2050*, Publications Office, 2021, [DOI: 10.2833/3575](https://doi.org/10.2833/3575)

⁽⁸⁾ COM (2021) 550 final

⁽⁹⁾ SWD (2022) 230 final

⁽¹⁰⁾ See for instance Ringkjøb, H. K., et al. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy Reviews*, 96, 440-459 and Angenendt, E., et al. (2018). Modelling and tools supporting the transition to a bioeconomy. *Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy*, 289-316.

from a team of highly experienced staff who have been working alongside the European Commission for many years in policy analysis, and therefore understand the scientific, technical and policy requirements to carry out modelling exercises. The models combine technical and economic methodologies assessing GHG pathways and associated system cost. It allows to project the evolution of all GHG net emissions from the EU economy up to 2050.

The GHG pathways are assessed through high-quality sectoral-specific models: the PRIMES and PRIMES-TREMOVE models are the core elements of the modelling framework for energy, transport, and CO₂ emission projections. The PRIMES model has been assessed and used extensively by several services in the European Commission in the past, which has led to significant model development and refinement over time. It is also used extensively by Member States and stakeholders and has been at the basis of numerous refereed publications in the past decades ⁽¹¹⁾.

The GAINS model was used as the main modelling tool to estimate air pollutant emissions and their impacts on human health and the environment, as well as non-CO₂ GHG emissions. The GAINS model has been assessed and used extensively by several services in the European Commission, which has led to significant model development and fine-tuning over time. In addition, GAINS is extensively used by Member States and stakeholders and has been at the basis of numerous peer-reviewed publications over the last decades ⁽¹²⁾.

The GLOBIOM/G4M model-suite (called “GLOBIOM” in this impact assessment) was used to cover all LULUCF-related GHG emissions in this impact assessment, biomass supply for bioenergy, and aspects of biodiversity. GLOBIOM has been used extensively by the European Commission in the past ⁽¹³⁾ and has been refined and developed over time fitting the Commission’s needs and Member States feedback. In addition, the model-suite is being continuously enhanced in collaboration within large research consortia, including over 30 Horizon Europe and Horizon 2020 projects ⁽¹⁴⁾. The models are the basis of more than 200 refereed publications ⁽¹⁵⁾ and have been supporting national ⁽¹⁶⁾ and international policy processes (UN ICAO, IPCC, IPBES) ⁽¹⁷⁾. GLOBIOM has also been frequently challenged in model intercomparisons ⁽¹⁸⁾.

⁽¹¹⁾ PRIMES, selected publications: <https://e3modelling.com/publications/>

⁽¹²⁾ GAINS, selected publications: https://gains.iiasa.ac.at/models/gains_tech_reports.html

⁽¹³⁾ GLOBIOM/G4M was amongst others used in the following European Commission’s policy impact assessments: European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy (COM (2018) 773); 2030 Climate Target Plan (SWD (2020) 176 final); proposal for a revision of the LULLUCF Regulation under the Fit-for-55 policy package (COM (2021) 554 final); FMRL calculations under the JRC Approach, UNFCCC (2011). Synthesis report of the technical assessments of the forest management reference level submissions. Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol Sixteenth session, part four Durban, 29 November 2011. FCCC/KP/AWG/2011/INF.2.

⁽¹⁴⁾ e.g., <https://www.lamasus.eu/>; <https://www.forestnavigator.eu/>; <https://brightspace-project.eu/>

⁽¹⁵⁾ <https://iiasa.github.io/GLOBIOM/publications.html#>

⁽¹⁶⁾ E.g. EPA Technical Document, EPA-420-R-23-017.

⁽¹⁷⁾ ICAO: <https://iiasa.ac.at/impacts/jan-2021/assessing-biofuels-for-transport>; IPCC: Guivarch, C., et al. (2022). Annex III: Scenarios and modelling methods. In: IPCC 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Eds. Shukla, A.R., et al., pp. 1842-1908 Cambridge University

The CAPRI model was used to assess impacts from agricultural, trade and environmental policies on agriculture as well as biodiversity aspects linked to agriculture. The CAPRI model is constantly updated and further developed through projects for different Commission services⁽¹⁹⁾ including Horizon projects and assessments of the Common Agricultural Policy⁽²⁰⁾. It has proven its quality to assess agricultural GHG emissions in numerous peer-reviewed publications⁽²¹⁾ and is used by several research teams in the field throughout Europe⁽²²⁾.

Three macro-economic models with distinct methodological underpinnings were used to assess the socio-economic impact of the target options and assess the robustness of the key findings. The JRC's GEM-E3 was used as the core model and is a recursive dynamic computable general equilibrium model. The model has underpinned numerous refereed publications⁽²³⁾. DG ECFIN's E-QUEST model complemented the analysis. It is a variant of QUEST, a dynamic stochastic general equilibrium model in the New-Keynesian tradition that has been used by the European Commission for macro-economic policy and research for decades and has led to numerous refereed publications⁽²⁴⁾. Finally, Cambridge Econometrics' E3ME macro-econometric model has been used as a third tool to assess the robustness of the results. It has been used extensively by a range of stakeholders and has been the basis of many refereed publications⁽²⁵⁾. The POLES-JRC model is used to provide the global climate and energy policy context⁽²⁶⁾.

The Modelling Inventory and Knowledge Management System of the European Commission MIDAS contains detailed model description, together with a list of impact assessments and a

Press. 10.1017/9781009157926.022.; *IPBES* (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Brondizio, et al. (edt's). IPBES secretariat, Bonn, Germany. 1148 pages. <https://doi.org/10.5281/zenodo.3831673>.

⁽¹⁸⁾ E.g., <https://agmip.org/global-economics/>; Fricko, O., Havlik, P, et al. (2017). The marker quantification of the Shared Socioeconomic Pathway 2: A middle-of-the-road scenario for the 21st century. *Global Environmental Change* 42 251-267.; Popp, A., Calvin, K., Fujimori, S., Havlik, P., et al. (2017). Land-use futures in the shared socio-economic pathways. *Global Environmental Change* 42 331-345.

⁽¹⁹⁾ <https://www.capri-model.org/doku.php?id=capri:project>

⁽²⁰⁾ European Commission, Joint Research Centre, Barreiro-Hurle, J., Bogonos, M., Himics, M. et al., Modelling environmental and climatic ambition in the agricultural sector with the CAPRI model – Exploring the potential effects of selected farm to fork and biodiversity strategies targets in the framework of the 2030 climate targets and the post 2020 Common Agricultural Policy, Publications Office, 2021, <https://data.europa.eu/doi/10.2760/98160>

⁽²¹⁾ CAPRI, selected publications: https://www.capri-model.org/doku.php?id=capri:capri_pub

⁽²²⁾ E.g., DG-JRC (IPTS, Seville and IES Ispra); European Centre for Agricultural, Regional and Environmental Policy Research (EUROCARE)

⁽²³⁾ JRC-GEM-E3, selected publications: https://joint-research-centre.ec.europa.eu/gem-e3/gem-e3-publications_en

⁽²⁴⁾ QUEST (E-QUEST), selected publications: https://economy-finance.ec.europa.eu/economic-research-and-databases/economic-research/macroeconomic-models/quest-macroeconomic-model_en

⁽²⁵⁾ E3ME, selected publications: <https://www.e3me.com/how/papers/>

⁽²⁶⁾ The POLES-JRC model is the main tool used for the JRC “Global Energy and Climate Outlook” GECO report series, which provides a detailed analysis of the evolution of global GHG emissions under national climate and energy pledges and of global pathways compatible with the Paris Agreement temperature objectives.

selection of most relevant peer-reviewed publications where the models have been used ⁽²⁷⁾. A summary, including specific information on how the model has been applied in the impact assessment, is reported in the Table 1 below.

Table 1: Models from the main modelling suite for GHG pathways

Model	Main Purpose of the model in the Impact Assessment
CAPRI ⁽²⁸⁾	A global agro-economic model used to assess impacts on agriculture of agricultural, trade and environmental policies. CAPRI provides results at a regional level and for economic and environmental, biodiversity-related variables.
GAINS ⁽²⁹⁾	GAINS is an analytical framework for assessing future potentials and costs for reducing air pollution impacts on human health and the environment while simultaneously mitigating climate change through reduced greenhouse gas emissions. It explores synergies and trade-offs in cost-effective emission control strategies so as to maximize benefits across multiple scales.
GLOBIOM ⁽³⁰⁾	GLOBIOM is a global bio-economic land use model covering the sectors of agriculture, forestry, and bioenergy. The model has spatially explicit supply side representation covering different management systems and land use activities. It simulates economic market equilibrium for the analysis of economic as well as environmental consequences of future land use drivers and policies. GLOBIOM is coupled with G4M (called "GLOBIOM" in this impact assessment)
G4M ⁽³¹⁾	The model estimates the impact of forestry and land use change activities (forest management, afforestation, and deforestation) on biomass and carbon stocks. G4M is coupled with GLOBIOM (called "GLOBIOM" in this impact assessment)
PRIMES ⁽³²⁾	Energy system model designed to project the energy demand, supply, prices, trade, and emissions for European countries and assess policy impacts.
PRIMES-TREMOVE ⁽³³⁾	PRIMES-TREMOVE simulates the transport modelling system and projects the evolution of the demand for passenger and freight transport by mode, energy consumption by fuel and emissions. The model is rich in the representation of policy measures and is used to assess policy impacts.

2.1.2 Complementary tools on energy and industry CO₂ emissions

The analysis of the different target options uses a multi-model approach to cross-validate results for several critical aspects of the analysis. Additional state-of-the-art models evaluated independently the impacts on the energy system and industrial sector, increasing the robustness of the conclusions.

In complement to the PRIMES model, the transformation of the energy system (energy and industry CO₂ trajectories, energy demand and supply, etc.) has been analysed with the peer-reviewed POTEnCIA model, as well as by AMADEUS-METIS, EU-TIMES and POLES models. The POTEnCIA model has been used in parallel to PRIMES, interacting with other

⁽²⁷⁾ MIDAS: <https://web.jrc.ec.europa.eu/policy-model-inventory/>

⁽²⁸⁾ CAPRI, selected publications: https://www.capri-model.org/doku.php?id=capri:capri_pub

⁽²⁹⁾ GAINS, selected publications: https://gains.iiasa.ac.at/models/gains_tech_reports.html

⁽³⁰⁾ GLOBIOM, selected publications: <https://iiasa.ac.at/models-tools-data/globiom>

⁽³¹⁾ G4M, selected publications: <https://iiasa.ac.at/models-tools-data/g4m>

⁽³²⁾ PRIMES, selected publications: <https://e3modelling.com/publications/>

⁽³³⁾ PRIMES TREMOVE, selected publications: <https://e3modelling.com/publications/>

sectoral models to produce similar energy system scenarios resulting from the main modelling suite. AMADEUS-METIS, EU-TIMES and POLES have been used to indicate high-level cost-effective decarbonisation pathways for the energy and industry CO₂ sectors. The FORECAST model has been used independently to study the impact of selected circular economy actions on industrial decarbonisation pathways.

In complement to the GLOBIOM-G4M, for this impact assessment, forest sector related results have been cross validated with the with the JRC forest sector carbon model (FSCM) ⁽³⁴⁾, which includes the forest carbon model (EU-CBM-HAT) ⁽³⁵⁾ and the harvested wood products (HWP) module. The models independently estimate the forest sink (emissions and removals from forest land, i.e., the major component for the LULUCF net removal) and the changes in carbon stocks in harvested wood products. Given the importance and the uncertainty of the forest sink in the EU, the EU-CBM-HAT model has been used to reproduce scenario S2 from GLOBIOM (with harmonization made for the main input data and assumptions) to test the robustness of the results and to increase quality assurance.

2.1.2.1 POTEnCIA

The Policy Oriented Tool for Energy and Climate Change Impact Assessment (POTEnCIA) ⁽³⁶⁾ is an energy system, peer-reviewed simulation model designed to compare alternative pathways for the EU energy system, covering energy supply and all energy demand sectors (industry, buildings, transport, and agriculture). Developed in-house by the Joint Research Centre (JRC) to support EU policy analysis, POTEnCIA allows for the evaluation of technology-focused policies, combined with policies addressing the decision-making of energy users. POTEnCIA has been previously used by the European Commission to model the use of conventional and biofuels in the EU Agricultural Outlook 2022-2032⁽³⁷⁾ and describe the technological outlook in the Clean Energy Technology Observatory (CETO) Report 2023 ⁽³⁸⁾.

⁽³⁴⁾ See: Pilli, R., Kull, S. J., Blujdea, V. N., & Grassi, G. (2018). The carbon Budget model of the Canadian forest sector (CBM-CFS3): customization of the archive index database for European Union countries. *Annals of forest science*, 75(3), 1-7.; Pilli, R., Alkama, R., Cescatti, A., Kurz, W. A., & Grassi, G. (2022). The European forest Carbon budget under future climate conditions and current management practices. *Biogeosciences*, 19(13), 3263-3284.; Pilli, R., Grassi, G., Kurz, W. A., Fiorese, G., & Cescatti, A. (2017). The European forest sector: past and future carbon budget and fluxes under different management scenarios. *Biogeosciences*, 14(9), 2387-2405.

⁽³⁵⁾ European Commission, Joint Research Centre, Blujdea, V., Rougieux, P., Pilli, R. et al., The JRC Forest Carbon Model – Description of EU-CBM-HAT, Publications Office of the European Union, 2022, <https://data.europa.eu/doi/10.2760/244051>

⁽³⁶⁾ POTEnCIA, references for policy support: <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-potencia/references/>, and selected publications: <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-potencia/references/>

⁽³⁷⁾ European Commission, DG Agriculture and Rural Development, *EU agricultural outlook for markets, income and environment, 2022-2032*, 2022.

⁽³⁸⁾ Georgakaki, A., Kuokkanen, A., Letout, S., Koolen, D., Koukoulakis, G., Murauskaite-Bull, I., Mountraki, A., Kuzov, T., Długosz, M., Ince, E., Shtjefni, D., Taylor, N., Christou, M. and Pennington, D., Clean Energy Technology Observatory: Overall Strategic Analysis of Clean Energy Technology in the European Union - 2023 Status Report, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/150096, JRC135404.

2.1.2.2 AMADEUS-METIS, EU-TIMES, POLES

The EU-TIMES model ⁽³⁹⁾ is the multi-region European version of TIMES, which is designed for analysing the role of energy technologies and their innovation needs for meeting European policy targets related to energy and climate change. The EU-TIMES model is operated by E4SMA and considers both the supply and demand sides and includes the following seven sectors: primary energy supply (including transformation); electricity generation; industry; residential; commercial; agriculture; and transport. EU-TIMES can consider policies that affect either the entire energy system, sectors, group of technologies/commodities, or single technologies/commodities.

The POLES-Enerdata model ⁽⁴⁰⁾ is a recognised multi-issue energy model that belong to the Integrated Assessment Modelling (IAM) tools in support of the Paris Agreement ⁽⁴¹⁾. It relies on national energy balances combined with economic, policy and technological scenarios to withdraw energy production, consumption, and greenhouse gas (GHG) emission projections. The model is operated by Enerdata and provides a complete endogenous calculation from upstream activities (supply, prices of several energies including oil, gas and coal) to final user demand. POLES-Enerdata offers a mixed approach based on:

- a “top-down” modelling for sectorial demand, which is directly related to activity, prices and technologies through econometric equations; for each key economic sector energy consumption is distinguished between substitutable fuels and electricity; and
- a “bottom-up” approach for the power sector (explicit representation of each type of technology as well as their costs).

The AMADEUS-METIS cluster is composed by two coupled models. METIS ⁽⁴²⁾ is an Energy system peer-reviewed model well-known to the scientific community designed to simulate the operation of electricity, gas and heat markets and to assess impacts of policy initiatives on the European energy system and markets. METIS is operated by Artelys and supports DG ENER’s evidence-based policy making, and it has been largely used in previous modelling exercises underpinning the RES policy development and implementation ⁽⁴³⁾ or the revision of the Gas Market Directive ⁽⁴⁴⁾, among others. In certain project and in this impact assesement, it is coupled with the model AMADEUS, which is a bottom-up model owned by

⁽³⁹⁾ EU-TIMES, description and selected publications: https://www.i2am-paris.eu/detailed_model_doc/eu_times https://www.i2am-paris.eu/detailed_model_doc/eu_times

⁽⁴⁰⁾ POLES-Enerdata description and selected publications <https://www.enerdata.net/solutions/poles-model.html>

⁽⁴¹⁾ https://www.i2am-paris.eu/detailed_model_doc/eu_times

⁽⁴²⁾ METIS, selected publications: <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-metis/references/>

⁽⁴³⁾ European Commission, Directorate-General for Energy, Torres Vega, P., Beaussant, O., De Vita, A. et al., *Technical support for RES policy development and implementation – Delivering on an increased ambition through energy system integration: Final report*, Publications Office, 2021. DOI 10.2833/86135.

⁽⁴⁴⁾ European Commission, Directorate-General for Energy, Joint Research Centre, Bossmann, T., Cornaggia, L., Vautrin, A. et al., *Assistance to assessing options improving market conditions for bio-methane and gas market rules – Final report*, Publications Office, 2021, DOI 10.2833/912333.

Engie Impact and used to define the future energy demand ⁽⁴⁵⁾ and follows a detailed bottom-up approach where the energy demand of each end-user is projected individually. The main categories of end-users are the transport, residential, industry and tertiary sectors.

2.1.2.3 FORECAST

The FORECAST modelling platform aims to develop long-term scenarios for future energy demand of individual countries and world regions until 2050. It is based on a bottom-up modelling approach considering the dynamics of technologies and socio-economic drivers. The model is owned by Fraunhofer ISI and allows to address various research questions related to energy demand including scenarios for the future demand of individual energy carriers like electricity or natural gas, calculating energy saving potentials and the impact on greenhouse gas (GHG) emissions as well as abatement cost curves and ex-ante policy impact assessments ⁽⁴⁶⁾. The model has been applied to a number of studies for the European Commission, Member States or private entities ⁽⁴⁷⁾. The industrial module of the FORECAST models is used in this exercise to address the impact of specific circular economy actions on the energy and CO₂ emissions of most energy-intensive industrial sectors.

2.1.2.4 JRC forest sector carbon model (FSCM)

The purpose of the JRC FSCM is to independently estimate the current and future forest carbon dynamics, both as a verification tool (i.e., to compare the results with the estimates provided by other models and/or Member States' GHG inventories) and to support to the EU legislation (e.g., the recent EU Regulations 2018/841 and 2023/839). The JRC FSCM ⁽⁴⁸⁾ is a state-of-the-art model containing two components: the forest carbon model (EU-CBM-HAT) ⁽⁴⁹⁾ and the harvested wood products (HWP) module. The EU-CBM-HAT is an inventory-based, yield and increment-curve-driven model, applying rules-based forest management and distribution of the harvest demands that simulates the stand- and landscape-level carbon dynamics of all forest carbon pools. The core of EU-CBM-HAT is the CBM-CFS3 model, which has been applied in this Impact Assessment to estimate the forest carbon dynamics both at EU and at the country level. The HWP module is plugged into EU-CBM-HAT outputs. This implements the 'production approach' based on IPCC instantaneous oxidation and default values, on the activity data submitted by the countries in the latest submission to

⁽⁴⁵⁾ ENGIE, *Trajectoires de décarbonation de l'Europe : le scénario ENGIE*, 2023. <https://www.engie.com/decarbonation-scenario-engie>

⁽⁴⁶⁾ Fleiter T., et al. 'A methodology for bottom-up modelling of energy transitions in the industry sector: the FORECAST model', *Energy Strategy Reviews*, Volume 22, 2018, pp 237-254.

⁽⁴⁷⁾ FORECAST, projects and selected publications: <https://www.forecast-model.eu/forecast-en/index.php>

⁽⁴⁸⁾ See: Pilli, R., Kull, S. J., Blujdea, V. N., & Grassi, G. (2018). The carbon Budget model of the Canadian forest sector (CBM-CFS3): customization of the archive index database for European Union countries. *Annals of forest science*, 75(3), 1-7.; Pilli, R., Alkama, R., Cescatti, A., Kurz, W. A., & Grassi, G. (2022). The European forest Carbon budget under future climate conditions and current management practices. *Biogeosciences*, 19(13), 3263-3284.; Pilli, R., Grassi, G., Kurz, W. A., Fiorese, G., & Cescatti, A. (2017). The European forest sector: past and future carbon budget and fluxes under different management scenarios. *Biogeosciences*, 14(9), 2387-2405.

⁽⁴⁹⁾ European Commission, Joint Research Centre, Blujdea, V., Rougieux, P., Pilli, R. et al., The JRC Forest Carbon Model – Description of EU-CBM-HAT, Publications Office of the European Union, 2022, <https://data.europa.eu/doi/10.2760/244051>

UNFCCC in 2023. The model has been used globally in numerous publications and research projects ⁽⁵⁰⁾.

2.2 Literature Review

In complement to the modelling work, the analysis makes use of an extensive review of relevant published papers and reports by the scientific community, private stakeholders or public entities. Whenever possible, projected numbers for the period 2030-2050 have been extracted and compared against the values obtained by the specific modelling exercise underpinning this impact assessment.

2.3 Historical data

2.3.1 Energy system in PRIMES

The modelling of the energy system has been calibrated on the 2023 edition of the Eurostat complete energy balances, which provide comprehensive energy balances up to 2021 for all EU Member States.

The associated CO₂ emissions are derived from these energy balances and the emission factors from the legislation on the monitoring and reporting of greenhouse gas emissions⁵¹. Calibration series allow to match emissions data from the 2023 GHG inventory.

2.3.2 Non-CO₂ emissions in GAINS

Activity data has been updated with statistics to reflect 2020 as a historical year. Calibration series allow to match emissions data from the 2023 GHG inventory.

2.3.3 LULUCF in GLOBIOM

Activity data on land use, agriculture and forestry has been updated based on historical data and are aligned with the UNFCCC 2023 inventory data, reflecting 2021 as a historical year.

In addition, the initial land cover map for the base year of the models was updated from the Corine Land Cover Version 2009 to the Corine Land Cover Accounting layer 2019.

2.4 Key Assumptions

2.4.1 Population and GDP

Broad socio-economic assumptions describing the expected evolution of the European economy underpin all models used in this impact assessment. In particular, long-term projections on population dynamics and economic activity are exogenous variables, ie. used as inputs into the energy model and to build the macro-economic baseline that underpins the assessment of the socio-economic impacts of the mitigation trajectories.

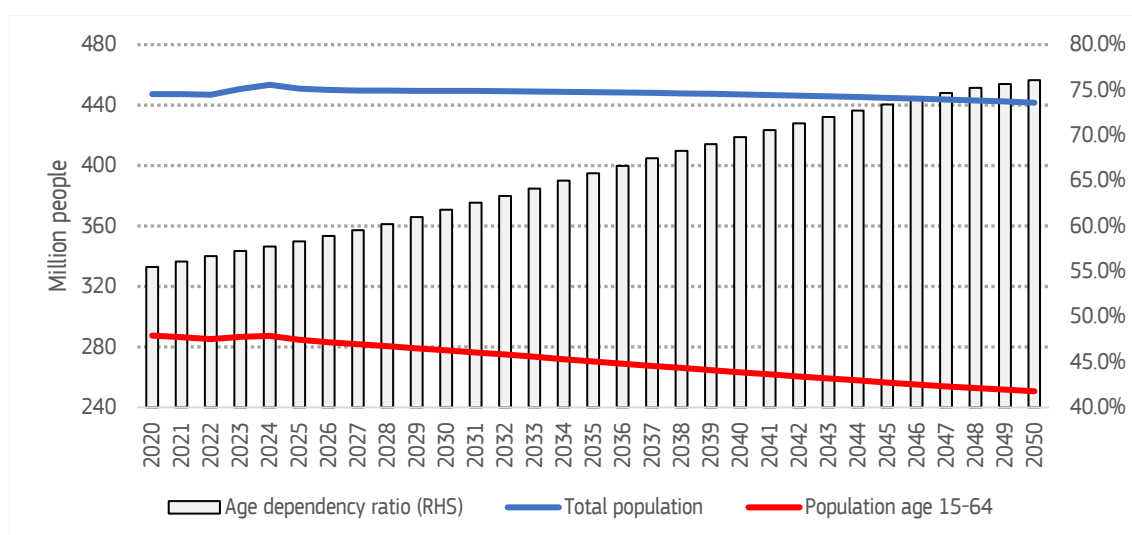
⁽⁵⁰⁾ For overview and selected publications:
<https://forest.jrc.ec.europa.eu/en/activities/forestbioeconomy/modelling/>

⁽⁵¹⁾ Commission Implementing Regulation (EU) 2018/2066 of 19 December 2018, Annex VI

Population projections rely on Eurostat’s long-term projections (EUROPOP2019) combined with the short-term update of the projected population for the period 2022-2032⁽⁵²⁾. The latter provides an update of the baseline long-term projection, together with two sensitivity tests to assess the impact of the flow of refugees from Ukraine. The population assumptions used here rely on Eurostat’s “very high number of refugees sensitivity test”, which assumes that the influx of refugees occurs during 2022 and 2023, and that it is followed by annual returns at a constant rate such that the remaining number of refugees at the end of 2031 amounts to 15% of the cumulated influx of refugees in 2022 and 2023. At EU level, this translates into an increase in total population of 2.6 million people (+0.6%) compared to the baseline. The increase is not evenly spread across Member States.

As of 2033, the population assumptions revert to EUROPOP2019 in terms of annual growth rates, though not in levels, in order to account for the increase in absolute numbers due to the inflow of refugees. The EU population is projected to remain broadly stable over the projection period to 2050. However, there is a noticeable trend towards the ageing of the population, with a 13% decline in the population aged 15 to 64 between 2020 and 2050 and an increase in the dependency ratio from 55.5% to 76.1% (Figure 2).

Figure 2: Population assumptions



Source: Eurostat

Economic projections have taken place in an unusually unstable context in the past few years, as the EU and world economies were hit first by the COVID pandemic and second by Russia’s war of aggression against Ukraine, with the ensuing sharp increase in international energy prices. The GDP projections for 2022-2024 rely on the Autumn Forecast⁽⁵³⁾ of the Directorate General for Economic and Financial Affairs (DG ECFIN). From 2025 onwards, the GDP growth projections converge to those prepared by DG ECFIN for the 2021 Ageing Report⁽⁵⁴⁾. The real GDP assumptions therefore integrate an update of short-term economic projections and revert to the growth rates used for the 2020 Reference Scenario and the

⁽⁵²⁾ EUROPOP2019 (proj_19n) and short-term update of the projected population (2022-2032) (proj_stp22), which was the latest available projection at the time the key assumptions were adopted as a framework for all models used in the impact assessment.

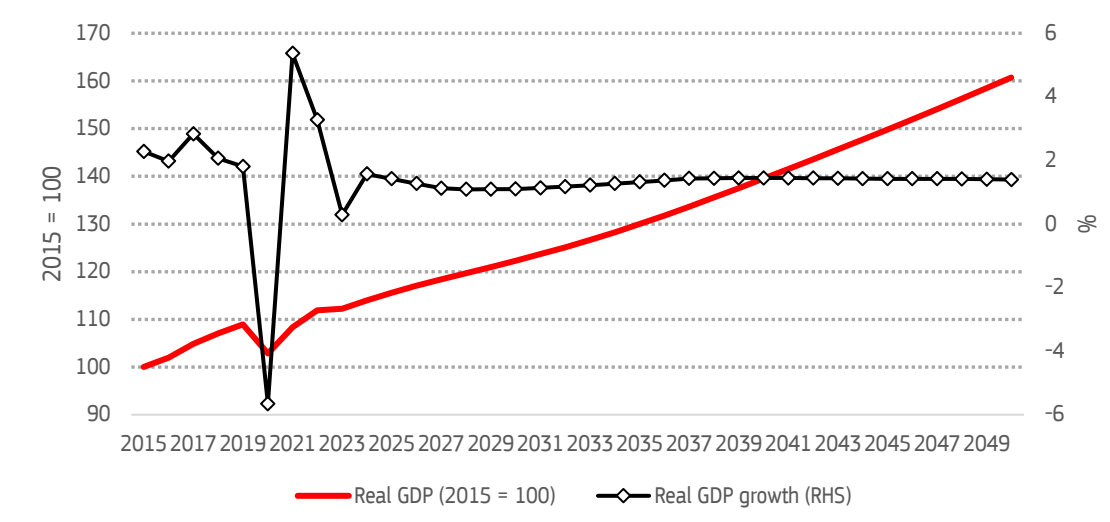
⁽⁵³⁾ DG ECFIN. Autumn 2022 Economic Forecast: The EU economy at a turning point.

⁽⁵⁴⁾ DG ECFIN. The 2021 Ageing Report: Underlying Assumptions and Projection Methodologies.

modelling of policy scenarios in the impact assessments backing the Fit for 55 legislative proposals. At EU level, real GDP is projected to be 40% higher in 2040 than in 2015, and 61% higher in 2050 compared to 2015 (Figure 3).

The short-term projections do not reflect DG ECFIN's Winter 2023 Economic Forecast as they became available after the cut off date of this exercise. The impact over the projection horizon is nevertheless minimal, as the difference in EU GDP is less than 1% in 2024 between the Winter 2023 forecast and the Autumn 2022 forecast and the COVID recession, the recovery and the slowdown in activity in 2022-2023 are fully captured.

Figure 3: EU GDP (2015 = 100) and GDP growth (%)



Source: DG ECFIN.

2.4.2 Sectoral economic activity

Projections on the sectoral composition of GDP were prepared using the GEM-E3 computable general economic model. It is projected that the EU economy will continue to become increasingly services-oriented, with the sector's share rising from close to 74% of total gross value added (GVA) in 2016-2020 to 75.5% in 2040 and 76.4% in 2050. While the share of the transport sector in total GVA declined significantly during the COVID pandemic, the projections assume that this was only a temporary phenomenon, and that the sector's share remains broadly constant at around 5% of the total. This is consistent with recent economic developments. The share of industry in total GVA is projected to decline from currently around 17% to around 16% by 2050. In absolute terms, however, industrial GVA is still projected to be 26% and 42% higher in 2040 and 2050 respectively compared to 2016-2020.

Energy intensive industries (iron and steel, non-ferrous metals, chemicals, non-metallic minerals and pulp and paper) currently represent less than 5% of total GVA in the EU economy. Their share is projected to decline by somewhat less than 1 percentage point by 2050, even though total output in these sectors is expected to continue growing, with GVA projected to be 25% higher in 2040 than on average in 2016-2020 and 37% higher in 2050. There are nevertheless some disparities within the energy intensive industries, with GVA in iron and steel and in non-ferrous metals expected to grow very moderately, while more sustained growth is expected in chemicals, pulp and paper and non-metallic minerals. In all cases, an increase in the GVA intensity of output is projected, together with an increase in the volume of production (with the exception of iron and steel).

In the construction sector, GVA is also projected to continue to grow, in part due to renovations, but at a slightly lower pace than total GVA, as the moderate decline in

population at EU level and ageing imply lower requirements for new constructions in the residential sector. Overall, the share of the construction sector in total GVA is projected to decline only marginally from around 5% of the total currently. In absolute terms, it is still projected to be 27% and 40% higher in 2040 and 2050, respectively, compared to 2016-2020.

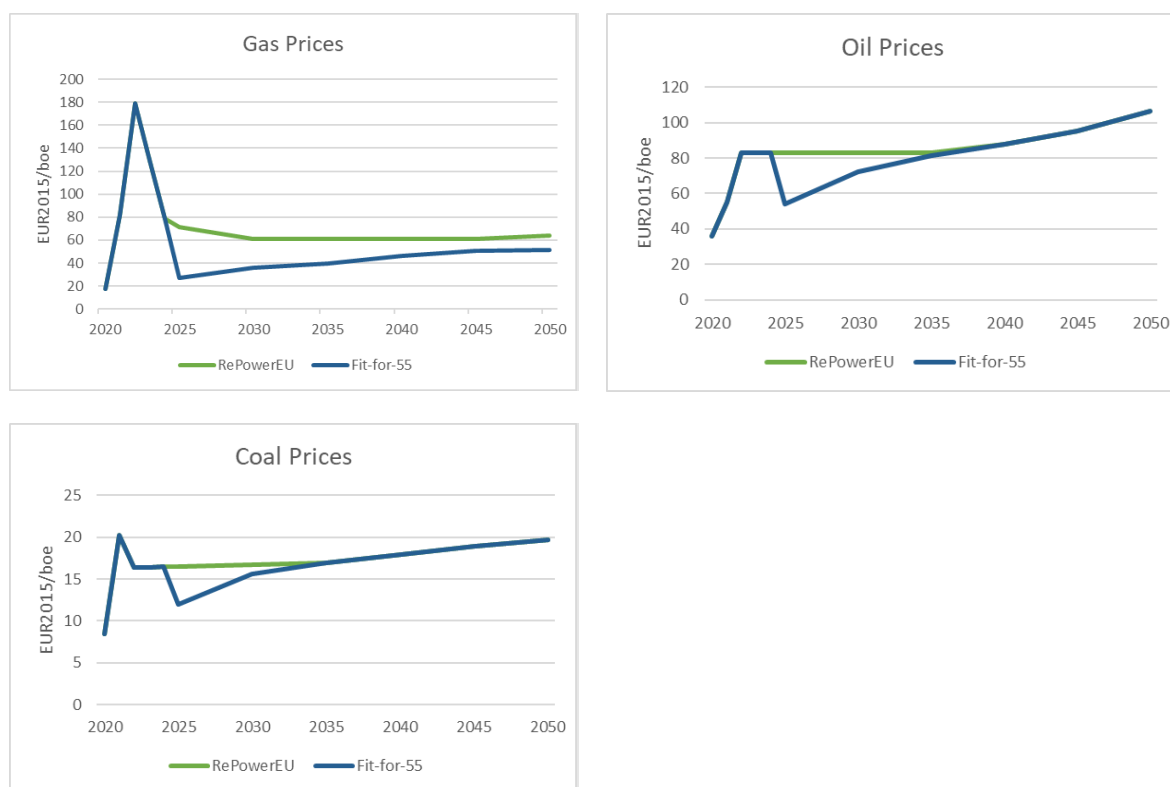
2.4.3 Energy Prices Trajectory between 2020 and 2050

Alongside socio-economic projections, EU energy modelling requires projections of international fuel prices. The trajectories for the price of gas, oil and coal are those presented in the Staff Working Document accompanying the REPowerEU plan ⁽⁵⁵⁾ (see Figure 4). The projections of the POLES-JRC model – elaborated by the Joint Research Centre in the context of the annual publication of the Global Energy and Climate Outlook – are used to obtain long-term estimates of the international fuel prices. These long-term projections are close to assumed in the EU Reference Scenario 2020. They show an increasing trend for fossil fuel prices in the long term due to depletion of conventional resources (that are replaced by more expensive unconventional ones).

The fuel price trajectories take also into account structural changes in supply and demand. In particular, the Russian invasion of Ukraine is expected to have long-term repercussions on gas price as pipeline supply is replaced by more expensive LNG. Following a short-term peak, gas price is assumed to remain higher than in the Fit-for-55-scenario in the long run. These market considerations are interpolated to the long-term trend to obtain the trajectories shown in Figure 4.

⁽⁵⁵⁾ SWD Implementing the REPowerEU Action Plan: investment needs, hydrogen accelerator and achieving the bio-methane targets, SWD(2022) 230 final.

Figure 4: International fuel prices



Source: REPower SWD⁽⁵⁵⁾

2.4.4 Technologies

The assumption on the development of technologies is an important driver of projections. Mapping existing, emerging and new technologies and their future cost and performance is crucial for better understanding the future evolution of GHG emissions.

For this impact assessment – and considering the rapidly changing context in the past few years – the technology assumptions of the main model suite have been updated with respect to those used in the Reference Scenario 2020 ⁽⁵⁶⁾. The update was based on a rigorous literature review carried out by external consultants in collaboration with the JRC. The most important updates are reported below while the assumptions are published in dedicated excel files for energy technologies, transport, non-CO2 and LULUCF.

The following chapter defines the list of technologies considered for this impact assessment, with their main characteristics including in particular their purchasing costs and level of efficiency.

2.4.4.1 Energy technologies

For each technology the modelling considers a range, ordered from a more common category to an advanced category. The technical and economic characteristics of each technology category change over time as a result of learning by doing and economies of scale in industrial production. Not all technology categories are considered as fully mature from a

⁽⁵⁶⁾ https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

user's perspective, but in general the users' acceptance of advanced technologies improves over time. Policy assumptions may drive acceleration of learning-by-doing and users' acceptance in the context of modelling a scenario. An advanced technology category is more efficient than an ordinary one and in general more expensive to purchase at a given point in time. However, depending on its learning potential, an advanced technology may, however, become cheaper than an ordinary technology in the long term.

Power and Heat

The technologies described in the models for the power sector include the main technologies for producing electricity from fossil fuels, nuclear fuel and renewables. The technology for producing heat include boilers for the main fuels (including biomethane) and heat pumps used in heat plants for both district heating and industry.

Compared to the Reference Scenario 2020, the segmentation of the solar PV market has been improved and several cost assumptions revised (with, in particular, a moderate increase in PV costs and a decrease in several heating technologies).

Domestic

It includes technologies for the buildings sector (residential and services). The values shown include ranges of purchasing costs (that refer to total acquisition costs) and efficiency by vintage (reference year of purchase), for several space and water heating technologies and appliances.

Compared to the Reference Scenario 2020, a distinction is made between air-to-air and air-to-water heat pumps. Their characteristics have been defined separately and their purchasing cost has been adapted in a post-energy crisis context. Given also the growing importance of self-consumption in the energy transition post-2030, small scale renewable technologies, such as PV, Hydrogen-based CHP, batteries and other storage solutions have been included in the list of available technologies.

Building renovation

Building renovation refers to average renovation costs by climate type and level of renovation, as used in the PRIMES buildings module. Four climate types are considered (Centre/West, North, South and East) and three levels of renovation (light, medium and deep), differentiating when renovation occurs in windows, including walls, roof and basement. The energy savings rate refers to a reference building⁽⁵⁷⁾ as in the current stock of existing buildings, not to savings in new constructions, which follow the buildings codes' insulation standards. Investment costs, both in Euro per household and Euro per square meter, defines the energy related expenditures needed to implement the indicated level of renovation of a building, (excluding usual renovation expenditures needed for other purposes: structure, finishing materials, decoration ...). Renovation costs are unchanged compared to those used in the Reference Scenario 2020.

Industry

⁽⁵⁷⁾ The model includes several house types, house ages and geographical categories. The reference building aggregate all these categories in a single item.

The main assumptions described are investment costs, the level of learning by doing, and the energy efficiency index for technologies used in the industrial sector. As for the domestic sector, the model considers, for each technology, seven categories ordered from an ordinary up to an advanced and a future category. Efficiency is expressed as an index compared to 2015 and an increase in its rate implies a more efficient technology. No significant update was necessary compared to the assumption used in the Reference Scenario 2020.

Industrial carbon management

Industrial carbon management technologies have gained momentum in recent years with expectations of decreasing cost-curves and new projects ⁽⁵⁸⁾ and are thus integrated in the model assumptions. These technologies are defined mainly as Bioenergy with Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS), which capture fossil-fuel free carbon and store it permanently either underground or in materials. Biogenic carbon that is captured and stored during the upgrading of biogas into biomethane is also included in the modelling and the three technologies are differentiated across scenarios according to level and timeline of uptake. Biochar is not represented, as it is assumed that all products resulting from pyrolysis of biomass during production of biofuels is under gaseous form and subsequently captured. Other removal technologies are not considered in the analysis.

Renewable hydrogen, e-fuels and storage

Technologies for the production, transmission, and distribution of e-fuels (including renewable hydrogen), as well as storage technologies, are included in this impact assessment. For each technology, the following items are listed: Investment costs, Fixed Operation and Maintenance costs, Heat rate (ratio of energy input requirements over output), “Feedstock input requirements” (feedstock input required to produce one unit of output from each technology) and technical lifetime. Given the progress made in the development of these fuels in recent years, an updated set of Reference Scenario assumptions has been employed.

Biofuels and biogases

The list of biofuels and biogases available in the model includes all the liquid and gaseous biomass-based energy technologies addressed by European policies. The model includes different pathways to produce liquid and gaseous bioenergy from starch, sugar and oil crops, as well as bioenergy from lignocellulosic biomass and algae based on biochemical and thermochemical conversion processes. Regarding biogases, different processes are described to produce biogas and biomethane from different feedstocks. For each technology and pathway, the model contains detailed technical information including investment costs, fixed operation and maintenance costs, lifetime, energy consumption factors and self-consumption factors.

Transport technologies

The assumptions on transport technologies cover all transport modes, including passenger cars, vans, trucks, buses, coaches, powered 2-wheelers, rail, inland waterways, shipping and aviation. The assumptions describe the evolution of the investment costs of the various

⁽⁵⁸⁾ IEA (2021). Is carbon capture too expensive?, IEA, Paris <https://www.iea.org/commentaries/is-carbon-capture-too-expensive>

technologies until 2050 in 10-year time steps, and they are presented similarly for each mode and technology: multiple efficiency improvement levels are available at different costs, for each mode, each type of technology, and each time period. The efficiency improvements are compared against a 2015 reference vehicle.

Present and future costs of technologies are based on a literature review. The costs of the efficiency improvement options are assumed to improve over time, due to learning effects for example. Compared to the assumptions made in the Reference Scenario 2020, the segmentation of aircraft and Heavy-Duty Vehicle technologies has been improved, and several cost assumptions have been revised based on more recent estimates (for instance, this is the case for various vessel and aircraft technologies, as well as re-charging and re-fuelling infrastructure).

2.4.4.2 Mitigation of non-CO₂ GHG emissions

The assumptions used in the modelling of non-CO₂ greenhouse gases in the GAINS model have been updated from those employed in the Reference Scenario 2020. This update benefitted from a dedicated consultation workshop held on 27 October 2022.

Emission factors, mitigation potentials and cost information of mitigation options have been updated to the extent possible using newly available information.

Furthermore, the methodology to estimate CH₄ emissions from gas distribution networks has been further developed to reflect the impact of network material on leakage rates. Country-specific information from EUROSTAT (2022) and national sources on the length of networks from cast iron, steel, PE/PVC, and other materials, respectively, was coupled with measurement information on average leakage rates for respective materials, and calibrated to emissions from gas distribution networks reported to the UNFCCC.

New non-CO₂ source sectors introduced are fugitive CH₄ emissions from LNG import terminals and CH₄ and N₂O emissions from the use of bunker fuels in international shipping. Mitigation options targeting enteric methane from livestock were revisited to reflect the latest state of knowledge, e.g., regarding the effectiveness and costs of feed additives 3-NOP and red seaweed.

The vintage structure of wastewater treatment plants has been updated to better reflect country-specific age structures of existing plants. This is important for the estimation of costs as a shift to less emission-intensive technology is considerably less expensive when implemented as part of a natural turnover of capital at the end of the plant lifetime than when implemented pre-maturely.

2.4.4.3 LULUCF sector

The modelling of the LULUCF sector with GLOBIOM/G4M has been updated from that used in the Reference Scenario 2020. This update benefitted from a dedicated consultation workshop held on 27 October 2022.

Mid-term projections have been aligned with projections from the AGLINK model completed for the EU Agricultural Outlook 2022, which is assumed to reflect the Common Agricultural Policy at the time of publication.

As a new mitigation measure, rewetting of drained organic soils has been implemented in the modelling framework, relying on data from the UNFCCC 2023 inventory, the IPCC wetlands

supplement ⁽⁵⁹⁾ and spatial explicit areas presented by the CAPRI model ⁽⁶⁰⁾ (Fellmann et al., 2021).

Future climate change impacts on the agricultural and forest sectors have been estimated based on CMIP6 data and subsequently implemented in GLOBIOM and G4M. The options comprise scenarios from four climate models and three RCP scenarios, both with and without CO₂ fertilization effects. In addition, first steps have been taken towards the integration of natural disturbances are done for the forest sector.

Furthermore, an update of the mitigation potentials of improving management of degraded grasslands has been completed in GLOBIOM. An explicit representation of protected, primary and likely-old-growth forests with a possibility of simulating different forest management for the forests has been implemented in G4M.

2.4.5 Bioenergy potential

The analysis assumes a cap on the amount of the “gross available energy”⁽⁶¹⁾ from biomass and waste at the level indicated by the ESABCC as the environmental risk level associated “primary bioenergy use” (9 EJ)⁽⁶²⁾ in order to limit possible impacts on land-use and the environment ⁽⁶³⁾. Furthermore, a restriction on the use of harvestable stemwood and forest residues is implemented based on the scientific literature related to biodiversity and sustainable wood biomass use ⁽⁶⁴⁾: all scenarios assume a cap on bioenergy from harvestable stemwood (30 Mtoe) and from forest residues (20 Mtoe) ⁽⁶⁵⁾. The net imports of bioenergy are capped at levels close to recent historical levels of around 10 Mtoe.

⁽⁵⁹⁾ IPCC 2014, 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds). Published: IPCC, Switzerland.

⁽⁶⁰⁾ Fellmann, Thomas, et al. (2021). "Greenhouse gas mitigation technologies in agriculture: Regional circumstances and interactions determine cost-effectiveness." *Journal of Cleaner Production* 317 (2021): 128406.

⁽⁶¹⁾ Gross available energy means the overall supply of energy for all activities in the EU, including for use in international aviation and international maritime bunkers, and including net imports.

⁽⁶²⁾ ESABCC (2023), Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. Table 6.

⁽⁶³⁾ Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

⁽⁶⁴⁾ Creutzig, F. et al., 2015; JRC, Biomass production, supply, uses and flows in the European Union, Policy Report, 2023; Verkerk et al. 2019; Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo Cano, J.I. and Mubareka, S., The use of woody biomass for energy production in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27867-2, doi:10.2760/831621, JRC122719.

⁽⁶⁵⁾ Historical levels from 2015 show biomass supply for bioenergy from harvestable stemwood of around 25 Mtoe and from forest residues of around 15 Mtoe.

2.5 Policies

2.5.1 EU policies

This section describes the elements of the EU legislative framework that have been considered in the modelling analysis.

2.5.1.1 Climate legislation

The European Climate Law ⁽⁶⁶⁾ enshrines into law the EU's commitment to become climate neutral by 2050, thereby providing a clear direction of travel for the transition. Furthermore, it expresses the EU's commitment to reduce net GHG emissions by at least 55% in 2030 relative to 1990, as the European contribution to the achievement of the Paris Agreement goals. As an essential part of the European Green Deal, the "Fit for 55" legislative package established the policy framework to meet the 2030 climate target, ensuring a just and socially fair transition, while strengthening innovation, preserving the competitiveness of EU industry and promoting a more efficient use of our natural resources.

The revised EU ETS Directive ⁽⁶⁷⁾ increases the ambition of the existing ETS emissions reduction target from 43% to 62% by 2030, compared to 2005 levels, strengthening the carbon price signal for power, centralised heat, industry and intra-EU aviation. The ETS scope is extended to maritime transport ⁽⁶⁸⁾, and the global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will be implemented through the EU ETS ⁽⁶⁹⁾. The Carbon Border Adjustment Mechanism (CBAM) ⁽⁷⁰⁾ should ensure that the emissions reduction efforts of the EU are not offset by increasing emissions outside its borders through the relocation of production to non-EU countries or through increased imports of carbon-intensive products.

⁽⁶⁶⁾ Regulation (EU) 2021/1119.

⁽⁶⁷⁾ Directive 2003/87/EC, as amended notably by Directive 2008/101/EC, Decision (EU) 2015/1814, Regulation (EU) 2017/2392, Directive 2018/410, Regulation (EU) 2023/435, Directive (EU) 2023/958 and Directive (EU) 2023/959.

⁽⁶⁸⁾ Including CO₂ emissions and, from 2026, CH₄ and N₂O emissions. The ETS covers all emissions that occur at berth and within an EU port, all emissions produced during voyages between EU ports (as defined by the MRV Regulation), and 50% of the emissions produced during voyages between an EU port and a non-EU port.

⁽⁶⁹⁾ Other important features of the revision of the ETS Directive include: (i) tightening of the ETS cap with a two-step rebasing and an increasing linear reduction factor; (ii) updating the parameters of the Market Stability Reserve including an extension of the intake rate of 24% until 2030; (iii) an obligation for the Member States to spend the entirety of their emissions trading revenues on climate and energy-related projects and to address social aspects of the transition; (iv) increasing the sizes of the Innovation Fund and the Modernisation Fund; (v) phasing out gradually free allocation in the sectors covered by the new Carbon Border Adjustment Mechanism over the period 2026-2034; (vi) requiring that installations benefitting from free allocation, to avoid losing 20% of their free allocation, implement energy efficiency measures and establish and implement a climate neutrality plan in the case of worst performing industrial emitters; (vii) strengthening the rules on market transparency and making the mechanism in the event of excessive price fluctuations automatic and more reactive; (viii) a requirement for the Commission to report by 31 July 2026 on the feasibility of including municipal waste incineration installations in the EU ETS from 2028 onwards.

⁽⁷⁰⁾ Regulation (EU) 2023/956.

A separate emissions trading system (ETS2) will apply from 2027 onwards to combustion fuels in road transport and buildings and additional sectors ⁽⁷¹⁾, further incentivising and ensuring an emission reduction of 42% compared to 2005 in the sectors covered. With the extension to new sectors, around 75% of total EU emissions will be subject to carbon pricing, making the ETS a crucial instrument to achieve the 2030 target.

The revised Effort Sharing Regulation (ESR) ⁽⁷²⁾ increases the EU greenhouse gas emission reduction target from 30% to 40% by 2030, compared to 2005, for the sectors covered (i.e., all sectors not covered by the ETS, excluding the LULUCF sector).

The new LULUCF Regulation ⁽⁷³⁾ sets an overall EU-level objective of 310 Mt CO₂-eq of net removals of greenhouse gases in the LULUCF sector in 2030. Binding national targets are defined for each member state. The proposed EU-wide voluntary framework to reliably certify high-quality carbon removals will boost innovative carbon removal technologies and sustainable carbon farming solutions. Tackling climate change and ensuring healthy and biodiverse ecosystems are intrinsically linked. Natural sinks are of crucial importance to capture and store carbon. The new law to restore ecosystems such as wetlands and forests (i.e., the Nature Restoration Law) will make an important contribution to maintaining, managing and enhancing natural sinks and to increasing biodiversity while fighting climate change.

The CO₂ emission performance standards for new passenger cars and new light commercial vehicles were revised and strengthened in line with the EU's increased climate ambition ⁽⁷⁴⁾, notably through setting a target to reduce CO₂ emissions by 55% for new cars and by 50% for new vans from 2030 to 2034 compared to 2021 levels, and a 100% reduction target from 2035 onwards. In February 2023, the European Commission proposed a more ambitious emission reduction target for heavy duty vehicles (i.e., lorries, buses, coaches and trailers) through updated CO₂ performance standards ⁽⁷⁵⁾. If adopted, the proposal would reduce CO₂ emissions per km from new heavy-duty vehicles by 90% by 2040, compared to the reference period (July 2019 to June 2020). In addition, the proposal would ensure that all new city buses are zero-emission vehicles as of 2030.

2.5.1.2 Energy legislation

For energy it includes the revised Renewable Energy Directive ⁽⁷⁶⁾ which sets a binding target of at least 42.5% of renewable energy share in the energy mix in 2030. It includes a binding sub-target for renewable hydrogen which requires 42% of hydrogen consumed in industry to come from renewable fuels of non-biological origin (RFNBOs). In the transport sector, the RED III regulatory framework includes the possibility for Member States to choose between a new binding target of 14.5% reduction of greenhouse gas intensity in transport from the use of renewables by 2030 or a binding target of at least 29% share of renewables within the final

⁽⁷¹⁾ That is to say, CO₂ emissions from fuel combustion in industry not covered by the existing EU ETS.

⁽⁷²⁾ Regulation (EU) 2018/842, as amended by Regulation (EU) 2023/857.

⁽⁷³⁾ Regulation (EU) 2018/841, as amended by Regulation (EU) 2023/839.

⁽⁷⁴⁾ Regulation (EU) 2019/631, as amended by Regulation (EU) 2023/851.

⁽⁷⁵⁾ COM (2023) 88 final.

⁽⁷⁶⁾ Directive EU/2018/2001, as amended by Directive (EU) 2023/2413.

consumption of energy in the transport sector by 2030. Further, it includes a binding sub-target of 5.5% for advanced biofuels and RFNBO, including a minimum binding 1% level for RFNBO. In the heating and cooling sector, the Directive introduces a mandatory annual increase of the renewables share, namely 0.8 pp between 2021 and 2025, and 1.1 pp between 2026 and 2030.

It also includes the recast of the Energy Efficiency Directive (EED recast) ⁽⁷⁷⁾. The Directive significantly raises the EU's ambition, by making it binding for EU countries to collectively achieve an additional 11.7% reduction of final energy consumption (FEC) by 2030 compared to the projections of the 2020 EU Reference Scenario so that the Union's final energy consumption amounts to no more than 763 Mtoe. Member States shall make efforts to collectively contribute to the indicative Union primary energy consumption (PEC) target amounting to no more than 992,5 Mtoe in 2030.

In addition, in Article 8 of the EED recast, an annual energy savings obligation has been set, with new savings each year of 1.49% of FEC on average, from 2024 to 2030. Articles 25-26 of the EED recast set targets and pathways for the heating and cooling technologies that can be installed or supported. Article 5 in the EED recast asks Member States to ensure that the total final energy consumption of all public bodies combined is reduced by at least 1.9% each year, when compared to 2021.

The proposal ⁽⁷⁸⁾ for a revised Energy Performance of Buildings Directive (EPBD) ⁽⁷⁹⁾ encourages the continuous improvement of the energy performance of the national building stock through renovation, contributing to the long-term goal of a decarbonised building stock by 2050. It includes measures for both existing and new buildings. Minimum Energy Performance Standards (MEPS) trigger the energy efficient renovation of the worst performing part of the existing building stock by mandating them to meet gradually improving energy performances. The Zero-Emission Buildings provision – replacing the current provision for nearly-zero energy buildings – requires that as of 2027 and 2030 new public buildings and all new buildings respectively must be zero-emission buildings. “Zero-Emission Building” refers to a building with a very high energy performance, where the very small residual energy requirement is covered by regulated renewable energy or district heating and cooling systems. Additionally, the EPBD proposal introduces notable new provisions on national voluntary building renovation passport schemes, on rooftop solar energy, on revision of the energy performance certificates, on the introduction of national energy performance databases and on e-mobility.

The “Hydrogen and Gas Markets Decarbonisation” package ⁽⁸⁰⁾ should help to decarbonise the EU gas market by facilitating the uptake of renewable and low carbon gases, including hydrogen.

⁽⁷⁷⁾ Directive (EU) 2023/1791 (recast).

⁽⁷⁸⁾ COM(2021) 802 final.

⁽⁷⁹⁾ Directive 2010/31/EU, as amended by Directive (EU) 2018/844.

⁽⁸⁰⁾ Proposal for a directive (COM(2021) 803 final) and Proposal for a regulation (COM(2021) 804 final).

2.5.1.3 Transport policy

To complement the legislation on CO₂ standards for vehicles, the Alternative Fuels Infrastructure Regulation (AFIR) ⁽⁸¹⁾ will ensure the supply of systems for re-charging and re-fuelling zero-emission vehicles, ships and planes.

The ReFuelEU Aviation Regulation (ReFuelEU Aviation) ⁽⁸²⁾ aims to increase both demand for and supply of sustainable aviation fuels (SAF), which are one of the key short- and medium-term tools for decarbonising aviation. It should provide a way out of the situation which is hindering their development: low supply and prices that are still much higher than fossil fuels. ReFuelEU Aviation includes the obligation for aviation fuel suppliers to ensure that all fuel made available to aircraft operators at EU airports contains a minimum share of SAF from 2025 and, from 2030, a minimum share of synthetic fuels, with both shares increasing progressively until 2050. In addition, this regulation establishes the obligation for aircraft operators to ensure that the yearly quantity of aviation fuel uplifted at a given EU airport is at least 90% of the yearly aviation fuel required, to avoid emissions related to extra weight caused by tankering practices.

The FuelEU Maritime Regulation ⁽⁸³⁾ aims to increase the demand for and consistent use of renewable and low-carbon fuels and reduce the greenhouse gas emissions from the shipping sector. To this end, this regulation includes measures to ensure that the greenhouse gas intensity of fuels used by the shipping sector will gradually decrease over time, by 2% in 2025 to as much as 80% in 2050 (compared to the reference value of 91,16 g CO₂-eq/MJ), and a special incentive regime to support the uptake of the so-called renewable fuels of non biological origin (RFNBO) with a high decarbonisation potential. The regulation also includes an obligation for passenger ships and containerships to use on-shore power supply for all electricity needs while moored at the quayside in major EU ports as of 2030.

The European Commission's Sustainable and Smart Mobility Strategy and Action Plan ⁽⁸⁴⁾ outlines several milestones that are assumed to be met in the modelling analysis, particularly the following ones: a) increase of rail freight traffic by 50% in 2030 and by 100% in 2050 relative to 2015; b) increase of high-speed rail traffic by 100% in 2030 and by 200% in 2050 relative to 2015; and c) increase of transport activity by inland waterways and short-sea shipping (taken together) by 25% in 2030 and by 50% in 2050 compared to 2015.

To support the transition to a cleaner, greener and smarter mobility in line with the European Green Deal and the Sustainable and Smart Mobility Strategy, the Commission proposed in 2021 ⁽⁸⁵⁾ to revise the TEN-T Regulation of 2013. It aims at reaching four main objectives: to make transport greener and more efficient; to facilitate seamless transport, fostering multimodality and interoperability between transport modes and better integrating the urban nodes; to increase the resilience of TEN-T to climate change and other natural hazards; and to improve the efficiency of the TEN-T governance tools. The objective is to facilitate that more people take the train, and more goods are transported by rail, inland waterways, and short sea

⁽⁸¹⁾ Regulation (EU) 2023/1804.

⁽⁸²⁾ Regulation (EU) 2023/2405.

⁽⁸³⁾ Regulation (EU) 2023/1805.

⁽⁸⁴⁾ COM (2020) 789 final.

⁽⁸⁵⁾ COM (2021) 812 final.

shipping. To address the missing links and modernise the entire network, quality standards should be improved. For this, major TEN-T passenger rail lines will allow trains to travel at 160 km/h or faster by 2040. Canals and rivers must ensure good navigation conditions for a minimum number of days per year. Trans-shipment terminals should be improved, and piggy-back services should be possible on the TEN-T's rail network. All major cities should develop sustainable urban action plans to promote zero-emission mobility. In addition to the core and the comprehensive network, an extended core network will be introduced which should be completed by 2040. The core network corridors should be merged with the rail freight corridors to become European Transport Corridors. In 2021, the Commission also proposed to update the the ITS Directive ⁽⁸⁶⁾, and the Action Plan to boost long-distance and cross-border passenger rail ⁽⁸⁷⁾.

In addition, in July 2023 the Commission proposed the Greening transport package ⁽⁸⁸⁾ including a proposal to increase the use of railway infrastructure capacity in the Single European railway area, a proposal to revise the rules on weights and dimensions of heavy-duty vehicles to enable (among other ambitions) the uptake of zero-emission vehicles, a proposal on the accounting of the GHG emissions of transport services (CountEmissioEU), and the revision of the Combined Transport Directive ⁽⁸⁹⁾. The first initiative includes measures to better manage and coordinate international rail traffic. It is expected to increase the passenger and freight rail capacity and punctuality, thus increasing the modal share of rail transport. Secondly, the revision of the Combined Transport Directive incentivises the use of intermodal freight transport through economic support to compensate for the price gap between road-only and intermodal transport. It is expected to increase the modal share of rail transport, inland waterway transport and short sea shipping. Thirdly, the CountEmissions EU initiative will define rules for WTW GHG emissions accounting at the transport service level. It will be based on a common methodology recently defined at global level (ISO 14083). The emissions accounting at service level will not be mandatory but, if operators decide to calculate emissions, they will have to do it according to CountEmissions EU. The impact is expected to be a limited increase of the modal share of passenger and freight rail transport at the expense of air and road transport. Finally, the revision of the Weights and Dimensions Directive (WDD) provides for increasing the maximum gross vehicle weight (GVW) of new zero-emission heavy goods vehicles by a maximum of 2 tonnes and the maximum length of the vehicle combination by up to 90 cm. The weight allowance for zero-emission heavy goods vehicles also applies to 2-axle rigid buses. The purpose of this measure is to compensate for the weight and the size of zero-emission powertrains (i.e., weight of electric batteries and space for hydrogen tanks) thus preventing the loss of payload capacity and/or range in comparison with diesel vehicles. In addition, the revised WDD incentivizes the shift from road-only to intermodal transport operations by allowing for extra height to accommodate high-cube containers in intermodal transport and by aligning the definition of intermodal transport with the Combined Transport Directive, to include all intermodal loading units.

⁽⁸⁶⁾ Directive 2010/40/EU, as amended by Directive (EU) 2023/2661.

⁽⁸⁷⁾ COM (2021) 810.

⁽⁸⁸⁾ Proposal for a Regulation on the use of railway infrastructure capacity in the single European railway area (COM (2023) 443), Proposal for a Revision of the Weights and Dimensions Directive (COM (2023) 445), and Proposal for a Regulation on the accounting of greenhouse gas emissions of transport services (COM (2023) 441)

⁽⁸⁹⁾ Directive 92/106/EEC.

The International Maritime Organisation (IMO) adopted in July 2023 the “2023 IMO Strategy on Reduction of GHG Emissions from Ships”, with enhanced targets to tackle harmful emissions. The revised IMO GHG Strategy includes an enhanced common ambition to peak GHG emissions from international shipping as soon as possible and to reach net-zero GHG emissions by or around, i.e., close to 2050, taking into account different national circumstances, whilst pursuing efforts towards phasing out the emissions, consistently with the long-term temperature goal set out in Article 2 of the Paris Agreement. Indicative checkpoints were also defined, specifying the targets to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008; and to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008.

2.5.1.4 Energy Taxation

The proposal for a revised Energy Taxation Directive⁽⁹⁰⁾, which regulates the taxation of energy products and electricity, aims to: a) align the taxation of energy products and electricity with the EU's energy, environment and climate policies; b) preserve and improve the EU internal market by updating the scope of energy products and the structure of rates and by rationalising the use of tax exemptions and reductions by member states; and c) preserve the capacity to generate revenues for the budgets of the member states.

2.5.1.5 Legislation relevant for non-CO2 emissions

The proposal for a “Regulation on methane emissions reduction in the energy sector”⁽⁹¹⁾ aims to track and reduce methane emissions in the energy sector. This is a crucial contribution to climate action, as methane is the second most important greenhouse gas following carbon dioxide. The proposal introduces new requirements for the oil, gas and coal sectors to measure, report and verify methane emissions (MRV) at the highest standard. Operators will need to carefully document all wells and mines, trace their emissions and take appropriate mitigation measures to prevent and minimise methane emissions in their operations. Under the new rules, operators will have to detect and repair methane leaks. Operators will need to carry out surveys of methane leaks in different types of infrastructures at set intervals, using devices with proposed minimum leak detection limits. Operators will then need to repair or replace all leaking components above certain levels immediately after detection, and no later than five days for a first attempt and 30 days for a complete repair. The operators will have to prioritise repairs of larger leaks. Venting and flaring practices, which release methane into the atmosphere, will be banned except for narrowly defined exceptional circumstances.

The proposals to revise the “Fluorinated Greenhouse Gas (F-gas) Regulation” and the “Ozone Depleting Substances (ODS) Regulation”, presented by the European Commission in April 2022, aim at further reducing the emissions from these highly potent, human-made greenhouse gases. The legislative proposal⁽⁹²⁾ to update the “F-gas Regulation”⁽⁹³⁾ aligns this regulation with the European Green Deal, the European Climate Law, recent international obligations on HFCs under the Montreal Protocol, and progress made and lessons learned.

⁽⁹⁰⁾ COM (2021) 563 final.

⁽⁹¹⁾ COM (2021) 805 final.

⁽⁹²⁾ COM (2022) 150 final.

⁽⁹³⁾ Regulation (EU) No 517/2014.

The review is intended, in particular, to deliver higher ambition (e.g., through a tighter quota system for HFCs and new restrictions on the use of certain F-gases in equipment), ensure compliance with the Montreal Protocol's requirements, improve enforcement and implementation, and achieve more comprehensive monitoring. The proposal ⁽⁹⁴⁾ to revise the "ODS Regulation" ⁽⁹⁵⁾ addresses the need to achieve a higher level of emission reduction in view of the European Green Deal, improve the efficiency of some measures in the regulation, ensure more comprehensive monitoring, and improve the coherence of the regulation with other rules. The proposal would prevent climate-relevant and ozone-depleting emissions from insulation foams during renovation or demolition activities.

EU legislation on the landfill of waste ⁽⁹⁶⁾ limits the type of waste that can be landfilled, encourages recycling and promotes the recovery of landfill gas. More specifically, it introduces restrictions on landfilling of all waste that is suitable for recycling or other material or energy recovery from 2030, and it limits the share of municipal waste landfilled to 10% by 2035. In addition, it establishes rules for the mitigation and monitoring of landfill gas, and it defines targets for the reduction of biodegradable municipal waste going to landfills, thus reducing the source of landfill gas in the first place. Furthermore, the Waste Framework Directive ⁽⁹⁷⁾ establishes targets for the separate collection of different waste types (to increase recycling and reuse of materials), as well as targets for food waste reduction.

The Urban Wastewater Treatment Directive (UWWTD) in force since 1991 ⁽⁹⁸⁾ requires: the collection and treatment of wastewater in all urban areas of more than 2000 people; secondary treatment of all discharges from urban areas of more than 2000 people, and more advanced treatment for urban areas of more than 10000 people in catchments with sensitive waters; pre-authorisation of all urban wastewater discharges, discharges from the food-processing industry and industrial discharges into urban wastewater collection systems; monitoring of the performance of treatment plants and receiving waters; controls of sewage sludge disposal and reuse, and treated wastewater reuse whenever it is appropriate. In October 2022, the Commission proposed a revision of this Directive ⁽⁹⁹⁾, adapting it to the newest standards. The revision aims to: reduce pollution, energy use and greenhouse gas emissions; improve water quality by addressing remaining urban wastewater pollution; improve access to sanitation especially for the most vulnerable and marginalised; make industry pay to treat micropollutants; require EU countries to monitor pathogens in wastewater; and lead to a more circular sector.

The Industrial Emissions Directive (IED) ⁽¹⁰⁰⁾ is the main EU instrument regulating pollutant emissions from industrial installations. In 2022, the Commission adopted a proposal to revise the IED ⁽¹⁰¹⁾. One of the most relevant elements is that the revised Directive would cover additional intensive farming and industrial activities, ensuring that sectors with significant

⁽⁹⁴⁾ COM (2022) 151 final.

⁽⁹⁵⁾ Regulation (EC) 1005/2009.

⁽⁹⁶⁾ Directive 1999/31/EC, as amended by Directive (EU) 2018/850.

⁽⁹⁷⁾ Directive 2008/98/EC.

⁽⁹⁸⁾ Council Directive 91/271/EEC.

⁽⁹⁹⁾ COM (2022) 541 final.

⁽¹⁰⁰⁾ Directive 2010/75/EU.

⁽¹⁰¹⁾ COM (2022) 156 final/3.

potential for high resource use or pollution also curb environmental damage at source by applying Best Available Techniques.

2.5.1.6 Carbon capture and storage

Several barriers still exist today to the development of the carbon capture and storage technology. The public consultation highlighted that main factors hindering the development of carbon capture (in association with storage) are cost of CCS, price signal, CO₂ storage availability and maturity of technology. Academic stakeholders as well as civil society organisations rank price signals as the most difficult barrier, while business associations, companies (including SMEs), EU citizens and public authorities rank cost as first.

To overcome these barriers and trigger a carbon capture and storage industry, the European Commission has proposed in the Net-Zero Industry Act an annual injection capacity of at least 50 million tonnes of CO₂ to be achieved by 2030⁽¹⁰²⁾. This target is supported by several CO₂ storage projects that are currently in different stages of the exploration and permitting process in the EEA.

To encourage the development of carbon industry, encompassing all capture and industrial removals technologies, sources, applications and corresponding value chains, the “Industrial Carbon management Strategy” aims at creating an industrial carbon management market by 2030 to support efforts in hard-to-abate sectors who need to apply carbon capture and storage, carbon capture and utilisation or industrial carbon removals to become climate neutral.

2.5.2 National Developments

2.5.2.1 Long Term Strategies and National Energy and Climate Plans

The Governance of the Energy Union and Climate Action (‘Governance Regulation’)⁽¹⁰³⁾ requires EU Member States to communicate and implement integrated National Energy and Climate Plans (NECPs) and to regularly report on their progress in implementing them, and to submit Long-term strategies (LTS). NECPs are ten-year plans outlining a path to achieve the Member States’ objectives, targets and contributions in five dimensions: decarbonisation (greenhouse gas reduction and renewables), energy efficiency, energy security, internal energy market and research, innovation and competitiveness. The NECPs for the period from 2021 to 2030 were submitted by 31 December 2019, and updates are to be submitted by 30 June 2024.

By 15 March 2023, and every two years, Member States need to take stock of the progress achieved towards the objectives, targets and contributions set out in their initial plans and submit it to the Commission as National Energy and Climate Progress Report (NECPR). Eight Member States submitted a full progress report by the 15 March deadline, and ten more submitted their progress report relatively close to the deadline. As of 24 August 2023, all Member States submitted their NECPRs and only 4 of the submissions are still partial.

The policies and measures at national level included in the analysis are largely based on the ones implemented during the modelling of the EU Reference Scenario 2020, which reflects

⁽¹⁰²⁾ COM (2023) 161 final.

⁽¹⁰³⁾ Regulation (EU) 2018/1999.

the first version of the NECPs (submitted in 2019). Furthermore, this Impact Assessment takes into consideration LTS updates as of 1st February 2023 ⁽¹⁰⁴⁾, and benchmarks, to the extent possible, 2021 and, whenever available, 2023 projections for GHG emissions reported in NECPRs.

Beyond long-term strategies and NECPRs, specific items concerning announced national policies have also implemented and described in the following sections.

2.5.2.2 Nuclear

Policies for nuclear energy are based on National Energy and Climate Plans ⁽¹⁰⁵⁾ submitted by Member States in 2019. These policies include political commitments by some Member States (including Germany, Belgium and France) to either ban or reduce nuclear from their power mix by 2035. These announcements were already included in Reference Scenario 2020 and projections for nuclear energy by Member States were published online ⁽¹⁰⁶⁾. Since then, certain MS have announced increases (or lifetime extension) in their nuclear capacity.

In line with these announcements, the following capacity additions were taken into account in the modelling:

- BE: Lifetime extension of around 2 GW of existing capacity until 2035, as of RPE
- CZ: Additional capacity of min 1.2 GW and with flexibility up to around 2 GW for 2040.
- FR: Maximum capacity cap of around 62 GW in 2035 and 64 GW in 2040 ⁽¹⁰⁷⁾.
- NL: Additional capacity of up to 3.2 GW in 2040, with flexibility of around 1.6 GW in 2035.
- PL: Maximum capacity cap of around 15 GW in 2040 ⁽¹⁰⁸⁾.
- SK: Possible additional capacity of around 2.4 GW in 2040.

These assumptions reflect the situation until March 2023. In June 2023, France has adopted a law which, among others, removes the objective of reducing the share of nuclear power in the electricity mix to 50% by 2035, as well as the capping of nuclear production capacity at 63.2 GW ⁽¹⁰⁹⁾. The impacts in the energy system of the 2023 French Law are discussed in section 6.2.1. of the main document of the Impact Assessment.

⁽¹⁰⁴⁾ European Commission, National long-term strategies (as of 1 February 2023) .

⁽¹⁰⁵⁾ Regulation (EU) 2018/1999

⁽¹⁰⁶⁾ https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en

⁽¹⁰⁷⁾ This capacity is higher than in the REPowerEU scenario. In REPowerEU, nuclear capacity is forecast to decrease from 63 GWe in 2030 to 36 GWe in 2040. Due to the [planned further extension of plant lifetimes](#), all capacity operational in 2030 could be assumed to be operational in 2040. Additional capacity of at least 1.65 GW could be assumed to be coming online in 2035. The potential 14 new plants announced would correspond to roughly one per year on average and thus an additional ~8 GWe capacity (five plants) by 2040 could be a potential limit. This would correspond to 71.4 GWe.

⁽¹⁰⁸⁾ This value is much higher than RPE. RTE (2022). Futures Énergétiques 2050 – Chapitre 4 La production d'électricité.

⁽¹⁰⁹⁾ Related to the acceleration of procedures linked to the construction of new nuclear installations near existing nuclear sites and the operation of existing installations.

Future analysis will include any resulting legislative changes by the Member States and the update of the NECPs to deploy newly build nuclear capacities or extend further operating lifetime of the existing ones. See Annex 8 and the box in Section 6.2.1 for more details ⁽¹¹⁰⁾.

2.5.2.3 Projects for Carbon Capture, Utilisation and Storage

Market research identified 186 key companies worldwide active in the CCS business ⁽¹¹¹⁾. 24% of the key players are European or are active in the field through their European subsidiaries. In the EU, companies have been mostly involved in project development in the energy-intensive industries (steel, cement, chemicals) and in recent years the number of announcements on carbon capture and storage projects have grown exponentially.

In view of the update of a previous published study on the topic ⁽¹¹²⁾, the JRC screened widely stakeholders' activity to compile a list with all CO₂ projects that are operational, in construction, in a feasibility or pre-FID (financial investment decision) stage. The list includes projects focusing either on the whole value chain (carbon capture, transportation and storage, including storage in products) or to a single step: carbon capture only (often associated to a certain industrial subsector), carbon storage only, or creation of a carbon terminal or transportation hub. Considering a cut-off date of 1 May 2023, the total yearly capacity of carbon capture and storage projects in the EU by 2030 corresponds to 64 MtCO₂/y (capture) and 71 MtCO₂ (storage) ⁽¹¹³⁾.

Member State also supported directly proposals of Projects of Common/Mutual Interest (PCI/PMI) for the 6th List under the TEN-E regulation, adding up to 34 MtCO₂/y of transport capacity in the period 2030-2032, that could increase up to a peak of 88 MtCO₂/y.

These elements helped to define the assumptions for the maximum short-term (up to 2030) potential and geographical distribution of CCS projects.

Concerning geographical distribution of capture projects, initially the CO₂ will be captured in industrial centres located in different Member States around the North Sea coast and its hinterland, to be aggregated with onshore transport infrastructure for CO₂. The storage capacity will be concentrated primarily in the North Sea region (DK, NL), and, if business cases allow, in the Adriatic and Black Sea. NO and UK also announced the construction of several projects ⁽¹¹⁴⁾,⁽¹¹⁵⁾,⁽¹¹⁶⁾, with an indicative storage capacity of around 110MtCO₂/y by 2030.

⁽¹¹⁰⁾ As a consequence, French nuclear capacity is projected to decline in 2040 in the scenarios analysed (see Annex 8). Current estimates suggest that French nuclear capacity could actually increase to 54-71 GWe (as discussed in footnote ⁽¹⁰⁷⁾). In the EU, this would translate to an estimated nuclear capacity of between 82 GWe and 101 GWe in 2040.

⁽¹¹¹⁾ However, depending on the boundaries set for the value chain, other research suggests about 17 000 companies involved in all aspects of the CCUS supply chain including technology providers, services, legal aspects (Kapetaki, 2022).

⁽¹¹²⁾ Morbee J, et al. *The Evolution of the Extent and the Investment Requirements of a Trans-European CO₂ Transport Network*. EUR 24565 EN. Luxembourg (Luxembourg): Publications Office of the European Union; 2010. JRC61201

⁽¹¹³⁾ JRC (2024). Tumara, D., Uihlein, A. and Hidalgo González, I. Shaping the future CO₂ transport network for Europe, European Commission, Petten, 2024, JRC136709.

⁽¹¹⁴⁾ Adomaitis, N., Kartit, D., 'Factbox: Carbon capture and storage projects across Europe', *Reuters*, 2023.

3 SCENARIOS ⁽¹¹⁷⁾

The specific objectives of this initiative are to identify and assess pathways towards climate neutrality in 2050 and an intermediate target for 2040.

3.1 Scenarios

All scenarios assessed aim at meeting climate neutrality by 2050. Three scenarios share the same key assumptions (S1, S2, S3) and allow to compare three levels of GHG emissions in 2040. The analysis is complemented by a variant, “LIFE”, which illustrates the additional impact of different assumptions on circular economy, mobility and the food system.

3.1.1 Common policy elements

The analysis factors in, to the extent possible, relevant policies as well as policy proposals adopted up to May 2023. Table 2 shows an overview of the EU policies that were considered in the definition of all scenarios. The table also shows whether the scenarios consider that these policies have specific effects only up to 2030 or also beyond 2030.

⁽¹¹⁵⁾ Watt, R., ‘Five proposed UK carbon capture projects meet government's eligibility test’, *Upstreamonline*, 2021.

⁽¹¹⁶⁾ Northern Endurance Partnership Partners, *Endurance Storage Development Plan: Key Knowledge Document*, 2021.

⁽¹¹⁷⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

Table 2: Main common legislative elements considered in all scenarios

Element	Status at the time of the analysis*	Quantitative effects/targets in 2030 (included in the modelling)	Quantitative effects/targets post-2030 (included in the modelling)
Emission Trading System Directive	Adopted	Yes	See discussion
Effort Sharing Regulation	Adopted	Yes	No
LULUCF Regulation	Adopted	Yes	No
CO2 emission standards for cars and vans	Adopted	Yes	Yes
Alternative Fuel Infrastructure Regulation	Adopted	Yes	Yes
FuelEU Maritime	Adopted	Yes	Yes
ReFuelEU Aviation	Adopted	Yes	Yes
Energy Efficiency Directive	Adopted	Yes	No
Renewable Energy Directive	Adopted	Yes	No
Energy Performance of Buildings Directive	Proposal	Yes	No
Regulation on methane emissions reduction in the energy sector	Agreed	Yes	Yes
CO2 emission standards for heavy-duty vehicles	Proposal	Yes	Yes
Energy Taxation Directive	Proposal	Yes	No
Intelligent Transport Systems Directive	Adopted	Yes	Yes
TEN-T Regulation	Agreed	Yes	Yes
Greening Freight Package	Proposal	Yes	Yes
F-Gas Regulation	Agreed	Yes	Yes
Net Zero Industry Act	Proposed	Yes	No
Landfill Directive	Not recently reviewed	Yes	Yes
Waste Framework Directive	Not recently reviewed	Yes	Yes
Urban Wastewater Treatment Directive	Proposal	Yes	Yes
Industrial Emissions Directive	Proposal	Yes	Yes

Note: “Adopted” means formally adopted by the European Parliament and European Council. “Agreed” means that a political agreement between the co-legislators has been reached, but they have not yet formally adopted the act. “Proposal” means proposed by the European Commission, but still under negotiation between the co-legislators. “Not recently reviewed” means that this legislation is in force and has not been revised in recent years.

The ETS by default has no end date for the application of the Linear Reduction Factors (LRF) that set the yearly emission reduction cap. However, the ETS will be reviewed in view of being compliant with the 2040 climate target once that target has been set. Consequently, the analysis does not assume by default a prolonged unchanged application of the LRFs post-2030. The analysis looks at the sectoral reductions compatible with the different 2040 target levels, including for the sectors covered by the ETS.

3.1.1.1 Energy and industrial process CO2 emissions

By 2030, scenarios are defined in line with relevant Fit For 55 and REPowerEU policies:

- The Emission Trading System Directive ⁽¹¹⁸⁾, targeting a reduction of 62% for the sectors under the ETS1 and a reduction of 42% for the sectors under the ETS2, both compared to 2005.
- The Effort Sharing Regulation ⁽¹¹⁹⁾, setting national targets for Member States to collectively contribute at EU level to an emission reduction of 40% compared to 2005 levels.
- The Renewable Energy Directive ⁽¹²⁰⁾, including the binding target for 2030 of at least 42.5%, but aiming for 45% ⁽¹²¹⁾, and corresponding sectoral sub-targets.
- The Energy Efficiency Directive ⁽¹²²⁾, aiming at ensuring an additional 11.7% reduction of energy consumption by 2030, compared to the 2020 Reference Scenario projections.
- The revised Regulation on CO2 performance standards for new passenger cars and vans ⁽¹²³⁾, with CO2 standards for new cars and vans established for years 2025 and 2030, namely -15% and -55% (-50% for vans) compared to 2021.
- The European Commission's proposal for a revised Regulation of CO2 emission standards for HDVs ⁽¹²⁴⁾, establishing CO2 performance standards of -43% for new lorries and coaches and -100% for urban buses by 2030 (relative to the reference period, 1 July 2019 – 30 June 2020).
- The FuelEU Maritime Regulation ⁽¹²⁵⁾, which establishes limits on the GHG intensity of energy used on-board by ships, and the obligation to use on-shore power supply or zero-emission technology while ships stay at EU ports.
- The ReFuelEU Aviation Regulation ⁽¹²⁶⁾, which specifies that, from 2025 onwards, aviation fuel suppliers shall ensure that all aviation fuel made available to aircraft operators at every Union airport contains a minimum share of sustainable aviation fuels (SAF), including a minimum share of synthetic aviation fuels. The SAF share targets in 2025 and 2030 are 2% and 6%, respectively.
- The Regulation on the deployment of alternative fuels infrastructure ⁽¹²⁷⁾, which sets mandatory deployment targets for electric recharging and hydrogen refuelling

⁽¹¹⁸⁾ Directive 2003/87/EC, as amended by Directive (EU) 2023/959.

⁽¹¹⁹⁾ Regulation (EU) 2018/842, as amended by Regulation (EU) 2023/857.

⁽¹²⁰⁾ Directive EU/2018/2001, as amended by Directive (EU) 2023/2413.

⁽¹²¹⁾ COM(2022) 230 final

⁽¹²²⁾ Directive (EU) 2023/1791.

⁽¹²³⁾ Regulation (EU) 2019/631, as amended by Regulation (EU) 2023/851.

⁽¹²⁴⁾ COM(2023) 88 final

⁽¹²⁵⁾ Regulation (EU) 2023/1805.

⁽¹²⁶⁾ Regulation (EU) 2023/2405.

⁽¹²⁷⁾ Regulation (EU) 2023/1804, repealing Directive 2014/94/EU.

infrastructure for the road sector, for shore-side electricity supply in maritime and inland waterway ports, and for electricity supply to stationary aircraft.

- Other policies and proposals such as the Energy Taxation Directive ⁽¹²⁸⁾ and the Energy Performance of Buildings Directive ⁽¹²⁹⁾.

Beyond 2030, the following policies will extend their application and implement additional guidelines, i.e.:

- The CO₂ performance standards for cars and vans establish that from 2035 onwards, there should be no new vehicle which is not a zero-emission vehicle in the (regulated) new fleet of that year.
- The CO₂ standards for HDVs establishes a mandate to decrease CO₂ emissions per km from new lorries and coaches by 90% from 2040 onwards (relative to the reference period 1 July 2019 – 30 June 2020), with intermediate targets for 2035 (64%). Note that there is some degree of differentiation between scenarios, with some scenarios having stricter CO₂ standards for HDVs than others from 2040 or 2045 onwards.
- FuelEU Maritime defines a GHG intensity limits more stringent over time until 2050.
- ReFuelEU Aviation increases the minimum shares of sustainable aviation fuels as of 2030 (6%) over time until 2050 (70%). Note that there is some degree of differentiation between scenarios, with some scenarios having stricter CO₂ standards for HDVs than others from 2035 onwards.

The scenarios remain neutral on the post-2030 evolution of the ETS, which will be reviewed in 2026. Instead, modelling drivers are defined for one or more sectors (see 3.2). In addition to the policies mentioned above, the following transport-related policies are included in the analysis: the revision of the Intelligent Transport Systems Directive ⁽¹³⁰⁾, the revision of the Trans-European Transport Network (TEN-T) Regulation ⁽¹³¹⁾, the Action Plan to boost long-distance and cross-border passenger rail ⁽¹³²⁾, and the proposed Greening freight package ⁽¹³³⁾. These initiatives contribute towards the milestones of the Sustainable and Smart Mobility Strategy and Action Plan ⁽¹³⁴⁾. The IMO Strategy on Reduction of GHG Emissions

⁽¹²⁸⁾ Directive 2003/96/EC, and the European Commission’s proposal for recasting (COM(2021) 563 final).

⁽¹²⁹⁾ Directive 2010/31/EU, as amended by Directive (EU) 2018/844, and the European Commission’s proposal for a revision of this directive (COM(2021) 802 final).

⁽¹³⁰⁾ Directive 2010/40/EU, as amended by Directive (EU) 2023/2661.

⁽¹³¹⁾ COM (2021) 812.

⁽¹³²⁾ COM(2021) 810.

⁽¹³³⁾ The “Greening freight package” includes: Proposal for a Regulation on the use of railway infrastructure capacity in the single European railway area (COM (2023) 443); Proposal for a Revision of the Weights and Dimensions Directive (COM (2023) 445); Proposal for a Regulation on the accounting of greenhouse gas emissions of transport services (COM (2023) 441); and Proposal for a Directive as regards a support framework for intermodal transport of goods (COM (2023) 702).

⁽¹³⁴⁾ Particularly the milestones related to rail, inland waterways and short-sea shipping. See: COM (2020) 789 final.

from Ships ⁽¹³⁵⁾ is also reflected, with differentiation between scenarios. The modelling also considers the impact of initiatives described in the Circular Economy Action Plan ⁽¹³⁶⁾.

Beyond policies, consolidated trends such as further electrification of the building sector through sustained deployment of heat pumps, a more decarbonised and efficient power system with a progressively higher share of renewable facilitated by system optimisation (interconnection, storage and demand-side response) are also implemented.

3.1.1.2 Non-CO2 GHG emissions

In all scenarios, the evolution of non-CO2 GHG emissions is consistent with the relevant existing legislation or legislative proposals, including the proposals for a revised Urban Wastewater Treatment Directive ⁽¹³⁷⁾, a revised F-gas regulation ⁽¹³⁸⁾ and a revised Industrial Emission Directive ⁽¹³⁹⁾. On top of that, the evolution of the non-CO2 GHG emissions from the energy sector is driven by the decarbonisation of the energy sector and is consistent with the proposal for a regulation to reduce methane emissions in the energy sector ⁽¹⁴⁰⁾.

3.1.1.3 LULUCF

The EU has agreed on a new target to achieve 310 MtCO₂ of net removals in 2030 according to the amended LULUCF regulation ⁽¹⁴¹⁾. There is no specific post-2030 policy framework related to LULUCF emissions.

3.1.2 S1

S1 aims at reaching net GHG emission reductions of close to 78.5% in 2040 compared to 1990, to be aligned with a “linear” trajectory between 2030 and 2050, and climate neutrality in 2050.

3.1.2.1 Energy and industry CO₂

The S1 scenario projects beyond 2030 the consolidated techno-economic policy trends that delivers the 2030 target, while it delays a large uptake of novel technologies until after 2040. The energy system gets further electrified, more efficient and decarbonised through a further deployment of renewables. A very limited uptake of e-fuels, carbon capture and industrial removals and additional deployment of bioenergy are projected until 2040. However, to ensure climate neutrality in 2050, deployment of these technologies is projected to strongly

⁽¹³⁵⁾ The 2023 IMO GHG Strategy states that GHG emissions from international shipping should reach net zero close to 2050. It also introduces indicative checkpoints, namely: 1) to reduce the total annual GHG emissions from international shipping by at least 20%, striving for 30%, by 2030, compared to 2008; and 2) to reduce the total annual GHG emissions from international shipping by at least 70%, striving for 80%, by 2040, compared to 2008.

⁽¹³⁶⁾ COM(2020) 98 final.

⁽¹³⁷⁾ COM (2022) 541 final.

⁽¹³⁸⁾ COM (2022) 150 final.

⁽¹³⁹⁾ COM/2022/156 final/3.

⁽¹⁴⁰⁾ COM (2021) 805 final.

⁽¹⁴¹⁾ Regulation (EU) 2018/841, as amended by Regulation 2023/839.

accelerate after 2040. The CO₂ standards for HDVs establish a mandate to decrease CO₂ emissions per km from new lorries and coaches by 43% in 2030, 64% in 2035 and 90% from 2040 onwards (relative to the reference period 1 July 2019 – 30 June 2020). The minimum shares of sustainable aviation fuels (SAF), related to ReFuelEU Aviation, are 20% in 2035, 34% in 2040, 42% in 2045 and 70% in 2050, and the minimum shares of synthetic aviation fuels are 5% in 2035, 10% in 2040, 15% in 2045 and 35% in 2050. The IMO GHG emissions reduction target for international shipping is set at the lower end of the range (i.e., 70% GHG emissions reduction in 2040 relative to 2008).

3.1.2.2 Non-CO₂ GHG emissions

By 2040 the S1 scenario assumes no further mitigation than delivered by the known policy sectoral policies (for instance, the revised F-gas regulation, the Landfill Directive and the revised Urban Wastewater Treatment Directive) and as a result of the decarbonising energy sector.

By 2050, the mitigation options are fully deployed in all sectors (including agriculture) in view of contributing to climate neutrality.

The evolution of non-CO₂ GHG emissions from the agriculture sector is consistent with the EU's agriculture activity policy as reflected in the EU Agricultural Outlook 2022 ⁽¹⁴²⁾.

3.1.2.3 LULUCF

LULUCF net removals are driven by the evolution of bioenergy demand in the scenario.

In addition, in the last decade, the scenario assumes the same policy intensity as the one necessary to achieve the 2030 LULUCF target (310 MtCO₂ of net removals) ⁽¹⁴³⁾ in view of contributing to climate neutrality by 2050.

3.1.3 S2

S2 aims at reaching net GHG emission reductions of at least 85% in 2040 compared to 1990 and climate neutrality in 2050.

3.1.3.1 Energy and Industry CO₂

S2 builds on S1 and generates a faster decarbonisation of the energy system until 2040. It projects by 2040 a higher deployment of novel technologies such as carbon capture and e-fuels than S1. Carbon is mostly captured from fossil fuels in the industrial and power sector and linked to carbon storage underground and in part to production of e-fuels. Industrial carbon removals starts appearing in the energy system in the 2031-2040 decade, with relative amount of BECCS and DACCS subject to uncertainties. A larger upscaling of current trends,

⁽¹⁴²⁾EC (2022), EU agricultural outlook for markets, income and environment, 2022-2032. European Commission, DG Agriculture and Rural Development, Brussels.

⁽¹⁴³⁾Regulation (EU) 2018/841 (amended by Regulation 2023/839).

for instance development of renewables and increased use of biomass (¹⁴⁴), that lead to power system close to full decarbonisation by 2040, is also assumed.

Compared to S1, the transport sector is characterised by a higher shift towards shared and collaborative mobility services and multimodal travel, more efficient operation of freight vehicles and delivery of goods (by optimising multi-modal delivery solutions), higher use of intermodal freight transport and a larger uptake of renewable H2 and e-fuels. The CO2 standards for HDVs establish a mandate to decrease CO2 emissions per km from new lorries and coaches by 43% in 2030, 64% in 2035, 90% in 2040 and 100% from 2045 onwards (relative to the reference period 1 July 2019 – 30 June 2020). The minimum shares of sustainable aviation fuels (SAF), related to ReFuelEU Aviation, are 21% in 2035, 36% in 2040, 44% in 2045 and 72.5% in 2050, and the minimum shares of synthetic aviation fuels are 6% in 2035, 12% in 2040, 17% in 2045 and 37.5% in 2050. The IMO GHG emissions reduction target for international shipping is set at the mid-point of the range (i.e., 75% GHG emissions reduction in 2040 compared to 2008).

3.1.3.2 Non-CO2 GHG emissions

The S2 scenario assumes the uptake of mitigation options in all sectors, notably in the agriculture sector, where technologies to reduce CH4 emissions are assumed to be largely deployed by 2040. In 2050, all the mitigation options required are fully deployed in all sectors in view of contributing to climate neutrality.

3.1.3.3 LULUCF

LULUCF net removals are driven by the evolution of bioenergy demand in the scenario.

In addition, the scenario assumes over 2030-2050 the same policy intensity as the one necessary to achieve the 2030 LULUCF target (310 MtCO₂ of net removals) (¹⁴⁵).

3.1.4 S3

S3 aims at reaching net GHG emission reductions of at least 90% in 2040 compared to 1990 and climate neutrality in 2050.

3.1.4.1 Energy and Industry CO2

The S3 scenario assumes large and fast uptake of all mitigation options, including development of novel technologies, already in the 2031-2040 decade. By 2040, S3 leads to a fully decarbonised power system and industrial sector and a high share of e-fuels in all sectors (including in hard-to-abate transport sectors, such as aviation and international shipping). This is supported by wide deployment of carbon capture, covering all industrial process emissions by 2040, and industrial carbon removals, compensating for the residual in the international maritime and aviation sectors covered by the ETS and delivering carbon to produce e-fuels.

(¹⁴⁴) Eurostat, *Complete Energy Balances European Union (27 countries) – 2021, 2023*.

(¹⁴⁵) Regulation (EU) 2018/841 (amended by Regulation 2023/839).

Compared to S2, S3 shows a higher shift towards shared and collaborative mobility services and multimodal travel, more efficient operation of freight vehicles and delivery of goods (by optimising multi-modal delivery solutions), higher shift towards intermodal freight transport, and a larger uptake of renewable H2 and e-fuels. The CO2 standards for HDVs establish a mandate to decrease CO2 emissions per km from new lorries and coaches by 43% in 2030, 64% in 2035, 100% from 2040 onwards (relative to the reference period 1 July 2019 – 30 June 2020). The minimum shares of sustainable aviation fuels (SAF), related to ReFuelEU Aviation, are 22% in 2035, 38% in 2040, 46% in 2045 and 75% in 2050, and the minimum shares of synthetic aviation fuels are 7% in 2035, 14% in 2040, 19% in 2045 and 40% in 2050. The IMO GHG emissions reduction target for international shipping is set at the higher end of the range (i.e., 80% GHG emissions reduction in 2040 relative to 2008). As a result of high emission reductions levels achieved already in 2031-2040, decarbonisation rate slows down in the decade 2041-2050 to smoothly achieve climate neutrality in 2050.

3.1.4.2 Non-CO2 GHG emissions

In 2040, the mitigation technology solutions are fully deployed in all sectors, including agriculture, as for 2050 in view of contributing to climate neutrality. In particular, in addition to the options deployed in S2, S3 builds on a large uptake by 2040 of technologies to reduce N2O emissions from agriculture.

3.1.4.3 LULUCF

LULUCF net removals are driven by the evolution of bioenergy demand in the scenario.

In addition, the scenario assumes over 2030-2050 the same policy intensity as the one necessary to achieve the 2030 LULUCF target (310 MtCO₂ of net removals) ⁽¹⁴⁶⁾.

3.1.5 LIFE

The LIFE scenario aims at reaching net GHG emission reductions of at least 90% in 2040 compared to 1990 and climate neutrality in 2050.

3.1.5.1 Activity assumptions

LIFE considers a more sustainable lifestyle guided by consumer climate-friendly choices and a more efficient use of the resources of the EU's economy (energy, material, and land), as well as the food system departing from the three scenarios in terms of material use, energy consumption and dietary changes. The assumptions underpinning the LIFE analysis are summarised in Table 3 and detailed in the following paragraphs.

⁽¹⁴⁶⁾ Regulation (EU) 2018/841 (amended by Regulation 2023/839).

Table 3: Key features of the LIFE scenario

Sector	Domain of Action	Action or group of actions	Impact on activity
Industry	Circular Economy & Sufficiency	Enhanced repair, reuse, renewal and recycling of end-user products	Long-Term reduction of industrial activity with respect to S1, S2 and S3 for the main energy-intensive sectors: steel (-15%), Aluminum (-20%), Paper (-20%), cement & clinker (-25%) and petrochemicals (-15%)*
		Extensions of product lifetime (e.g., cars, buildings)	
		Circularity by design	
Buildings	Sufficiency	Optimisation of energy consumption	Temperature setpoint lower in winter and higher in summer in comparison with S1, S2 and S3 of 0.5°C in 2030, 1°C in 2035 and 1.5°C from 2040 onwards.
Transport and mobility	Sufficiency	Stronger shift towards shared mobility, active modes and multimodal travel	Decrease in car transport activity (pkm) (-5% in both 2040 and 2050 compared to S1, S2 and S3. Increase in average car occupancy rate: 1.65 and 1.75 passengers/trip in 2040 and 2050, respectively, compared to around 1.55 passengers/trip in both 2040 and 2050 in S1, S2 and S3.
		Lower aviation demand and stronger shift to rail	Increase in passenger rail transport activity (pkm) in 2040 (+4% to +6%, compared to S1, S2 and S3, respectively) and in 2050 (+5% to +8%, compared to S1, S2 and S3, respectively). Decrease in international and domestic air transport activity (pkm): -10% in 2040 and -14% in 2050, compared to S1, S2 and S3.
Land Sector	Sustainable food consumption	Dietary Change, Food Waste reduction, more sustainable food production	Reduction of primary agriculture, producer, retail, and consumer food waste food waste reduction of around 11 Mton in 2040. Dietary change towards more sustainable diets (25% shift towards optimal sustainable and healthy diet 2040**). Implementation of the objectives from the Farm to Fork Strategy and Biodiversity Strategy (reduction of at least 20% mineral fertilisers application, 50% less pesticides use, 25% organic farming on EU's agriculture land, 10% area of high-diversity landscape features, and 50% reduction in nutrient surplus from organic and synthetic sources.)

*Note: * Reductions are implemented linearly from 0% to the value stated in the period 2030–2050, see also Table 8 in Annex 8. ** See section 3.1.5.3 for more details.*

3.1.5.2 Energy and Industry CO₂

The key principle for the energy and industrial sectors in LIFE is a more efficient use of materials across the whole EU value chain, which is put into practice by a number of Circular Economy (CE) and sufficiency actions, following and going beyond the Circular Economy

Action Plan⁽¹⁴⁷⁾. Consumers pay more attention to what they buy, preferring more sustainable products, and reusing, repairing, renewing, and recycling whenever possible. Lifetime of products like cars is extended and renovation of houses is preferred to new constructions. Existing buildings are used more effectively, and new ones are designed more efficiently. As result, there is lower needs for carbon-intensive end-user products, while the same level of services is maintained.

Supported by a larger deployment of smart energy management systems, consumers in residential and service buildings also optimise their energy consumption via setting heating and how water temperature set points that are lower in winter and higher in summer. The differences between LIFE and the scenarios amount to 0.5°C in 2030, 1°C in 2035 and 1.5°C from 2040 onwards.

In terms of mobility, LIFE assumes a stronger shift towards shared and collaborative mobility services and multimodal travel, including sustainable urban transport⁽¹⁴⁸⁾. Concerning air transport, LIFE assumes that the adoption of video-conferencing tools at large scale reduces the number of business trips. Furthermore, it assumes that increased awareness of the impacts of aviation on climate change reduces the number of long-distance leisure trips, and additionally results in a shift of some short distance leisure trips towards high-speed rail (where available). These assumptions follow the same rationale as various external studies⁽¹⁴⁹⁾⁽¹⁵⁰⁾⁽¹⁵¹⁾⁽¹⁵²⁾. The HDV CO₂ emission standards, the ReFuelEU Aviation targets

⁽¹⁴⁷⁾ COM/2020/98 final.

⁽¹⁴⁸⁾ In line with EU policy on urban mobility (see, for example, the ‘European Declaration on Cycling’, COM (2023) 566 final).

⁽¹⁴⁹⁾ CLEVER, (2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables, *Final Report*. https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf. This study assumes a significant increase in the EU’s average car occupancy rate (1.9 persons per car by 2050, i.e., a 19% increase relative to 2015) and a significant modal shift to active mobility (10% of land km/capita by 2050, whereas this share was 7% or lower in most EU countries in 2015) and collective transport (35% of land km/capita by 2050, i.e., 17 percentage points more than in 2015). In addition, it assumes a decrease in the air distance travelled (600 to 2 500 km/capita/year depending on the country by 2050, including international travel, whereas the value of this indicator was around 3 000 m/capita/year in 2019 for the whole EU).

⁽¹⁵⁰⁾ Kalcher, L. et al., (2023). Choices for a more Strategic Europe. *Strategic Perspectives*. <https://strategicperspectives.eu/wp-content/uploads/2023/07/Choices-for-a-more-Strategic-Europe.pdf> – The EU triple opportunity for energy security, reindustrialisation and competitiveness based on scenarios for 2040. This study describes two scenarios where the EU’s net GHG emissions decrease by 90% and 95% in 2040 relative to 1990, respectively. This study assumes an increase in the EU’s average car occupancy rate (1.7 persons per car by 2040, i.e., a 6% increase relative to 2019) and a decrease in the air distance travelled per capita per year (-1% to -20% in 2040 relative to 2015 levels in the two above-mentioned scenarios, respectively). Furthermore, this study assumes significant changes in modal split. More specifically, for urban transport, the modal share of cars and 2-wheelers is 64.5% in 2040 (i.e., 6.5 percentage points less than in 2019), the share of public transport is 18.5% (i.e., 4.5 pp more than in 2019), and the share of active modes is 17% (i.e., 2 pp more than in 2019). For inter-urban transport, the modal share of cars is 77.5% in 2040 (i.e., 2.5 pp less than in 2019), the share of rail is 12.5% (i.e., 1.5 pp more than in 2019), and the share of buses/coaches is 10% (i.e., 1 pp more than in 2019).

⁽¹⁵¹⁾ EUROCONTROL (2022). Aviation Outlook 2050 – Main Report. This study assumes that, in Europe, the number of flights increases by 44% between 2019 and 2050 in the “base” (or most-likely) scenario, but it increases much less (by 19%) in the “low-growth” scenario.

⁽¹⁵²⁾ International Energy Agency (2023). Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach. This report describes a feasible pathway for the global energy sector to contribute to the Paris

and the IMO GHG emissions reduction target for international shipping are defined as for the S3 scenario (see Section 3.1.4).

The analysis done with LIFE shows how climate action can answer societal needs in a lean and efficiency way: it specifically captures some of the most relevant opportunities of higher climate ambition emphasised by stakeholders in the public consultation, for instance improving energy security (66% of all respondents), and economic signals for embracing sustainable production and consumption models (70% of answers from business organisations) and is in line with possible expected individuals changes in daily life and willingness for action in changing consumption patterns of good and services.

3.1.5.3 Non-CO2 GHG emissions & LULUCF

LIFE evolves around a dietary change from consumers, the implementation of the Farm to Fork Strategy⁽¹⁵³⁾ and Biodiversity Strategy for 2030⁽¹⁵⁴⁾, and food waste reduction⁽¹⁵⁵⁾. Food diets can change in a comparably short time and recent history underlines the potential for widespread changes, including on more diverse and healthier diets⁽¹⁵⁶⁾. The scenario assumes that a variety of different motives such as healthier diets, awareness of climate impacts and animal welfare but also the increasing availability of meat alternatives leads to dietary shifts. Furthermore, increased consumer awareness for food as a valuable resource triggered by campaigns combined with the removal of systemic barriers to avoid food waste lead to a reduction in food waste in LIFE.

The LIFE variant combines the following three main food-related features:

- It assumes a voluntary moderate food demand change by European citizens towards a healthier diet. This shift is directed towards a more sustainable, climate-friendly and healthy diet, as it is proposed by the EAT-Lancet Commission⁽¹⁵⁷⁾. On average, the dietary pattern of EU citizens moves gradually towards the suggested optimal sustainable and healthy diet from the EAT-Lancet Commission by 25% in 2040. This shift does not come with a decrease of the overall caloric intake but assumes a substitution of some food products with others that are currently insufficiently consumed⁽¹⁵⁸⁾.

Agreement's goal of limiting the rise in global temperatures to 1.5 °C above pre-industrial levels. The report assumes that 9% of global aviation activity (expressed in passenger-km) is avoided in 2030 as a result of the implementation of behavioural measures. This percentage is 20% in 2050.

⁽¹⁵³⁾ COM (2020) 381 final

⁽¹⁵⁴⁾ COM (2020) 380 final

⁽¹⁵⁵⁾ Aligned with the legislative proposal by the European Commission on food waste (COM (2023) 420 final), proposing a similar total reduction of food waste. Note that this proposal was not adopted in time to be included in the main scenarios (S1, S2 and S3), and is therefore only reflected in LIFE.

⁽¹⁵⁶⁾ Vermeulen, S.J., et al., 'Changing diets and the transformation of the global food system', *Ann. N.Y. Acad. Sci.*, 1478, 3-17, 2020.

⁽¹⁵⁷⁾ Willet et al., 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', *Lancet*, 2019.

⁽¹⁵⁸⁾ Figure.1; Willet et al., 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', *Lancet*, 2019.

- In parallel, a similar evolution of the food supply is projected, which is driven by the objectives of the Farm to Fork Strategy and Biodiversity Strategy. Accordingly, the scenario aims for a reduction of at least 20% mineral fertilisers application, 50% less pesticides use, 25% organic farming on EU's agriculture land, 10% area of high-diversity landscape features, and 50% reduction in nutrient surplus from organic and synthetic sources.
- In line with the Commission's proposal on food waste reduction⁽¹⁵⁹⁾, a similar absolute reduction of food waste as in option 2 of the proposal is assumed⁽¹⁶⁰⁾.

The exact steering towards the different objectives from the Farm to Fork and Biodiversity strategy, the dietary changes, as well as the targets for the food waste reduction in the modelling is technically difficult, which results in the overfullfillment of some targets and missing the threshold for others in the LIFE scenario. Due to assumed projected changes from the LIFE case with regard to food supply and demand, the land sector assumes certain land use changes that take into account the decreasing livestock activity and food production for meat and dairy products. More agricultural land for carbon farming and set aside land with natural vegetation becomes available, which leads to higher potentials of nature-based removal solutions. Moreover, assumptions on more extensive agriculture due to restrictions on pesticide and fertilizer use as well as more organic agriculture and set aside land lead to increased changes in the demand for land use for agricultural production.

In LIFE, in 2040, all non-CO2 GHG emitting sectors (including agriculture) deploy all the mitigation technologies required (like in the scenarios). In 2050, the mitigation options required are fully deployed in all sectors in view of contributing to climate neutrality. However, the level of non-CO2 GHG emissions (both in 2040 and 2050) is expected to be lower than in the other scenarios, mainly because of changes in agriculture activity.

3.2 Modelling drivers

The policies and trends described are translated into modelling assumptions and implemented in the modelling tools to shape the different scenarios. The modelling assumptions can take the form either of explicit elements within the policies, such as targets of CO2 performance standards for cars and vans in a given year or induced by modelling drivers such as carbon values applied to the different sectors, which reflect generic incentives altering investment decisions towards abatement of GHG emissions.

The “carbon values” mentioned below (see Table 4) are used only as modelling drivers in the different models used and for this specific analysis and do not represent a forecast of possible future evolution of carbon prices. The expressed carbon values are the marginal abatement cost per ton of CO₂-eq covered in the respective scenario.

⁽¹⁵⁹⁾COM (2023) 420 final. This proposal was adopted in July 2023, and came too late to be implemented the core scenarios S1, S2 and S3. It is implemented in the LIFE case.

⁽¹⁶⁰⁾Total food waste reduction in the proposal in option 2 was around 13 Mton from primary production, processing and manufacturing, retail and consumption. In the LIFE variant a total food waste reduction of around 11 Mton in 2040 (compared to 2020) was achieved with reductions from primary agriculture, processing and distribution, as well as retail and households.

Table 4. Carbon values applied on emissions in the different sectors (excl. LULUCF)

EUR/tCO ₂ -eq	2040				2050
	S1	S2	S3	LIFE	
Energy and industry CO₂ (PRIMES model) and non-CO₂ covered by the ETS (GAINS model)	160	240	290	250	470
Non-CO₂ from sectors other than agriculture (GAINS model)	0	240	290	250	470
Non-CO₂ from agriculture (GAINS model)	0	55	290	250	470

Note: Expressed in EUR'2023.

In 2040, the scenario S1 relies on the application of a carbon value on CO₂ from fossil fuel combustion and industrial processes and on the effect of known policies affecting non-CO₂ GHG emissions by that time horizon. The scenario S2 equalises the carbon values applied to CO₂ from fossil fuel combustion, industrial processes and all non-CO₂ emissions associated to energy, industry and waste, while the same carbon value is applied in agriculture as in the LULUCF sector (see below). The scenario S3 equalises the carbon values applied to all sectors.

After 2040, all sectors need to reduce GHG emissions in order to contribute to meeting climate neutrality by 2050.

Specific aspect of the LULUCF sector

The size of future LULUCF net removals bears many uncertainties because of external factors such as climate change impacts or natural disturbances. In addition, implementing a high potential of additional nature-based carbon removals with high carbon values would require additional changes in land use. To represent these uncertainties, the analysis with the GLOBIOM model thus looks at a range of carbon values for LULUCF:

- a “lower” carbon value of 0 €/tCO₂-eq associated with the lower boundary for the LULUCF net removals;
- a “central” carbon value of 50 €/tCO₂-eq necessary to meet the 2030 target as a ‘central level’ for net LULUCF removals;
- an “upper” carbon value of 200 €/tCO₂-eq associated with the upper boundary of the LULUCF net removals.

To compute the overall net GHGs across the economy for the scenarios S1, S2 and S3, the “central” carbon value is applied in 2040 and 2050 (see Table 5), except for S1 in 2040 where the “lower” carbon value is applied. For more details, see Annex 8 section 1.8.

Table 5. Main carbon value applied for LULUCF

EUR/tCO ₂ -eq	2040				2050
	S1	S2	S3	LIFE	
LULUCF (GLOBIOM model)	0	50	50	50	50

Note: Expressed in EUR'2020.

3.3 Complementary Analysis

3.3.1 Energy system modelling

Complementary modelling analyses are performed to assure the robustness of the results and to investigate specific aspects of the emission trends, displaying also possible alternative sectoral mitigation pathways.

The key assumptions for these analyses are shared across all models and harmonised to the extent possible (reported in section 2.4 of Annex 6), and all resulting mitigation pathways fulfil the 2030 and 2050 climate targets. Appropriate, high-quality modelling tools complementary to the main modelling suite have been used (see section 2.1).

The sectoral distribution of the net GHG emissions and the role of carbon removals has been investigated by combining projections for the emissions in the energy system modelled by POTEnCIA, with the ones for the land sector developed by GLOBIOM and the non-CO2 emissions projected by GAINS. Three scenarios POTEnCIA-S1, POTEnCIA-S2 and POTEnCIA-S3 follow the same logic as S1-S2-S3, except for the cap on the amount of the biomass supply for bioenergy which is relaxed in the case of POTEnCIA-S3 (see 2.4.5 of Annex 6), and illustrate in a similar way the incremental uptake of the novel technology options.

The domestic energy and industry CO2 emissions are also explored by modelling pathways to climate neutrality via three other tools: EU-TIMES, POLES and AMADEUS-METIS. Each model produces a single pathway, based on relevant common policy elements described in section 3.1.1.1 and assuming overall cost-efficient decarbonisation of the energy and industry CO2 sector. The amount of carbon capture in the period 2030-2050 stays within the maximum threshold for feasibility indicated by the ESABCC ⁽¹⁶¹⁾ and lies between the minimum carbon captured in S1 and the maximum carbon captured in S3.

3.3.2 Industry

The impact of a group of selected Circular Economy (CE) action on the process of industrial decarbonisation of specific energy-intensive sectors are studied projecting material production, GHG emissions and energy demand in scenarios with (circular or CIRC) and without (standard or STD) implementation of those CE actions. The modelling tool FORECAST is used. Both scenarios assume already a well decarbonised energy system, with a GHG reduction of approximately 95% for the EU industrial sector by 2050 compared to 1990. The scenarios also implement hydrogen and e-fuels only when electrification is not possible and limit carbon capture to individual applications in sectors where emissions are difficult to avoid and alternative mitigation strategies (e.g., fuel and process switch) are lacking today, i.e., cement and lime production. The impact of CE actions across the whole economy falls outside the scope of this complementary analysis.

⁽¹⁶¹⁾ ESABCC, *Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050*, 2023. Table 5.

4 SOCIO-ECONOMIC ANALYSIS

4.1 Models ⁽¹⁶²⁾

Three state-of-the-art macro-economic models with distinct methodological underpinnings have been used to assess the socio-economic impacts of the target options and assess the robustness of the key findings. These models have been employed by the European Commission ⁽¹⁶³⁾, Member States and a variety of stakeholders in the past decades to assess the impact of climate and energy policies. These models have been used for numerous publications in peer-reviewed journals. Their methodological underpinnings are explained in these peer-review publications. For each model, a detailed description can also be found in the Modelling Inventory and Knowledge Management System of the European Commission MIDAS ⁽¹⁶⁴⁾, together with a list of impact assessments and peer reviewed publications where each of these models have been utilized.

This macro-economic analysis factors in the sectoral mitigation costs produced by the sectoral models described in section 2.1.1.

4.1.1 GEM-E3

GEM-E3 is a large scale multi-sectoral recursive dynamic computable general equilibrium (CGE) model that has been used to provide the sectoral economic assumptions as inputs for this Impact Assessment and to assess socio-economic impacts of the scenarios. GEM-E3 produced consistent sectoral value added and trade projections matching exogenous GDP and population projections by country taken from other sources such as the ECFIN t+10 projections for economic activity, Eurostat's population projections and the Ageing Report. The model was used to assess the impacts of the energy and climate targets on macroeconomic aggregates such as GDP, employment and sectoral output.

This Impact Assessment has used mainly the European Commission's JRC version JRC-GEM-E3, while the GEM-E3-FIT version operated by E3Modelling was used to generate exogenous assumptions on sectoral gross value added. Both models have underpinned numerous publications in peer-review journals ⁽¹⁶⁵⁾, ⁽¹⁶⁶⁾. A detailed description is also available in MIDAS ⁽¹⁶⁷⁾.

⁽¹⁶²⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

⁽¹⁶³⁾ For instance, the main modelling suite of Impact Assessment was used for the Commission's proposals for the Long-Term Strategy (COM (2018) 773), the 2030 Climate Target Plan (SWD (2020) 176 final), and the Fit for 55 (COM (2021) 550 final).

⁽¹⁶⁴⁾ MIDAS: <https://web.jrc.ec.europa.eu/policy-model-inventory/>

⁽¹⁶⁵⁾ JRC-GEM-E3, selected publications: https://joint-research-centre.ec.europa.eu/gem-e3/gem-e3-publications_en

⁽¹⁶⁶⁾ GEM-E3 Model Manual, E3-Modelling 2017. https://e3modelling.com/wp-content/uploads/2018/10/GEM-E3_manual_2017.pdf

⁽¹⁶⁷⁾ <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-gem-e3/>

4.1.2 E3ME

E3ME is a global, macro-econometric model designed to analyse economic and environmental policies. It includes:

- a high level of disaggregation, enabling detailed analysis of sectoral and country-level effects of a wide range of scenarios.
- a capacity to describe social impacts (including unemployment levels and distributional effects).

Its econometric specification provides a strong empirical basis for analysis. It can fully assess both short and long-term impacts. Its integrated treatment of the world's economies, energy systems, emissions and material demands enables it to capture two-way linkages and feedbacks between these components.

E3ME is frequently applied at national level, in Europe and beyond, as well as for global policy analysis. It has been used extensively by a range of stakeholders and has been the basis of many refereed publications ⁽¹⁶⁸⁾. A detailed description is also available in MIDAS. ⁽¹⁶⁹⁾

In this impact assessment, it has been used to complement the assessment of the macro-economic impacts of the energy and climate targets and assess the robustness of the results.

4.1.3 E-QUEST

QUEST is the global macroeconomic model that the Directorate General for Economic and Financial Affairs (DG ECFIN) uses for macroeconomic policy analysis and research. It is a dynamic stochastic general equilibrium model in the New-Keynesian tradition. Its microeconomic foundations are derived from utility and profit optimisation. It includes frictions in goods, labour and financial markets. It has been used for numerous publications in peer-review journals ⁽¹⁷⁰⁾. A detailed description is also available in MIDAS ⁽¹⁷¹⁾. There are different versions of the QUEST model, estimated and calibrated, each used for specific purposes.

In this impact assessment the E-QUEST model variant (a two-region, multisector model specifically developed for climate and energy related policy analysis) is used. The main innovation in this model compared to the standard DSGE models is the inclusion of energy input substitution that allows for a more detailed description of the substitution possibilities between different energy sources. E-QUEST has been used to complement the assessment of the macro-economic impacts of the energy and climate targets.

⁽¹⁶⁸⁾ E3ME, selected publications: <https://www.e3me.com/how/papers/>

⁽¹⁶⁹⁾ <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-e3me/>

⁽¹⁷⁰⁾ QUEST (E-QUEST), selected publications: https://economy-finance.ec.europa.eu/economic-research-and-databases/economic-research/macro-economic-models/quest-macro-economic-model_en

⁽¹⁷¹⁾ <https://web.jrc.ec.europa.eu/policy-model-inventory/explore/models/model-quest/>

4.2 Complementary Inputs

For the quantitative analysis of the regional impacts, we used regional emission data from the Emissions Database for Global Atmospheric Research (EDGAR) ⁽¹⁷²⁾. Published by the Joint Research Centre of the European Commission, it includes data on greenhouse gas emissions at sub-national level (NUTS2) in the EU from 1 January 1990 to 1 January 2021.

For the SME test, we used the Structural Business Statistics from Eurostat, and in particular the Enterprise statistics by size class and NACE Rev.2 activity, as well as data from the Eurostat Farm Structure Survey.

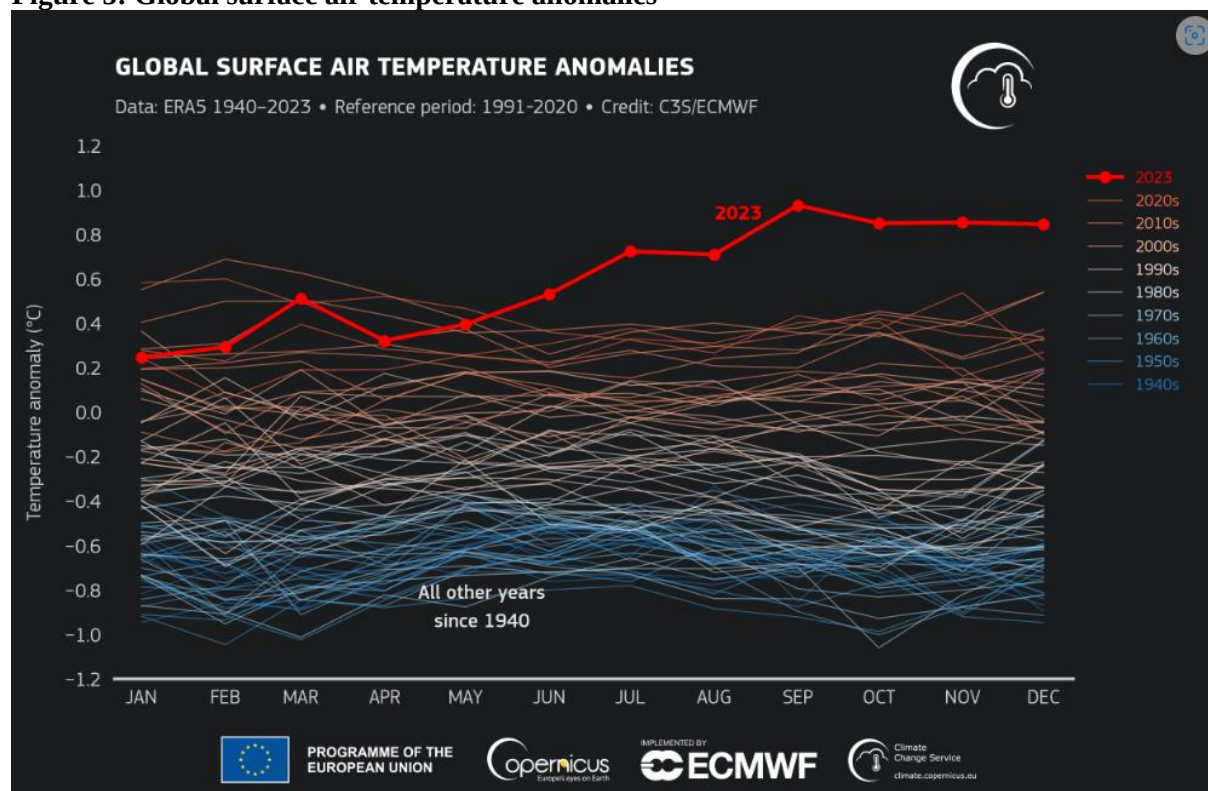
⁽¹⁷²⁾ Crippa, Monica; Guizzardi, Diego; Pagani, Federico; Pisoni, Enrico; (2023): GHG Emissions at sub-national level (v1.0). European Commission, Joint Research Centre (JRC) [Dataset]

Annex 7: Cost of climate change

1 GLOBAL WARMING

Human-induced climate change is a threat to people and nature around the world. Its impact on lives, livelihoods and nature are widespread, increasing and some are unavoidable. Extreme events, including heatwaves, droughts and floods, are rising in frequency and intensity, negatively affecting people, ecosystems, food systems, infrastructure, energy and water availability, public health and the economy. In addition, the extent and magnitude of the impacts taking place already are at the worst end of the spectrum estimate by scientists. The only way to lessen the impacts of climate change is by limiting global warming and enhancing adaptation action. The higher the level of global warming the more severe the impacts, and the higher the chances of triggering irreversible effects ⁽¹⁷³⁾.

Figure 5: Global surface air temperature anomalies



Note: Monthly global surface air temperature anomalies (°C) relative to 1991–2020 from January 1940 to December 2023, plotted as time series for each year. 2023 is shown with a thick red line while other years are shown with thin lines and shaded according to the decade, from blue (1940s) to brick red (2020s)

Source: ERA5. Credit: C3S/ECMWF.

Globally, the year 2023 was the warmest year on record, with global average temperatures 1.48°C warmer than the 1850–1900 pre-industrial average. It was the first year on record when

⁽¹⁷³⁾ IPCC 2023. Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland

every day exceeded 1°C above the pre-industrial level. July and August 2023 were the hottest two months on record, and the boreal summer (June to August) was the warmest ever recorded. From June to December 2023 each month was warmer than the corresponding month in any previous year, as shown in Figure 5, which shows global surface air temperature anomalies relative to 1991–2020 for over 80 years ⁽¹⁷⁴⁾.

Table 6 shows that while the short-term evolution of global surface temperature is expected to be similar across all representative concentration pathways (RCP), within only a few decades from now it displays striking differences depending on the intensity of global mitigation action in the coming years, between, on the one hand, a relatively contained climate change in trajectories compatible with RCP2.6 or below and, on the other hand, a potentially very large average global temperature increase with GHG trajectories above RCP4.5, which will translate into still much stronger local and global impacts and increasing risks to cross tipping points of the Earth climate system.

Table 6: Changes in the global surface temperature relative to 1850-1900 for different RCPs

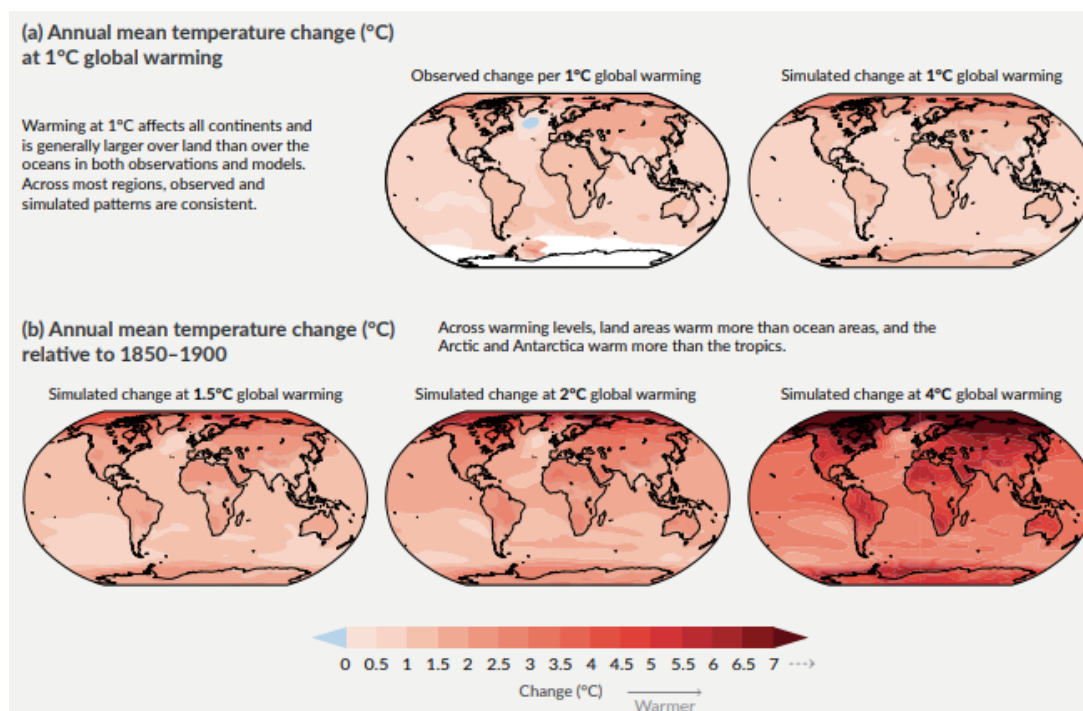
	Best estimate of near-term temperature increase (2021-2040) (°C) [Very likely range]	Best estimate for mid-term temperature increase (2041-2060) (°C) [Very likely range]	Best estimate for long-term temperature increase (2081-2100) (°C) [Very likely range]
RCP1.9	1.5 [1.2 - 1.7]	1.6 [1.2 - 2.0]	1.4 [1.0 - 1.8]
RCP2.6	1.5 [1.2 - 1.8]	1.7 [1.3 - 2.2]	1.8 [1.3 - 2.4]
RCP4.5	1.5 [1.2 - 1.8]	2.0 [1.6 - 2.5]	2.7 [2.1 - 3.5]
RCP7.0	1.5 [1.2 - 1.8]	2.1 [1.7 - 2.6]	3.6 [2.8 - 4.6]
RCP8.5	1.6 [1.3 - 1.9]	2.4 [1.9 - 3.0]	4.4 [3.3 - 5.7]

Note: The different Representative Concentration Pathways (RCP) are labelled after a possible range of radiative forcing values (expressed in W/m2) in the year 2100.
Source: based on IPCC AR6 WG I (2021), Table SPM.1

The impacts of climate change are not distributed evenly across regions and social groups. The communities that have historically contributed the least to global warming are disproportionately affected. Vulnerable people, including the poor, women, children, the elderly and Indigenous people, particularly in low-income countries and marginal geographies, are most affected by the impacts of climate change including by water and food insecurity and water-related extreme events such as floods and droughts. The most impacted communities are in Africa, Asia, Central and South America, Small Islands and the Arctic ⁽¹⁷⁵⁾.

⁽¹⁷⁴⁾<https://climate.copernicus.eu/global-climate-highlights-2023>
⁽¹⁷⁵⁾ IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001

Figure 6: Annual mean temperature change (°C) at different levels of global warming



Source: IPCC AR6 WG I (2021) Figure SPM.5

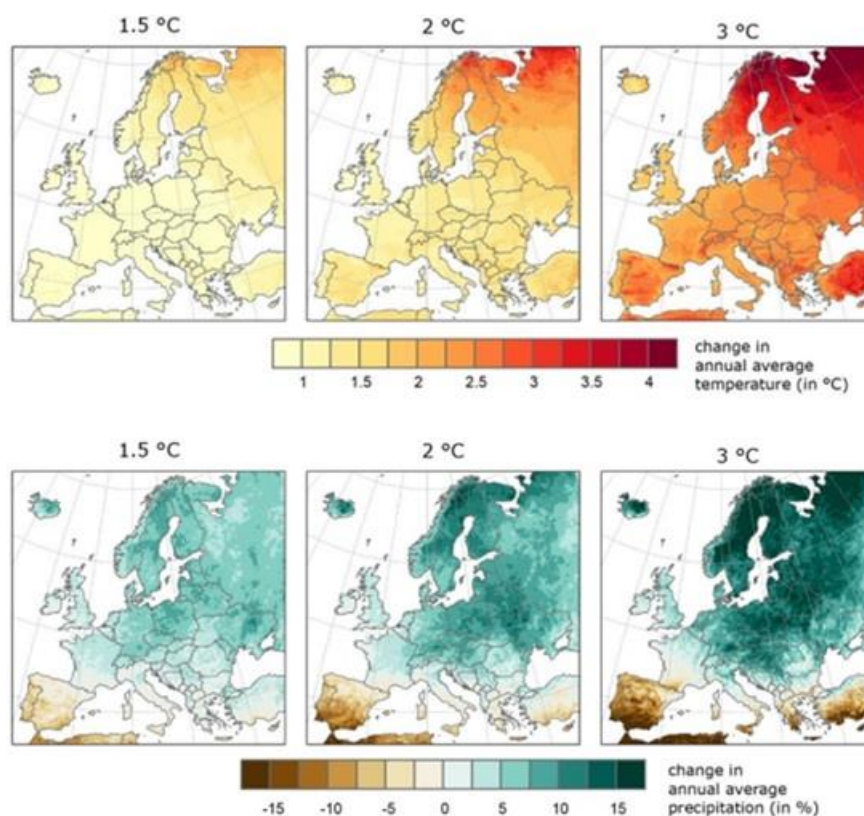
With increasing GHG emissions, global warming will increase in all regions, but the pace of change varies by region (Figure 6). Europe has been warming faster than any other continent, at more than twice the rate of the global average over the past 30 years, with temperatures increasing at an average rate of 0.5°C per decade. Surface air temperature in Europe has increased by 2.2°C (five-year average up to 2023) above pre-industrial era, while the global average for the same period is around 1.2°C ⁽¹⁷⁶⁾, and this trend is projected to continue in the future (Figure 7), increasing the severity of impacts.

The main risks associated with global warming for Europe are increased mortality and morbidity of people due to heat stress, damages to species and ecosystems, expansion of fire-prone areas, agricultural production losses, water scarcity impacting a wide range of users, and risks associated with flooding. Impacts on socio-economic systems are projected to intensify, including widespread damages to infrastructure and businesses. Beyond 2040 the severity of impacts from climate change depends on the level of warming and can be multiple times higher than currently observed. The level of risk in the future depends on the actions taken in the near-term ⁽¹⁷⁷⁾.

⁽¹⁷⁶⁾ Copernicus Climate Change Service (C3S), 2023: European State of the Climate 2022, Full report: climate.copernicus.eu/ESOTC/2022.

⁽¹⁷⁷⁾ IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001

Figure 7: Changes in local annual average temperature and precipitation in Europe



Note: Changes are from reference period (1981-2010), while the three global warming scenarios (1.5°C, 2°C, 3°C) are defined compared to pre-industrial times.

Source: JRC PESETA IV final report ⁽¹⁷⁸⁾

Climate change impacts human and natural systems in a number of ways, affecting ecosystems, people, settlements and infrastructure, which will be discussed in the following sections.

2 IMPACTS OF CLIMATE CHANGE

2.1 Global impacts of climate change and risks of climate tipping points

2.1.1 A very wide range of impacts

Anthropogenic climate change has resulted in widespread and adverse impacts on humans and nature across the globe, disproportionately affecting the most vulnerable people and systems. Increasing frequency and intensity of extreme events have led to human mortality from heat, increases in areas burnt by wildfires, adverse impacts from tropical cyclones due to sea-level rise and the increase in intensity of precipitation. Ecosystems are being severely damaged and climate change has driven species globally to shift polewards or to higher elevations, caused mass mortality events of species on land and in the ocean and at least one species extinction (see section 2.1.3). Climate change and biodiversity loss are interdependent and exacerbating

⁽¹⁷⁸⁾ Feyen L., Ciscar J.C., Gosling S., Ibarreta D., Soria A. (editors) (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. EUR 30180EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18123-1, doi:10.2760/171121, JRC119178.

each other. Climate change is also reducing food and water security, affecting, in particular, communities in Africa, Asia, Central and South America, Small Islands and Arctic. Human physical and mental health is also adversely affected by climate change, including through extreme heat events, increased occurrence of certain diseases, increased exposure to wildfire smoke, dust and aeroallergens, trauma from extreme weather and climate events, and loss of livelihoods and culture ⁽¹⁷⁹⁾.

All of the above-mentioned impacts of climate change have implications for international peace and security, including through potential migratory movements and displacement, pandemics, social unrest, instability and insecurity ⁽¹⁸⁰⁾. The impacts of climate change can be important drivers of migration and displacement, which are strongly influenced by other socio-economic processes. They often emerge when other forms of adaptation are insufficient or not viable. Currently, most climate-change related migrations happen within countries. Most common hazards that result in displacement include tropical cyclones, flooding, and drought. With increasing warming, extreme events are projected to increase in frequency and intensity, which might lead to more people being displaced, especially in most exposed areas ⁽¹⁸¹⁾.

2.1.2 *Climate tipping points*

One of the biggest concerns and uncertainties associated with climate change is the triggering of climate tipping points (Figure 8). Those are critical thresholds beyond which global or regional climate reorganises from one stable state to another, which may lead to abrupt, substantial, irreversible, and dangerous impacts for human and natural systems. Examples include a sudden or substantial sea level rise, the release of greenhouse gases from a thawing permafrost, and dieback of biodiverse biomes such as warm water corals or the Amazon rainforest. Several tipping elements, defined as large-scale Earth system components, are now increasingly unstable ⁽¹⁸²⁾ and a recent study ⁽¹⁸³⁾ found that the current level of global warming already puts us at risk of crossing five tipping points. With any additional increment of a degree of warming, this risk increases. Even within the Paris Agreement temperature range of 1.5°C to below 2°C global warming, the world will be at risk of ten currently

⁽¹⁷⁹⁾ IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001.

⁽¹⁸⁰⁾ Joint communication to the European Parliament and the Council: A new outlook on the climate and security nexus: Addressing the impact of climate change and environmental degradation on peace, security and defence. 28.6.2023.

⁽¹⁸¹⁾ Cissé, G., R. McLeman, H. Adams, P. Aldunce, K. Bowen, D. Campbell-Lendrum, S. Clayton, K.L. Ebi, J. Hess, C. Huang, Q. Liu, G. McGregor, J. Semenza, and M.C. Tirado, 2022: Health, Wellbeing, and the Changing Structure of Communities. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1041–1170, doi:10.1017/9781009325844.009.

⁽¹⁸²⁾ T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, H. J. Schellnhuber, Climate tipping points - too risky to bet against. *Nature* 575, 592–595 (2019).

⁽¹⁸³⁾ David I. Armstrong McKay et al., Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377, eabn7950 (2022). DOI:10.1126/science.abn7950.

identified tipping points being triggered, including the collapse of the Greenland and West Antarctic ice sheets, die-off of low-latitude coral reefs and widespread abrupt permafrost thaw.

Figure 8: The location of climate tipping elements.



Note: The location of climate tipping elements in the cryosphere (blue), biosphere (green), and ocean/atmosphere (orange), and global warming levels at which their tipping points will likely be triggered.

Source: McKay et al. 2022 (184)

Due to large uncertainties in the timing of tipping points being triggered, some may occur much sooner than previously estimated. One of such tipping elements is the Atlantic Meridional Overturning Circulation (AMOC), the key overturning current system in the South and North Atlantic oceans, that helps regulate the climate of the Northern Hemisphere. Its collapse would have severe impact on the global climate system and could impact the stability of other major tipping elements, including the Antarctic ice sheet, tropical monsoon system and the Amazon rainforest. There is evidence that the strength of AMOC has been weakening in the recent decades ⁽¹⁸⁵⁾ ⁽¹⁸⁶⁾ mainly as the result of the freshwater influx from the melting of the Greenland Ice Sheet as well as increased river discharge into the Arctic Ocean due to global warming. While the IPCC AR6 evaluated that an abrupt collapse before the end of the century is unlikely to occur ⁽¹⁸⁷⁾, recent research ⁽¹⁸⁸⁾ suggests that it could actually occur

⁽¹⁸⁴⁾ David I. Armstrong McKay et al., Exceeding 1.5°C global warming could trigger multiple climate tipping points. *Science* 377, eabn7950 (2022). DOI:10.1126/science.abn7950.

⁽¹⁸⁵⁾ Rahmstorf, S. et al. 2015. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Climate Change* 5, 475–480.

⁽¹⁸⁶⁾ Boers, N. 2021. Observation-based early-warning signals for a collapse of the Atlantic Meridional Overturning Circulation. *Nat. Clim. Chang.* 11, 680–688. <https://doi.org/10.1038/s41558-021-01097-4>

⁽¹⁸⁷⁾ Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy,

much earlier, with a central estimate of 2050 (95% confidence interval between 2025-2095) under current projections of future greenhouse gas emissions. If greenhouse gas emissions are not urgently reduced, the expected tipping point could therefore be triggered much earlier than previously estimated, with catastrophic impacts around the world, including on rain patterns in Asia, South America and Africa, increased storm weather and decrease in temperatures in Europe and increased sea level rise on the eastern coast of North America.

Reaching one climate tipping point could also result in triggering other ones with potentially catastrophic impacts (Figure 9). Crossing multiple tipping points would have implications for socio-economic and ecological systems in a timespan that is too short for them to adapt, which could cause severe impacts. Regional impacts of crossing individual tipping points include extreme temperatures, droughts, wildfires, and unprecedented weather, while globally they could result in a release of a significant amount of greenhouse gases, causing climate feedback loops and fast sea-level rise, leading to the global climate less suitable for human existence ⁽¹⁸⁹⁾.

J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011.

⁽¹⁸⁸⁾ Ditlevsen P and Ditlevsen S. 2023. 2023. Waiting for a forthcoming collapse of the Atlantic meridional overturning circulation. *Nature Communications*: 12 (4245).

⁽¹⁸⁹⁾ OECD, *Climate Tipping Points – Insights for Effective Policy Action*. 2022. <https://doi.org/10.1787/abc5a69e-en>

Figure 9: The connectivity of tipping points



2.1.3 Impacts on ecosystems and biodiversity

Climate change is one of the five main drivers of global biodiversity loss, together with change of land and sea use, direct exploitation, pollution and invasive alien species⁽¹⁹¹⁾. This fact seems to be known among respondents in the Public Consultation. The loss of biodiversity and natural habitats was ranked at the first place both by individuals (77%) and organisations (42%) on the question of which effects of climate change were most concerning for respondents.

⁽¹⁹⁰⁾ T. M. Lenton, J. Rockström, O. Gaffney, S. Rahmstorf, K. Richardson, W. Steffen, H. J. Schellnhuber, Climate tipping points - too risky to bet against. *Nature* 575, 592–595 (2019).

⁽¹⁹¹⁾ PBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. Available at: <https://doi.org/10.5281/ZENODO.3831673>

Terrestrial and freshwater ecosystems are adversely affected by climate change, which impacts their ranges, phenology, physiology and morphology. Local population extinctions due to climate change have been widespread, particularly affecting tropical regions and freshwater habitats. Many species are shifting their ranges to higher latitudes or elevations, altering community make-up. Particularly in northern latitudes exotic species can adapt to climate change better than native ones, leading to potential new invasive species. Water temperature of rivers and lakes has increased, and the extent and duration of ice cover has decreased in past decades. With warming, primary productivity generally increased and dissolved oxygen concentrations declined, affecting ecosystems. Climate change also increases the wildlife disease severity, outbreak frequency and emergence of novel vectors and diseases in new areas. Severity and extent of outbreaks of forest insect pests have increased in the northern North America and northern Eurasia, and climate change is fostering spread of invasive alien species, with ever increasing damages and costs ⁽¹⁹²⁾. Climate change induced increases in area burned by wildfire, increasing tree mortality and biome shifts in tropical, temperate and boreal ecosystems, are further damaging ecologic integrity.

Ecosystems provide various services critical for human health, wellbeing and livelihoods, including climate regulation, food and water provision, provision of medicine and other materials, water retention, protection against droughts, floods, urban heat and desertification, and pollination, which are already negatively affected by climate change. Increasing global warming levels will increase negative impacts on ecosystems, including increasing risk of species extinction, biome shifts and increase in area burned by wildfires. Ecosystems also remove carbon from the atmosphere and represent a carbon stock of more than four times the amount of carbon currently in the atmosphere. Processes related to climate change including wildfires, tree mortality, peatland drying and permafrost thaw, turn those ecosystems from a carbon sink into a carbon source by releasing the carbon stored in those ecosystems into the atmosphere, exacerbating positive climate feedbacks ⁽¹⁹³⁾⁽¹⁹⁴⁾. However, it is important to clarify that the effects of climate change are often worsen by human intervention, through unsustainable practices and natural resources depletion. For example, intensive forestry practices (clear-cuts, monoculture plantations) exacerbate the risks of extreme weather events, such as wildfires and floods ⁽¹⁹⁵⁾ ⁽¹⁹⁶⁾.

⁽¹⁹²⁾ IPBES assessment on invasive alien species and their control (2023)

⁽¹⁹³⁾ Parmesan, C., M.D. Morecroft, Y. Trisurat, R. Adrian, G.Z. Anshari, A. Arneth, Q. Gao, P. Gonzalez, R. Harris, J. Price, N. Stevens, and G.H. Talukdar, 2022: Terrestrial and Freshwater Ecosystems and Their Services. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 197–377, doi:10.1017/9781009325844.004.

⁽¹⁹⁴⁾ United Nations Environment Programme (2021). Making Peace with Nature: A scientific blueprint to tackle the climate, biodiversity and pollution emergencies. Nairobi. <https://www.unep.org/resources/making-peace-natur>

⁽¹⁹⁵⁾ Robbie S.H. Johnson, Younes Alila (2023) Nonstationary stochastic paired watershed approach: Investigating forest harvesting effects on floods in two large, nested, and snow-dominated watersheds in British Columbia, Canada, Journal of Hydrology, Volume 625, Part A, 129970, ISSN 0022-1694, <https://doi.org/10.1016/j.jhydrol.2023.129970>

⁽¹⁹⁶⁾ Lindenmayer, D.B., Kooyman, R.M., Taylor, C. *et al.* Recent Australian wildfires made worse by logging and associated forest management. *Nature Ecology and Evolution* **4**, 898–900 (2020). <https://doi.org/10.1038/s41559-020-1195-5>

Wildfires pose risk to people and ecosystems, they are becoming more frequent and intense at the global scale, and their likelihood is projected to further increase by the end of the century. They result from complex interactions between climate, land-use and land management practices, and demographics, and while some risks can be reduced with appropriate management, including ecosystem restoration, the risk posed by wildfires cannot be entirely eliminated. Climate change increases the frequency and magnitude of dangerous fire weather through increased drought, heat, decreased humidity, dry lighting, and strong winds. Wildfires affect the global carbon cycle by releasing CO₂ into the atmosphere, further exacerbating global warming. They cause loss of lives and livelihoods, impact health, devastate ecosystems and degrade watersheds. Increased fire frequency can have catastrophic impacts on biodiversity in fire-sensitive ecosystems and is especially damaging for long-lived plant species. The impacts of wildfires can be long-lasting, including in biodiversity hotspots, which might never fully recover. Very frequent fires can eliminate woody plant species which are replaced with herbaceous and often annual species, or invasives weeds. Fire also changes soil properties and increases soil erosion ⁽¹⁹⁷⁾. The recent wildfires in Greece, followed by massive floods, are an example of how the loss of forest due to fires weakened the water retention capacity of soils, leading to dramatic consequences.

Climate change is also altering the physical and chemical characteristics of the ocean, affecting ocean and coastal species and ecosystems in every region. The seas and ocean are one of the greatest sources of biodiversity and food, they regulate the climate, and are a major carbon sink ⁽¹⁹⁸⁾. Warming, acidification and deoxygenation are changing the distribution and abundance of species populations, altering ecological communities and leading to habitat loss and/or damage, population declines, increased risks of species extirpations and extinctions and the rearrangement of marine food webs.

The uptake of CO₂ in the sea is the cause of ocean acidification. Change in pH affects biological processes such as the primary production and reduces the carbonate available for the calcification of marine calcifying organisms such as shellfish and plankton. Changes in marine primary production will have an impact on the global carbon cycle and the absorption of atmospheric CO₂ in the ocean and reduce oceans capacity to mitigate climate change. These rapid chemical changes are an added pressure on marine ecosystems ⁽¹⁹⁹⁾ and affect food production from shellfish aquaculture and fisheries in some oceanic regions.

Marine heatwaves are increasing in frequency, duration and intensity and result in mass mortalities of open-ocean, coastal and shelf-sea ecosystems including coral reefs, kelp forests and mangroves. Climate change driven impacts are affecting industries, causing economic losses, impacting physical and mental health and altering cultural and recreational activities around the world ⁽²⁰⁰⁾. In 2023 global average sea surface temperatures reached record levels

⁽¹⁹⁷⁾ United Nations Environment Programme (2022). Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. Nairobi

⁽¹⁹⁸⁾ Report from the Commission to the European Parliament and the Council on the implementation of the Marine Strategy Framework Directive (Directive 2008/56/EC) COM (2020) 259.

⁽¹⁹⁹⁾ EEA, 2020, Ocean acidification. Indicator, European Environment Agency

⁽²⁰⁰⁾ Cooley, S., D. Schoeman, L. Bopp, P. Boyd, S. Donner, D.Y. Ghebrehewet, S.-I. Ito, W. Kiessling, P. Martinetto, E. Ojea, M.-F. Racault, B. Rost, and M. Skern-Mauritzen, 2022: Oceans and Coastal Ecosystems and Their Services. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S.

for the time of year every month from April to December. In the boreal summer, marine heat waves affected large sectors of the North Atlantic, parts of the North Pacific and Indian Oceans, around New Zealand, the Gulf of Mexico, the Caribbean and the Mediterranean, causing significant and devastating impacts on ocean ecosystems. Antarctic sea ice reached record low extends for the corresponding month in 8 months of 2023 ⁽²⁰¹⁾ ⁽²⁰²⁾.

In the North-East Atlantic region, the OSPAR Convention identified climate change as causing fundamental and possibly irreversible changes to the oceans including a significant risk for productivity and the long-term viability of marine ecosystems. Among the objectives described in the Strategy of the OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic 2030, one of them is to achieve seas resilient to the impacts of climate change and ocean acidification.

Biodiversity hotspots, which are areas of exceptional biodiversity and/or high endemism, are already affected by climate change. Climate change impacts are compounded by other anthropogenic impacts, including habitat loss and fragmentation, over-exploitation and pollution, which reduce ecosystem resilience. The risk of species extinction increases with global warming and is particularly high for endemic species in biodiversity hotspots on islands, on mountains and in the ocean ⁽²⁰³⁾.

2.1.3.1 Estimated impacts of biodiversity loss and ecosystem degradation on economy and human health

The impacts of climate change on biodiversity also have severe consequences for prosperity and well-being: the impacts of climate change on biodiversity undermine the ability to build a sustainable future based on healthy, functioning ecosystems. The economic importance of biodiversity has become a consensus, even within the largest international economic financial institutions, such as the OECD ⁽²⁰⁴⁾, the World Bank ⁽²⁰⁵⁾ or the World Economic Forum ⁽²⁰⁶⁾.

The World Economic Forum considers that US \$44 trillion of economic value generation – over half the world’s total GDP – is moderately or highly dependent on nature and its

Löschke, V. Möller, A. Okem, B. Rama (eds.)). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 379–550, doi:10.1017/9781009325844.005

⁽²⁰¹⁾ <https://climate.copernicus.eu/global-climate-highlights-2023>

⁽²⁰²⁾ <https://wmo.int/publication-series/provisional-state-of-global-climate-2023>

⁽²⁰³⁾ Costello, M.J., M.M. Vale, W. Kiessling, S. Maharaj, J. Price, and G.H. Talukdar, 2022: Cross-Chapter Paper 1: Biodiversity Hotspots. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2123–2161, doi:10.1017/9781009325844.018.

⁽²⁰⁴⁾ OECD (2019) 'Biodiversity: Finance and the Economic and Business Case for Action'. URL: <https://www.oecd.org/env/resources/biodiversity/biodiversity-finance-and-the-economic-and-business-case-for-action.htm>

⁽²⁰⁵⁾ World Bank (2021). The Economic Case for Nature: A Global Earth-Economy Model to Assess Development Policy Pathways. Available at: <http://hdl.handle.net/10986/35882>.

⁽²⁰⁶⁾ World Economic Forum (2023). The Global Risks Report 2023. Geneva, WEF.

services, especially sectors such as construction, agriculture, and food and beverages ⁽²⁰⁷⁾. The European Central Bank considers that nearly 75% of all bank loans in the euro area are to companies that are highly dependent on at least one ecosystem service, and that an integrated approach to climate and nature is critical because they are interconnected and amplify the effects of physical and transition risks ⁽²⁰⁸⁾. Studies carried out at national level are converging on the same conclusions: for example, 42% of the value of securities held by French financial institutions ⁽²⁰⁹⁾ and 44% of French gross value added appears to be 'heavily' or 'very heavily' dependent on natural capital ⁽²¹⁰⁾.

Because of the economy's dependence on the state of biodiversity, the impacts of climate change on biodiversity have major economic consequences. In 2020, the Global Futures report by WWF estimated the economic costs of inaction on climate and ecological crises to around USD 10 trillion in GDP by 2050 ⁽²¹¹⁾. By modelling changes in the average abundance of terrestrial species as an indicator of biodiversity and estimating biodiversity loss using a function that relates expenditure to temperature change, the OECD estimated that the impacts of climate change on biodiversity would entail significant costs for EU countries, ranging from 0.5% to 1.1% of GDP, for RCP6.0 and RCP8.5, respectively ⁽²¹²⁾. A systematic assessment of the climate change impacts on European forests and its capacity to deliver ecosystem services show significant welfare losses in all forest European regions, when considering cultural values, carbon sequestration and wood forest products ⁽²¹³⁾. Despite these figures, there are still very large gaps in the evaluation of the economics costs associated to the climate change impacts on biodiversity, starting with estimates of physical impacts, and including all aspects of the economic valuation of biodiversity and ecosystem services ⁽²¹⁴⁾.

The latest IPBES report on invasive species ⁽²¹⁵⁾ estimates that the yearly cost of invasive species in the global economy is already near EUR 400 billion. The authors underline that

⁽²⁰⁷⁾ WEF (2020) Nature Risk Rising: Why the Crisis Engulfing Nature Matters for Business and the Economy. URL: https://www3.weforum.org/docs/WEF_New_Nature_Economy_Report_2020.pdf

⁽²⁰⁸⁾ European Central Bank (2023) The economy and banks need nature to survive. Available at: <https://www.ecb.europa.eu/press/blog/date/2023/html/ecb.blog230608~5cffb7c349.en.html>

⁽²⁰⁹⁾ Svartzman, R. et al. (2021) 'A "Silent Spring" for the Financial System? Exploring Biodiversity-Related Financial Risks in France', SSRN Electronic Journal [Preprint]. URL: <https://doi.org/10.2139/ssrn.4028442>.

⁽²¹⁰⁾ Bouchet, V. et al. (2021) Évaluations économiques des services rendus par la biodiversité. DG Trésor. URL: <https://www.tresor.economie.gouv.fr/Articles/2021/12/09/evaluations-economiques-des-services-rendus-par-la-biodiversite>

⁽²¹¹⁾ Johnson, J.A., et al. 2020. Global Futures : modelling the global economic impacts of environmental change to support policy-making. Technical Report, January 2020. URL: <https://www.wwf.org.uk/globalfutures>

⁽²¹²⁾ OECD (2015) The Economic Consequences of Climate Change. OECD. URL: <https://doi.org/10.1787/9789264235410-en>.

⁽²¹³⁾ Ding, H. et al. (2016) 'Valuing climate change impacts on European forest ecosystems', Ecosystem Services, 18, pp. 141–153. Available at: <https://doi.org/10.1016/j.ecoser.2016.02.039>.

⁽²¹⁴⁾ COACCH (2018). The Economic Cost of Climate Change in Europe: Synthesis Report on State of Knowledge and Key Research Gaps. Policy brief by the COACCH project. Available at: <https://www.ecologic.eu/sites/default/files/publication/2018/2811-coacch-review-synthesis-updated-june-2018.pdf>

⁽²¹⁵⁾ IPBES (2023) Summary for Policymakers of the Thematic Assessment Report on Invasive Alien Species and their Control of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Roy, H. E., Pauchard, A., Stoett, P., Renard Truong, T., Bacher, S., Galil, B. S., Hulme, P. E., Ikeda, T., Sankaran, K. V., McGeoch, M. A., Meyerson, L. A., Nuñez, M. A., Ordonez, A., Rahlao, S. J.,

invasive species play a key role in 60% of the extinctions of plants and animals, and they are the sole responsible of 16% of the documented global extinctions.

By altering the composition and functioning of ecosystems, climate change impacts on biodiversity have also serious health consequences. Climate change affects the health of ecosystems, influencing shifts in the distribution of plants, viruses, animals, and even human settlements. This can create increased opportunities for animals to spread diseases and for viruses to spill over to humans ⁽²¹⁶⁾. In Europe, global warming is facilitating the spreading of a number of diseases transmitted by mosquitoes such as Zika fever, dengue and chikungunya and transmitted by tick such as Lyme's disease, thus exposing new populations and regions for extended period to these diseases ⁽²¹⁷⁾. Human health can also be affected by reduced ecosystem services, such as the loss of food, medicine and livelihoods provided by nature, or by the direct consequences of climate change on ecosystems. For instance, wildfire smoke impacts human health more than fine particles from other sources, including automobiles emissions ⁽²¹⁸⁾. Zoonotic diseases are also a consequence of the combination of biodiversity loss and climate change. Further warming will impact all forms of zoonoses be it water, food, vector, rodent, or airborne origin and will also increase the emergence of novel infections with pandemic potential ⁽²¹⁹⁾.

Since biodiversity underpins functions and services that are essential to agriculture, forestry and fisheries, climate change impacts on biodiversity threatens food security, water security and economic stability. At EU level, the ecosystem services provided by the Natura 2000 network alone are estimated to have a value of EUR 200-300 billion per year ⁽²²⁰⁾. In France, pioneering work on estimating the cost of inaction on climate change has shown that the upper limit of the impact of biodiversity loss on economic activity could be up to EUR 80 billion and hundreds of thousands of direct jobs ⁽²²¹⁾.

As regards food systems, climate change impacts on biodiversity leads to multiple deleterious consequences. In agriculture, climate change contributes significantly to the decline in density and diversity of pollinators, thus reducing the pollination efficiency of crop species ⁽²²²⁾. Such

Schwindt, E., Seebens, H., Sheppard, A. W., and Vandvik, V. (eds.). IPBES secretariat, Bonn, Germany.
<https://doi.org/10.5281/zenodo.7430692>

⁽²¹⁶⁾ WHO (2021) Nature, biodiversity and health: an overview of interconnections. URL: <https://www.who.int/europe/publications/i/item/9789289055581>

⁽²¹⁷⁾ Semenza, J.C. and Paz, S. (2021) 'Climate change and infectious disease in Europe: Impact, projection and adaptation', The Lancet Regional Health - Europe, 9, p. 100230. URL: <https://doi.org/10.1016/j.lanepe.2021.100230>.

⁽²¹⁸⁾ Aguilera, R. et al. (2021) 'Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California', Nature Communications, 12(1), p. 1493. Available at: <https://doi.org/10.1038/s41467-021-21708-0>.

⁽²¹⁹⁾ The Lancet Infectious Diseases (2023), Twin threats: climate change and zoonoses, Volume 23, Issue 1, Page 1, ISSN 1473-3099, [https://doi.org/10.1016/S1473-3099\(22\)00817-9](https://doi.org/10.1016/S1473-3099(22)00817-9).

⁽²²⁰⁾ European Commission. Directorate General for the Environment. (2013) The economic benefits of the Natura 2000 network :synthesis report. Available at: <https://data.europa.eu/doi/10.2779/41957>.

⁽²²¹⁾ Delahais, A. and Robinet, A. (2023) The cost of inaction on climate change: what do we know? France Stratégie. Available at: <https://www.strategie.gouv.fr/english-articles/cost-inaction-climate-change-what-do-we-know>

⁽²²²⁾ Marshman, J., Blay-Palmer, A. and Landman, K. (2019) 'Anthropocene Crisis: Climate Change, Pollinators, and Food Security', Environments, 6(2), p. 22. URL: <https://doi.org/10.3390/environments6020022>.

impacts can have costly consequences as EUR 15 billion of annual agricultural output is directly attributed to pollination in the EU (²²³). Climate change would increase the prevalence of insect pests exacerbating yield loss of crops: in Europe, the accelerating northward migration of agro-climatic zones (²²⁴) might be accompanied with an increasing spread of pest species and diseases, and mounting severity and economic impacts of outbreaks (²²⁵). Livestock sectors would also be heavily impacted, directly through animal diseases and indirectly through decreased feed availability and quality (²²⁶), or increased attacks on livestock by predators driven to human-dominated areas in search of food (²²⁷). In marine ecosystems, global warming threatens food security, as loss of fish habitats is modifying the distribution and productivity of both marine and freshwater species thus affecting the sustainability of fisheries and populations dependent on them (²²⁸). In particular, loss of coral reefs does not only mean loss of one of the most biodiverse ecosystems but will also have a huge impact on people. Tens of millions of people depend on coral reefs for protein and other services, and almost 500 million people, or 8% of the world's population, live within 100 km of a reef (²²⁹).

2.2 Impacts on selected most vulnerable regions

Not all the regions are equally affected by climate change. Risk, as a potential for adverse consequences, results from interactions between climate hazards, vulnerability, and exposure. There are geographical, social and contextual determinants of vulnerability, and so vulnerability differs across geographies, but also between and within societies and communities (Figure 10). Communities most vulnerable to climate change are located in West-, Central- and East Africa, South Asia, Central and South America and Small Island Developing States and the Arctic (²³⁰). Three of these most vulnerable regions are described in more detail below.

(²²³) Potts S., et al. (2015) Status and trends of European pollinators. Key findings of the STEP project. Pensoft Publishers, Sofia. URL: <http://step-project.net/img/uplf/STEP%20brochure%20online-1.pdf>

(²²⁴) Ceglar, A. et al. (2019) 'Observed Northward Migration of Agro-Climate Zones in Europe Will Further Accelerate Under Climate Change', *Earth's Future*, 7(9), pp. 1088–1101. URL: <https://doi.org/10.1029/2019EF001178>.

(²²⁵) Skendžić, S. et al. (2021) 'The Impact of Climate Change on Agricultural Insect Pests', *Insects*, 12(5), p. 440. URL : <https://doi.org/10.3390/insects12050440>.

(²²⁶) Godde, C.M. et al. (2021) 'Impacts of climate change on the livestock food supply chain; a review of the evidence', *Global Food Security*, 28, p. 100488. URL: <https://doi.org/10.1016/j.gfs.2020.100488>.

(²²⁷) Abrahms, B. (2021). Human-wildlife conflict under climate change. *Science*, 373(6554), 484–485. <https://doi.org/10.1126/science.abj4216>

(²²⁸) Salvatelli, R. et al. (2022) 'Smaller fish species in a warm and oxygen-poor Humboldt Current system', *Science*, 375(6576), pp. 101–104. URL : <https://doi.org/10.1126/science.abj0270>.

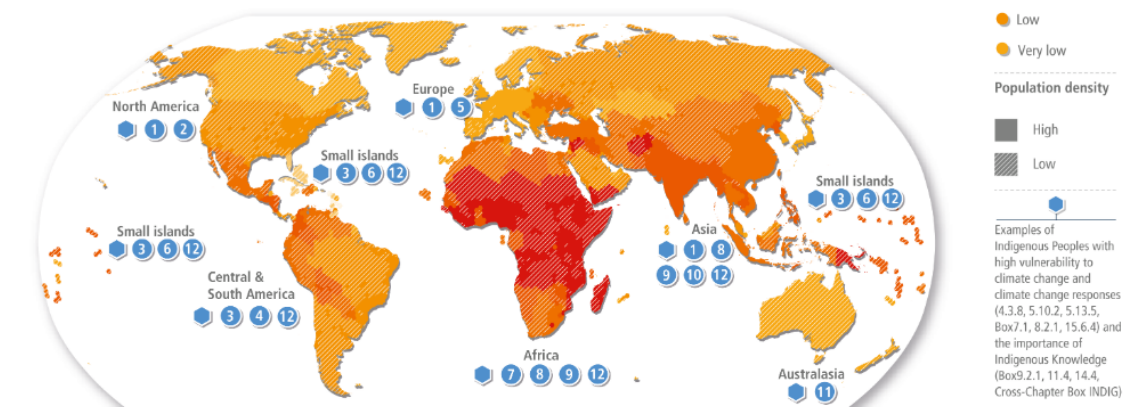
(²²⁹) Veron, J.E.N. et al. (2009) 'The coral reef crisis: The critical importance of <350ppm CO₂', *Marine Pollution Bulletin*, 58(10), pp. 1428–1436. <https://doi.org/10.1016/j.marpolbul.2009.09.009>.

(²³⁰) IPCC, 2022: Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)]. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33, doi:10.1017/9781009325844.001

Figure 10: Map of human vulnerability.

Observed human vulnerability differs between and within countries and strongly determines how climate hazards impact people and society

(a) Map of observed human vulnerability based on two comprehensive global indicator-systems using national data, plus examples of selected local vulnerable populations and Indigenous Peoples



Examples of local vulnerable populations | Examples of some aspects of vulnerability | Chapter references

1 Indigenous Peoples of the Arctic health inequality, limited access to subsistence resources and culture CCP 6.2.3, CCP 6.3.1 2 Urban ethnic minorities structural inequality, marginalisation, exclusion from planning processes 14.5.9, 14.5.5, 6.3.6 3 Smallholder coffee producers limited market access & stability, single crop dependency, limited institutional support 5.4.2 4 Indigenous Peoples in the Amazon land degradation, deforestation, poverty, lack of support 8.2.1, Box 8.6 5 Older people, especially those poor & socially isolated health issues, disability, limited access to support 8.2.1, 13.7.1, 6.2.3, 7.1.7 6 Island communities limited land, population growth and coastal ecosystem degradation 15.3.2	7 Children in rural low-income communities food insecurity, sensitivity to undernutrition and disease 5.12.3 8 People uprooted by conflict in the Near East and Sahel prolonged temporary status, limited mobility Box 8.1, Box 8.4 9 Women & non-binary limited access to & control over resources, e.g. water, land, credit Box 9.1, CCB-GENDER, 4.8.3, 5.4.2, 10.3.3 10 Migrants informal status, limited access to health services & shelter, exclusion from decision-making processes 6.3.6, Box 10.2 11 Aboriginal and Torres Strait Islander Peoples poverty, food & housing insecurity, dislocation from community 11.4.1 12 People living in informal settlements poverty, limited basic services & often located in areas with high exposure to climate hazards 6.2.3, Box 9.1, 9.9, 10.4.6, 12.3.2, 12.3.5, 15.3.4

Source: IPCC AR6 WG II (2022). Figure TS.7

2.2.1 Africa

African countries are highly vulnerable to anthropogenic climate change and are already experiencing adverse and widespread negative impacts. Climate change has caused a loss of biodiversity, reduced water availability and food security and led to the loss of life, and with increasing global warming the impacts are projected to intensify. Heat waves, drought and marine heatwaves have increased in frequency and intensity due to climate change ⁽²³¹⁾.

Africa has been warming more rapidly than the global average, and northern Africa has a higher warming trend compared to other African regions. The number of extreme warm days has been increasing over continental Africa. The rate of sea-level rise along African coasts is above the global mean, particularly along the Red Sea and south-west Indian Ocean. Relative sea-level rise is projected to continue, affecting the frequency and severity of coastal flooding. Climate change has also affected glaciers in equatorial East Africa, which are retreating at a rate faster than the global mean, and some are projected to disappear by 2030. Extreme and high-impact events attributed to climate change were observed in Africa in the past years, including extreme floods in South Sudan, and flooding in Niger, Congo, Benin, and Nigeria,

(231) Trisos, C.H., I.O. Adelekan, E. Totin, A. Ayanlade, J. Efitire, A. Gameda, K. Kalaba, C. Lennard, C. Masao, Y. Mgaya, G. Ngaruiya, D. Olago, N.P. Simpson, and S. Zakieldean, 2022: Africa. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1285–1455, doi:10.1017/9781009325844.011.

where it contributed to the spread of cholera. In 2021 Somalia experienced persistent drought conditions, affecting more than 3.2 million people and displacing 169 000 people. The same year Madagascar experienced the worst drought in 40 years, causing 70% of the population of southern Madagascar to lack access to basic drinking water ⁽²³²⁾. In 2022, eastern Africa experienced the fifth consecutive year of below average rainfall during the wet season, exposing an estimated 37 million people to acute food insecurity due to drought and other shocks ⁽²³³⁾. In March 2023, Tropical Cyclone Freddy caused extreme rainfall and flooding in Mozambique and Malawi. At least 844 fatalities were reported and over 659 000 people were internal displaced. Fatalities were also reported in Madagascar and Zimbabwe. The heatwaves in the summer of 2023 affected North Africa, while the Greater Horn of Africa saw unusually large rainfalls amounts during the Gu rain season, displacing at least 1.4 million people, in addition to the 2.7 million who were displace due to five consecutive seasons of drought. In September 2023 Libya experienced extreme rainfall that caused devastating flooding and heavy loss of life with 4345 confirmed deaths and more than 8500 people still missing ⁽²³⁴⁾ ⁽²³⁵⁾.

With increasing global warming, mean temperature is projected to increase across Africa, and temperatures extremes will increase over most of the continent. Eastern Sahel, eastern Africa and central Africa are projected to receive increased mean annual rainfall, while it is projected to decrease in southwestern and southern Africa and coastal northern Africa, which are projected to experience increased meteorological and agricultural drought. For most of the continent, except northern and southwestern Africa, increased frequency and intensity of heavy precipitation is projected. With increasing climate change, reductions in economic growth are projected for low- and middle-income countries.

IPCC WG II (2022) identified key risks for Africa (Figure 11) as species extinction and damage to ecosystems, reduced food production, reduced water security, reduced energy security, reduced economic growth and increased poverty, increased disease, mortality and morbidity, damage to critical infrastructure and human settlements due to extreme events and loss of natural and cultural heritage. At 1.5°C global warming, all of the listed risks will transition to high, and some become very high at below 2°C global warming. At 1.5°C a 9% decline in maize yield is projected in West Africa and 20-60% reduction in wheat yield in southern and northern Africa. Coffee and tea production in east Africa is projected to decline, as well as sorghum production in west Africa. A more than 12% decline in marine fisheries is projected for west Africa at 1.5°C global warming, which could expose millions of people to nutritional deficiencies. Climate change also increases the incidence of vector-borne diseases including malaria (east and southern Africa), dengue and zika (north, east and southern Africa). Decreased crop yields could expose millions of people to malnutrition, particularly in central, eastern and western Africa. Heatwaves are projected to cause more than 15 additional deaths per 100 000 people per year in parts of western, eastern and northern Africa.

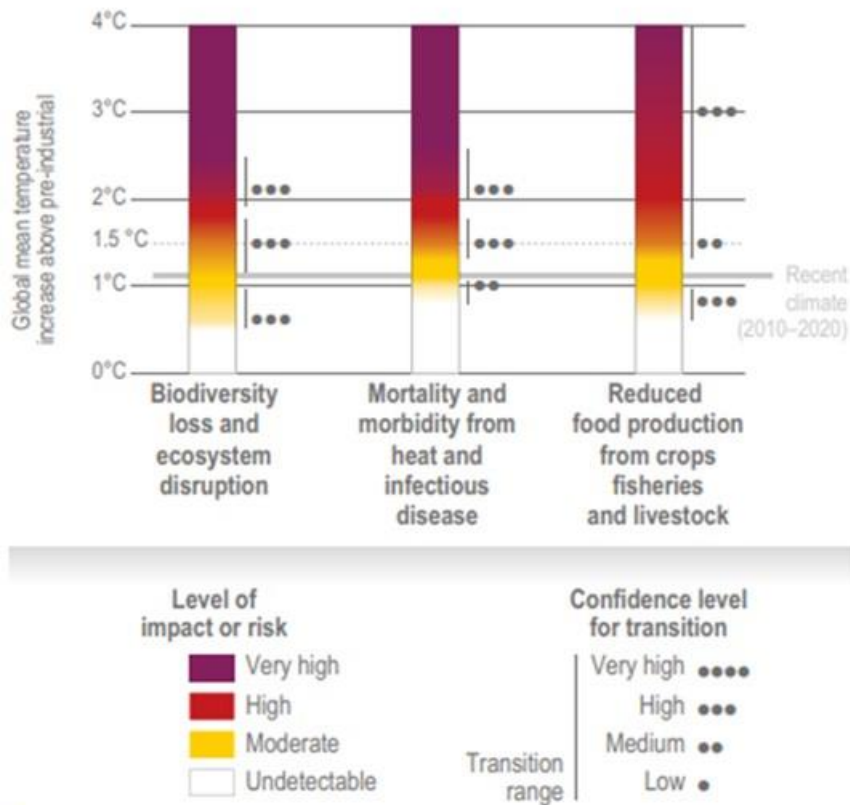
⁽²³²⁾ World Meteorological Organization: State of the Climate in Africa 2021 (WMO-No. 1300). 2022. Chair, Publications Board, WMO, Geneva, Switzerland, ISBN 978-92-63-11300-9

⁽²³³⁾ World Meteorological Organization (2023): State of the Global Climate 2022 (WMO-No. 1316). ISBN: 978-92-63-11316-0.

⁽²³⁴⁾ <https://public.wmo.int/en/media/news/storm-daniel-leads-extreme-rain-and-floods-mediterranean-heavy-loss-of-life-libya>

⁽²³⁵⁾ <https://wmo.int/files/provisional-state-of-global-climate-2023>

Figure 11: Key risks for Africa increase with increasing global warming.



Source: IPCC AR6 WG II (2022). Figure 9.6

Climate change impacts health, livelihoods and food security of different communities and social groups in Africa differently, depending on their social, cultural and geographical context. The vulnerability of individuals to the impacts of climate change interacts with non-climatic processes, including socio-economic processes. The most vulnerable groups include pastoralists, fishing communities, small scale farmers and urban settlement residents. Women are disproportionately affected by the impacts of climate change. Refugees and Internally Displaced People are also particularly affected. Some of the most vulnerable regions in Africa are the arid and semi-arid countries in the Sahelian belt and the greater Horn of Africa ⁽²³⁶⁾.

2.2.2 Small Islands

Small islands are adversely affected by increasing temperature, sea-level rise, heavy precipitation, increasing intensity of tropical cyclones, storm surges, droughts and coral

⁽²³⁶⁾ Trisos, C.H., I.O. Adelekan, E. Totin, A. Ayanlade, J. Efitre, A. Gemed, K. Kalaba, C. Lennard, C. Masao, Y. Mgaya, G. Ngaruiya, D. Olago, N.P. Simpson, and S. Zakieldeen, 2022: Africa. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1285–1455, doi:10.1017/9781009325844.011.

bleaching. Climate change is already negatively impacting their ecosystems, infrastructure and settlements, health and well-being, water and food security, economy and culture ⁽²³⁷⁾.

The intensity and intensification rates of tropical cyclones have increased in the past decades. They are threatening human life, settlements and infrastructure of small islands. In the past years, most Caribbean islands were affected by at least one tropical cyclone of category 4 or 5. In 2017 for example, Tropical Cyclone Maria (category 5) adversely affected Dominica, Saint Croix and Puerto Rico, causing over 3 000 casualties in Puerto Rico and Dominica alone. The economic losses amounted to USD 69.39 billion in Puerto Rico. Dominica saw its vegetation eradicated, 95% of houses destroyed and complete destruction of agriculture. Economic losses amounted to 224% of its GDP ⁽²³⁸⁾.

Small islands are among the most threatened on the planet by water insecurity. The reduction on freshwater volume due to sea level rise and drought threatens freshwater stress, which increases with increasing global warming.

Small islands, particularly those in the Pacific and Indian Ocean have experienced coral bleaching and loss of coral abundance, which are increasing. It is projected that above 1.5°C global warming 70-90% of reef building corals will be lost and at 2°C global warming the loss will increase to 99%, severely affecting multiple ecosystem services important to small island communities.

Projected changes in wave climate superimposed on sea-level rise will increase coastal flooding in small islands, which is a major concern, as a significant part of their population lives in the low-elevation coastal zone. It is projected that the frequency, extent, duration and consequences of coastal flooding will significantly increase from 2050.

IPCC WG II (2022) identified key risks for small islands as: loss of marine and coastal biodiversity and ecosystem services, submergence of reef islands, loss of terrestrial biodiversity and ecosystem services, water insecurity, destruction of settlements and infrastructure, degradation of human health and well-being, economic decline and livelihood failure and loss of cultural resources and heritage, all resulting in the reduced habitability of islands ⁽²³⁹⁾.

⁽²³⁷⁾ Mycoo, M., M.Wairiu, D. Campbell, V. Duvat, Y. Golbuu, S. Maharaj, J. Nalau, P. Nunn, J. Pinnegar, and O.Warrick, 2022: Small Islands. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2043–2121, doi:10.1017/9781009325844.017.

⁽²³⁸⁾ World Meteorological Organization: [Notable Tropical Cyclones | World Meteorological Organization \(wmo.int\)](https://www.wmo.int). Accessed 29.6.2023.

⁽²³⁹⁾ Mycoo, M., M.Wairiu, D. Campbell, V. Duvat, Y. Golbuu, S. Maharaj, J. Nalau, P. Nunn, J. Pinnegar, and O.Warrick, 2022: Small Islands. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2043–2121, doi:10.1017/9781009325844.017.

2.2.3 Asia

Surface air temperature has been increasing across Asia, increasing the likelihood of heatwaves, droughts, sand and dust storms, impacting the monsoon circulation, floods in monsoon regions and melting of glaciers. Ecosystems are negatively impacted by global warming, changes in precipitation, permafrost thawing and extreme events, which interplay with non-climatic factors, increasing their vulnerability.

Coastal communities in Asia are affected by the sea level rise and ocean acidification, affecting the multiple ecosystem services important for their lives and livelihoods. Urban residents are also affected by climate change due to extreme events, including due to urban heat-island effect.

Water supply and demand have been affected by climatic and non-climatic factors, leading to water stress conditions in most of Asia, which are projected to intensify with increasing global warming. Hotter summers and decreased precipitation are increasing energy demand, and winter savings do not compensate for the increased summer demand. Climate change is also affecting food production in Asia and risks are projected to increase with increasing global warming, which negatively affects fisheries, aquaculture, crop production and livestock production, increasing food insecurity. Climate change is already causing economic losses including through damage to infrastructure, disruptions in services and trade.

Climate change is affecting health and wellbeing of people across Asia, through heatwaves, flooding, droughts and air pollution, increasing vector- and water-borne diseases, undernutrition, mental health disorders and allergy related illness ⁽²⁴⁰⁾.

Extreme events, including tropical cyclones, heavy precipitation and flooding, droughts, heatwaves and wildfires, are increasing in frequency and intensity. Flood and storm events attributable to climate change resulted in thousands of fatalities, millions of people affected and causing significant economic damages in the past years. In 2022 the record-breaking rainfall led to extensive flooding in Pakistan, causing more than 1 700 deaths and affecting 33 million people. Economic damages were estimated to amount to US \$30 billion ⁽²⁴¹⁾ ⁽²⁴²⁾. In May 2023, an intense tropical cyclone Mocha triggered 1.7 million displacements across the sub-region from Sri Lanka to Myanmar, and through India and Bangladesh. Only in Myanmar, 148 lives were lost. The cyclone contributed to acute food insecurity in the region ⁽²⁴³⁾.

⁽²⁴⁰⁾ Shaw, R., Y. Luo, T.S. Cheong, S. Abdul Halim, S. Chaturvedi, M. Hashizume, G.E. Insarov, Y. Ishikawa, M. Jafari, A. Kitoh, J. Pulhin, C. Singh, K. Vasant, and Z. Zhang, 2022: Asia. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1457–1579, doi:10.1017/9781009325844.012

⁽²⁴¹⁾ World Meteorological Organization (2023): *State of the Global Climate 2022* (WMO-No. 1316). ISBN: 978-92-63-11316-0.

⁽²⁴²⁾ World Meteorological Organization (2022) *State of the Climate in Asia 2021* (WMO-No. 1303). ISBN: 978-92063-11303-0.

⁽²⁴³⁾ <https://wmo.int/files/provisional-state-of-global-climate-2023>

Vulnerability of population to climate change differs by geography and socio-economic context (Figure 12). Communities in semiarid, glacier-fed river basins and mega deltas are particularly affected by climate change. Bangladesh is one of the world's most vulnerable countries to climate risks, including due to frequent floods, cyclones, droughts, heat waves and storm surges. Agro-based economies, including India and Pakistan, are also particularly vulnerable to extreme climatic condition.

Figure 12: Key risks related to climate change in Asia.



Source: IPCC AR6 WG II (2022). Figure FAQ 10.1.1

Different social groups are differentially affected by the impacts of climate change, and women, Indigenous people, older and low-income groups are disproportionately affected. The poor are among the most vulnerable, and in Asia, approximately 400 million people live in extreme poverty, and more than a quarter of the population lives below the poverty line of US \$3.20 per day. Particularly in Southern Asia, a large share of the population also lacks access to basic services ⁽²⁴⁴⁾.

⁽²⁴⁴⁾ Shaw, R., Y. Luo, T.S. Cheong, S. Abdul Halim, S. Chaturvedi, M. Hashizume, G.E. Insarov, Y. Ishikawa, M. Jafari, A. Kitoh, J. Pulhin, C. Singh, K. Vasant, and Z. Zhang, 2022: Asia. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1457–1579, doi:10.1017/9781009325844.012

2.3 Impacts in the EU

Climate change is affecting people and ecosystems in Europe. All European regions have already experienced increases in extreme weather events, increases in mean temperature and extreme heat and decreases in cold spells ⁽²⁴⁵⁾. Record high annual temperatures were registered in Western Europe in 2022, with record glacier melting in the European Alps ⁽²⁴⁶⁾⁽²⁴⁷⁾, the second lowest river flow on record and the second largest wildfire burnt area on record. Droughts affected large areas of Europe in the spring and in the summer, and exceptional heatwaves occurred in much of Europe in 2022 ⁽²⁴⁸⁾. Further, in the summer of 2023 (June-August) the heatwaves yet again broke temperature records in several locations, while record heat was also registered in the United States and in Asia. A recent study found that such heatwaves would have been extremely unlikely without anthropogenic climate change, and such maximum temperatures would have been virtually impossible to occur ⁽²⁴⁹⁾. Overall, 2023 was the second warmest year for Europe, after 2020. Temperatures were above average for 11 months, and September was the warmest September ever recorded, with temperatures exceeding the 1991-2020 average by 2.52°C. Europe experienced significant wildfires, storms, and flooding. Heavy or record-breaking precipitation occurred in Italy, Norway, Sweden and Slovenia, causing significant floods, while storms and associated flooding affected Greece, parts of northern and western Europe and the Iberian Peninsula ⁽²⁵⁰⁾. Greece in particular experienced devastating wildfires, resulting in loss of life and evacuations ⁽²⁵¹⁾.

Climate change affects all the regions in the world and therefore impacts Europe directly and indirectly. It affects sectors and supply chains relevant for Europe including through impacts on ecosystems, people (e.g., migration and displacement), financial flows and trade. This has implications for food supply, security, and health and wellbeing. The impacts of climate change vary between and within regions (Figure 13), with southern regions experiencing the most severe effects, while northern and central regions could experience limited positive impacts at lower levels of warming, alongside negative impacts. Above 2°C of global warming, mean precipitation is projected to increase in northern Europe in the winter and decrease in the summer in the Mediterranean region. An increase in precipitation extremes is projected for all regions except for the Mediterranean. Pluvial flooding is projected to increase above 1.5°C global warming level. The highest winter warming is projected to be experienced by northern Europe and the biggest summer warming by the Mediterranean region. The Mediterranean region is projected to be the most affected by droughts. Sea

⁽²⁴⁵⁾ Ranasinghe, R., et al., 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

⁽²⁴⁶⁾ World Meteorological Organization (WMO). 2022. State of the Global Climate 2022 (WMO-No. 1316). ISBN: 978-92-63-11316-0

⁽²⁴⁷⁾ World Meteorological Organization (2023): State of the Climate in Europe 2022. ISBN 978-92-63-11320-7

⁽²⁴⁸⁾ Copernicus Climate Change Service (C3S), 2023: European State of the Climate 2022, Full report: climate.copernicus.eu/ESOTC/2022

⁽²⁴⁹⁾ Zachariah M. et al 2023. Extreme heat in North America, Europe and China in July 2023 made much more likely by climate change. Grantham Institute for Climate Change. <https://doi.org/10.25561/105549>

⁽²⁵⁰⁾ <https://climate.copernicus.eu/global-climate-highlights-2023>

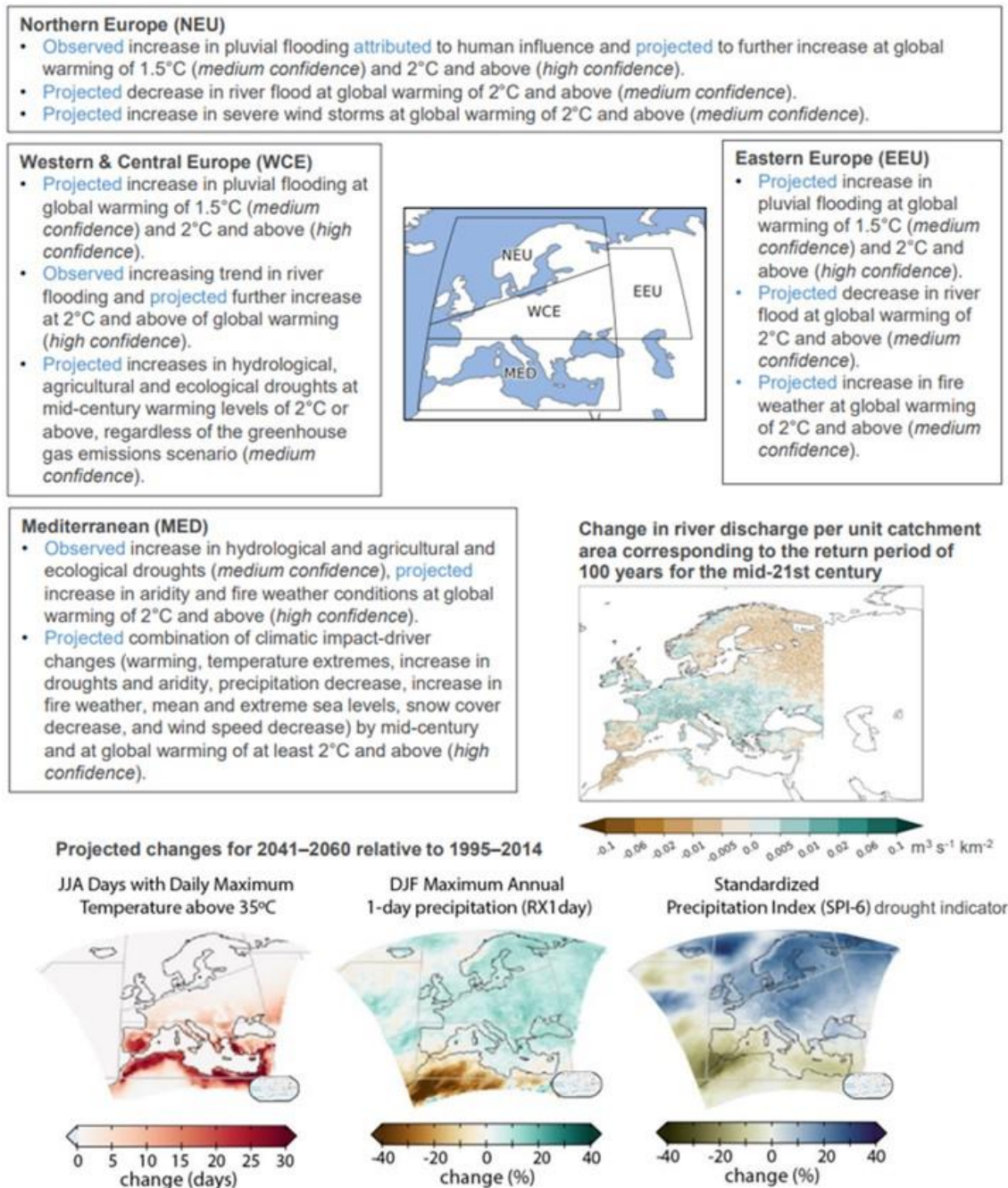
⁽²⁵¹⁾ <https://atmosphere.copernicus.eu/2023-year-intense-global-wildfire-activity>

surface warming and acidification have been observed over the past decades and are projected to continue. Relative sea level rise has occurred along European coastlines and it is projected to continue regardless of the warming level ⁽²⁵²⁾. Extreme sea-level events will increase in frequency and intensity, resulting in coastal flooding, and the retreat in shorelines along sandy coasts will continue ⁽²⁵³⁾.

⁽²⁵²⁾ Ranasinghe, R., A.C. Ruane, R. Vautard, N. Arnell, E. Coppola, F.A. Cruz, S. Dessai, A.S. Islam, M. Rahimi, D. Ruiz Carrascal, J. Sillmann, M.B. Sylla, C. Tebaldi, W. Wang and R. Zaaboul, 2021: Climate Change Information for Regional Impact and for Risk Assessment. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.)]. Cambridge University Press, Cambridge.

⁽²⁵³⁾ IPCC AR6 WG I. 2021. Regional fact sheet – Europe.

Figure 13: Observed and projected climate change impacts for different regions of Europe

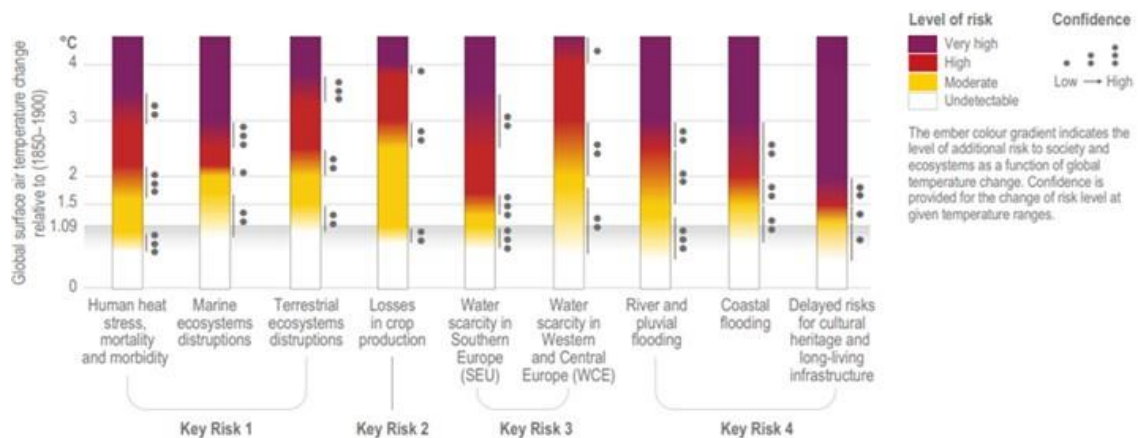


IPCC AR6 WG II (2022) ⁽²⁵⁴⁾ identified four key risks for Europe: i) heat, which will impact human health and ecosystems; ii) loss in agricultural production; iii) water scarcity; and iv)

⁽²⁵⁴⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børshiem, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

flooding (Figure 14). Risks are more severe at 2°C of global warming compared to 1.5°C. While the EU has higher adaptive capacity compared to other regions of the world, there are limits to adaptation and staying within 1.5°C would increase EU's ability to adapt to climate change.

Figure 14: Key risks for Europe under low to medium adaptation



Source: IPCC AR6 WG II (2022). Figure 13.28.

Climate change impacts different social groups differently, with poor households being disproportionately affected due to their lower capacity to adapt and recover from impacts. Traditional lifestyles, for example Sámi reindeer herding, are also threatened by climate change including due to unstable ice conditions, extreme weather conditions, more frequent forest fires and changes in plant composition.

The results of the recent Public consultation on the EU climate target for 2040 revealed that the effects of climate change that are of most concern to the respondents (in decreasing order): i) the loss of biodiversity and natural habitats; ii) damage from natural hazards (floods, wildfires, droughts, etc.) and rising sea levels; iii) loss of life due to natural hazards such as heatwaves, floods, droughts or wildfires; iv) varying capacity of different social groups to adapt (e.g. older people, persons with disabilities, displaced persons, low income households and other vulnerable groups); v) spread of new diseases (e.g. malaria) and pandemics; vi) a change of landscape and forests in areas they relate to or live in; vii) having to face changes in their private lives or activities; viii) increasing material losses to their properties; ix) loss of job or income due to changes in the sector in which they work.

The hazards induced by climate change that the respondents fear most are (in decreasing order) i) heatwaves, ii) droughts, iii) lack of water, iv) floods and intense rain, v) wildfires, vi) windstorms, and vii) rising sea levels.

Most of the respondents believe that the main climate change related impacts on society in their country in the next 20 years will be i) natural disasters (e.g. fires, droughts or floods), followed by ii) negative impacts on food production and iii) migration or refugee movements due to climate change and environmental crises.

2.3.1 Health

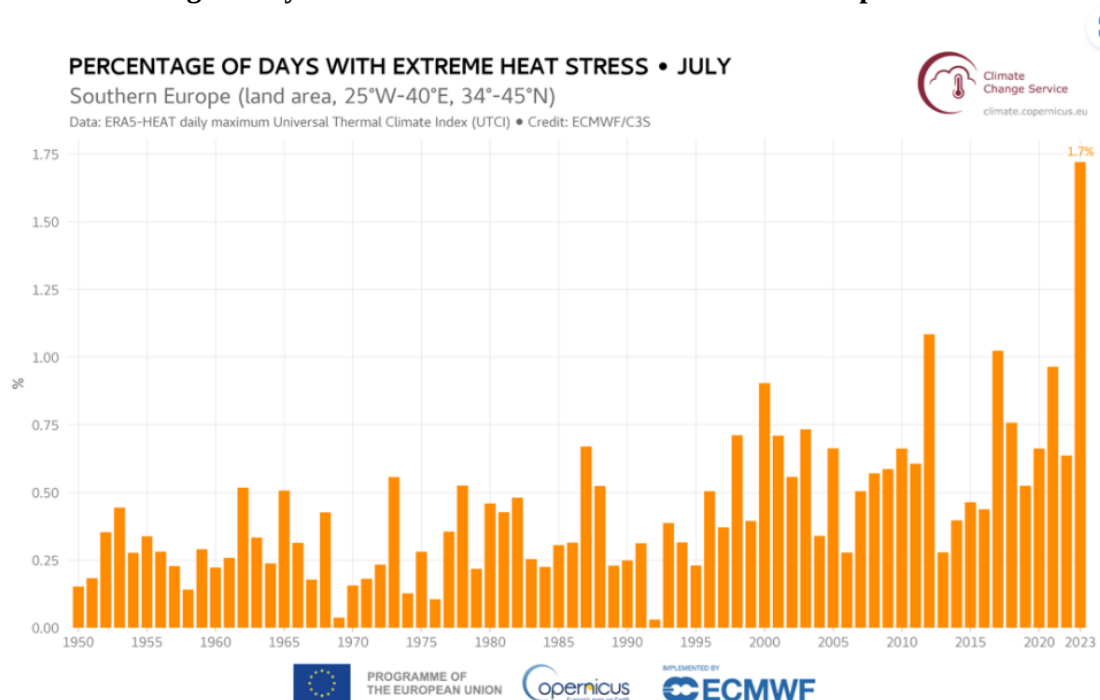
Climate change is already affecting the health and well-being of people in Europe. The record-breaking heatwave in the summer of 2022 resulted more than 60 000 ⁽²⁵⁵⁾ fatalities in Europe. The number of days with extreme heat stress has been increasing (Figure 15) and heatwaves are projected to further increase in intensity and frequency (Figure 16). They present a major health threat, exposing around 100 million Europeans per year to intense heatwaves at 1.5°C of global warming, 170 million per year at 2°C and almost 300 million at 3°C global warming, or more than half of European population. While Southern Europe will continue to be most affected by intense heatwaves, Western and Central Europe will also be impacted. Urban heat islands effect will increase urban temperatures, exposing an increasing number of people to extreme heat ⁽²⁵⁶⁾. Heat affects the elderly, pregnant women, children, socially isolated people and those with pre-existing medical conditions the most ⁽²⁵⁷⁾.

⁽²⁵⁵⁾ Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F. *et al.* Heat-related mortality in Europe during the summer of 2022. *Nature Medicine* **29**, 1857–1866 (2023). <https://doi.org/10.1038/s41591-023-02419-z>

⁽²⁵⁶⁾ Feyen L., Ciscar J.C., Gosling S., Ibarreta D., Soria A. (editors) (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. EUR 30180EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18123-1, doi:10.2760/171121, JRC119178

⁽²⁵⁷⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

Figure 15: Percentage of days with extreme heat stress for Southern Europe



Note: Percentage of July days with extreme heat stress index for Southern Europe, from 1950 to 2023.

Source: ERA5-HEAT. Credit: C3S/ECMWF.

Today heat stress causes more deaths in Europe than all other extreme weather-related events (cold, flooding, storm, wildfire) combined ⁽²⁵⁸⁾ ⁽²⁵⁹⁾. Mortality from long-lasting heatwaves has increased particularly strongly in central and eastern Europe since the 1950s ⁽²⁶⁰⁾ ⁽²⁶¹⁾.

Other extreme events, including floods, wildfires and windstorms also represent major health risks, and are projected to increase in frequency and intensity, affecting an increasing number of Europeans.

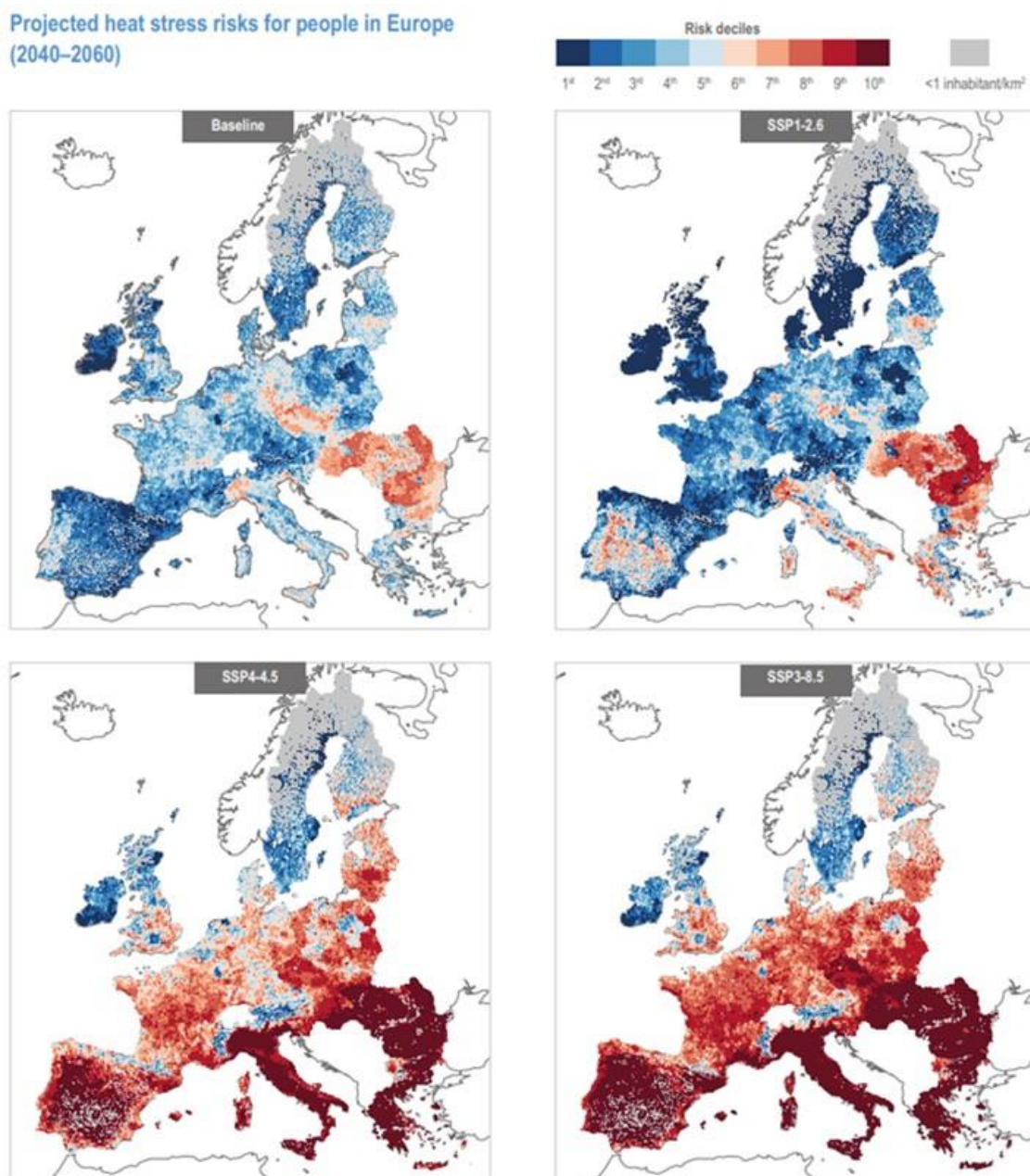
⁽²⁵⁸⁾ European Academies' Science Advisory Council, EASAC (2019) The imperative of climate action to protect human health in Europe. EASAC policy report 38.

⁽²⁵⁹⁾ Zhao Q., Guo Y., Ye T., Gasparrini A., Tong S., Overcenco A. 2021. Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. The Lancet Planetary Health. 5(7) 415-235. [/doi.org/10.1016/S2542-5196\(21\)00081-4](https://doi.org/10.1016/S2542-5196(21)00081-4)

⁽²⁶⁰⁾ Lorenz, R., Stalhandske, Z., & Fischer, E. M. (2019). Detection of a climate change signal in extreme heat, heat stress, and cold in Europe from observations. Geophysical Research Letters, 46, 8363–8374.

⁽²⁶¹⁾ van Daalen K.R. et al. 2022. The 2022 Europe report of the Lancet Countdown on health and climate change: towards a climate resilient future. The Lancet Public Health. 7(11) 942-965. [https://doi.org/10.1016/S2468-2667\(22\)00197-9](https://doi.org/10.1016/S2468-2667(22)00197-9)

Figure 16: Projected heat stress for Europe



Source: IPCC AR6 WG II (2022). Figure 13.23.

Air pollution is the largest environmental health risk in Europe and increases the incidence of a range of diseases, including respiratory and cardiovascular diseases. Air pollutants include short-lived reactive gases such as ozone, and particulate matter (PM), which is a wide range of particles suspended in the atmosphere and dangerous for human health. Methane, a powerful short-lived climate forcer is a precursor of ozone, an important air pollutant. Human activities that release GHG in the atmosphere also lead to the increase in concentration of ozone and PM in the atmosphere. It is estimated that in 2015 approximately 391 000 of Europeans (EU+UK) died prematurely due to long-term exposure to PM_{2.5} ⁽²⁶²⁾. Climate

⁽²⁶²⁾ European Environment Agency, 2018. Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe. EEA Report No 22/2018.

change can increase air pollution through extreme heat, desert dust, increases in wildfire due to increases in temperature and changes in precipitation patterns ⁽²⁶³⁾. Mortalities due to exposure to PM_{2.5} are projected to increase by 73% at 2.5°C global warming levels in Europe. Premature mortalities from near-surface ozone exposure are also projected to increase in Western, Central and Southern Europe and decrease in Northern Europe. Southern Europe is projected to be particularly affected by reduced air quality due to wildfires. Indoor air quality could also be decreased due to projected increases in flood risks and heavy precipitation leading to mould and dampness ⁽²⁶⁴⁾.

Changing climatic conditions in Europe have already facilitated outbreaks of vector-borne climate sensitive infectious diseases including chikungunya, dengue, and West Nile fever. Tick-borne Lyme disease and encephalitis are projected to expand in geographical range further north and to higher elevations. Water-borne and food-borne disease outbreaks have occurred due to extreme precipitation events and higher temperatures, and the risk is projected to increase with increasing warming ⁽²⁶⁵⁾.

Climate change contributes to the spread of some allergenic plants and the earlier start and extension of the pollen season. The concentrations of air-borne pollen are projected to increase across Europe. This could increase the prevalence of allergies.

Climate change related events also impact the mental health of Europeans. Extreme weather events have been linked to post-traumatic stress disorder, anxiety, and depression ⁽²⁶⁶⁾.

2.3.2 *Water stress and scarcity*

Water scarcity is already affecting many regions in Europe and currently around 11% of the population in the European Union and the United Kingdom are living in water scarce regions. Southern Europe is particularly affected, and it is projected that the conditions of water

⁽²⁶³⁾ WMO Bulletin: heatwaves worsen air quality and pollution. 6. September 2023. URL: <https://public.wmo.int/en/media/press-release/wmo-bulletin-heatwaves-worsen-air-quality-and-pollution>

⁽²⁶⁴⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽²⁶⁵⁾ J.C. Semenza and S. Paz. 2021. Climate change and infectious disease in Europe: Impacts, projection and adaptation. The Lancet Regional Health. Volume 9, 100230.

⁽²⁶⁶⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

scarcity will increase in particular in regions that are already experiencing it ⁽²⁶⁷⁾. In 2022 a significant and prolonged drought affected much of Europe, especially during spring and summer and contributed to numerous wildfires, affected ecosystems and society ⁽²⁶⁸⁾⁽²⁶⁹⁾. The European Environment Agency estimates that water stress (i.e. when the demand for water exceeds the available amount during a certain period or when poor quality restricts its use) affects 20% of the European territory and 30 % of the European population on average every year, while droughts cause economic damage of up to EUR 9 billion annually and additional unquantified damage to ecosystems and their services ⁽²⁷⁰⁾.

Water scarcity does not only affect the water sector, but also other interconnected sectors, including agriculture, energy, fluvial transport and industry. Extraction of water amplifies pressure on water resources and water dependent ecosystems. In Southern Europe, agriculture, public water supply and tourism represent the key pressures on water resource availability ⁽²⁷¹⁾.

In 2022 river discharge was the second lowest on record across all of Europe, and it came after five consecutive years of below-average river flows. The affected area was the largest on record, and 63% of all European rivers had below-average discharge ⁽²⁷²⁾. The low water levels on the River Po affected agricultural production and allowed the intrusion of saltwater 40 km inland, which impacted river ecosystems ⁽²⁷³⁾. The flow patterns of the rivers are affected also by the shrinking of glaciers and snow cover in the Alps, which has been happening since the 19th century as the result of increasing temperature and changes in precipitation patterns. In winters high rainfall causes higher water discharges, increasing flood risks. Lower extent and mass of glaciers and snow decrease the inflow of water into the rivers, particularly during spring and summer. The flow of Rhône River for example, has decreased significantly in the past 60 years and is projected to decrease further. The flows of some of its tributaries have already been reduced by 30-40%. Climate change is projected to further decrease river discharges ⁽²⁷⁴⁾. Due to reduced river flow and sea level rise, seawater is projected to intrude estuaries further upstream in the summer. These changes have major impacts on water quality, energy generation, agriculture, forestry, tourism, and ecosystems.

The risk of water scarcity for Europe increases with higher global warming, and Southern Europe will be exposed to more persistent droughts. For Southern Europe at 2°C global warming level, a 54% increase in population facing at least moderate levels of water shortage

⁽²⁶⁷⁾ Feyen L., Ciscar J.C., Gosling S., Ibarreta D., Soria A. (editors) (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. EUR 30180EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18123-1, doi:10.2760/171121, JRC119178

⁽²⁶⁸⁾ World Meteorological Organization (WMO). 2023. State of the Climate in Europe 2022 (WMO-No. 1320).

⁽²⁶⁹⁾ Copernicus Climate Change Service (C3S), 2023: European State of the Climate 2022, Full report: climate.copernicus.eu/ESOTC/2022

⁽²⁷⁰⁾ European Environment Agency, 2021. Water resources across Europe — confronting water stress: an updated assessment. EEA Report No 12/2021.

⁽²⁷¹⁾ European Environment Agency, 2021. Water resources across Europe — confronting water stress: an updated assessment. EEA Report No 12/2021.

⁽²⁷²⁾ Copernicus Climate Change Service (C3S).

⁽²⁷³⁾ World Meteorological Organization (2023): State of the Climate in Europe 2022. ISBN 978-92-63-11320-7

⁽²⁷⁴⁾ https://www.eaurmc.fr/jcms/pro_118307/fr/les-debits-d-etiage-du-rhone-en-baisse-sous-l-effet-du-changement-climatique [Accessed on 2.8.2023].

is projected. At 3°C global warming, water scarcity will become more widespread and severe, and affect currently non water scarce areas of Western and Central Europe ⁽²⁷⁵⁾. Southern and south-western Europe is projected to be most affected, and river discharge reductions could reach 40% in the summer in some basins. Drought frequency is projected to double over nearly a quarter of the Mediterranean and a third of the Atlantic region.

In addition to the effects of climate change on water resources, in many European river basins, water is over-abstracted, which impacts ecological processes, or it is returned to surface water and groundwater with significant levels of pollution. Groundwater is often seen as a solution to replace other freshwater sources, but over-exploitation has negative impacts on the future availability of water and on biodiversity ⁽²⁷⁶⁾.

2.3.3 Flood risks

Risk of coastal and river floods in Europe is projected to increase substantially over the 21st century. Bosello and Leon ⁽²⁷⁷⁾ find that coastal damages from sea-level rise and riverine flooding are the main sources of GDP losses as a result of climate change, amounting to more than 70% of all climate change related losses in the EU.

2.3.3.1 Coastal flooding

Sea level rise is already affecting European coastal areas, and compounded by storm surges, rainfall and river runoff, risks of coastal flooding in Europe's low-lying coasts will increase with increasing global warming and affect an increasing number of people, particularly beyond 2040 ⁽²⁷⁸⁾. It is estimated that without mitigation, 2.2 million people in the EU and UK could be exposed to coastal flooding by the end of the century. Moderate mitigation action could reduce the damages by half and reduce the exposed population to 1.4 million people per year. Adaptation action such as rising dykes would reduce exposed population and damages by 60% and 90% respectively by 2100. Other solutions are also available, such as green infrastructures/nature-based solutions (e.g. give rivers more space during floods, restoring reefs, marshes or dunes), often more cost-efficient and with lower environmental

⁽²⁷⁵⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽²⁷⁶⁾ EEA (2021): *Water resources across Europe — confronting water stress: an updated assessment*, report 12/2021. Luxembourg: Publications Office of the European Union

⁽²⁷⁷⁾ Bosello F. and Leon C.J. 2022. *Climate change impacts in the EU: new evidence from recent research*. EAERE Magazine, 16 Spring 2022 – Climate Impacts and Adaptation

⁽²⁷⁸⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

impact, and come with many co-benefits including for biodiversity and human health and well-being ⁽²⁷⁹⁾.

2.3.3.2 Riverine and pluvial flooding

Climate change affects the frequency and intensity of climate and weather extremes, including heavy precipitation. River flood hazards have increased in the Western and Central Europe in the past decades and decreased in Southern Europe. In Europe, the past three decades had the largest number of floods in the past 500 years, affecting an increasing number of people and causing economic damages.

River flood hazards are projected to continue to increase in Central and Western Europe and decrease in Northern and Southern Europe. Overall, damages from river flooding are projected to increase with continued warming.

Pluvial flooding and flash floods constitute the majority of flood events in Europe and have caused considerable impacts, including loss of human life and economic and non-economic damages. With increasing global warming, the risk of pluvial flooding and flash floods are also projected to increase ⁽²⁸⁰⁾.

2.3.4 *Infrastructure: Impacts on energy systems, transport systems and tourism*

2.3.4.1 Energy systems

Climate extremes and changes in weather patterns are already impacting energy systems in Europe. The most relevant long-term trends from an energy system perspective are changes in ambient temperature and water inflow patterns and availability. Extreme events, including heat waves, heavy precipitation events, storms and extreme sea level also impact energy systems ⁽²⁸¹⁾, by increasing the risk of damaging critical energy infrastructure ⁽²⁸²⁾. In recent years, parts of Europe have experienced reductions and interruptions of power supply due to water-cooling constraints on power plants during exceptionally dry or hot years, an increase in the number of days where energy demand for cooling increases (known as cooling-days) and decrease in heating-days ⁽²⁸³⁾.

⁽²⁷⁹⁾ European Commission (2020) Nature-Based Solutions for Flood Mitigation and Coastal Resilience Analysis of EU-funded Projects. Luxembourg: Publications Office of the European Union.

⁽²⁸⁰⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽²⁸¹⁾ Troccoli (2018). Weather & climate services for the energy industry. DOI:10.1007/978-3-319-68418-5

⁽²⁸²⁾ Varianou Mikellidou et al. (2018). Energy critical infrastructures at risk from climate change: A state of the art review.

⁽²⁸³⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K.

The IPCC projects an increase in mean precipitation in Northern Europe, increase of river flooding in Western and Central Europe and increased aridity and ecological droughts in the Mediterranean area. Water availability is set to increase in northern Europe and decrease in southern Europe with marked seasonal differences.

Thermal power plants (powered by fossil fuel, biomass or nuclear fuel) often rely on large quantities of water for cooling. Thermal plants can suffer from reductions in generation in the event of decreases in cooling water availability and increases in cooling water temperature. Modelling shows that climate change can decrease usable water capacity for thermoelectric power plants in certain regions of Europe by more than 15% in some cases by the middle of the century ⁽²⁸⁴⁾. The effects can range from a decrease in power plant reliability, for instance with extreme events leading to unplanned shutdowns and curtailments ⁽²⁸⁵⁾, to a reduction of performance and generation capacity of turbines ⁽²⁸⁶⁾ due to a reduction of volume or increase in temperature of cooling water ⁽²⁸⁷⁾.

By definition, hydropower plants generate electricity from water streamflow or water reservoirs. Variation in rainfall, snowfall, and snow and glacier melt will change inflow patterns and affect plant productivity, resilience and reliability. Reduced availability of water leads to reduced electricity generation, while increased streamflow above regulating capacity can affect the functioning of hydropower plants. In case of hydropower used for flexibility services, such as pumped hydro-storage technology, reliability of dispatching might also be negatively affected by the increased variability of weather patterns. In a 2°C scenario, water resource and hydro production increases by 2050 in Northern Europe, while Southern Europe experiences the opposite trend ⁽²⁸⁸⁾.

Wind and PV do not rely on water for cooling or producing electricity and, at EU scale, they are little impacted by climate change. The variation of wind energy potential linked to changes in wind availability is less than 5% overall ⁽²⁸⁹⁾, ⁽²⁹⁰⁾ while studies have shown that the projected range of variation for solar irradiance and temperature increase will only marginally impact the PV potential in EU ⁽²⁹¹⁾. However, uncertainty still exists ⁽²⁹²⁾ on the

Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)). Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽²⁸⁴⁾ EEA (2019). *Adaptation challenges and opportunities for the European energy system*.

⁽²⁸⁵⁾ Reuters (2018). France's EDF halts four nuclear reactors due to heatwave'.

⁽²⁸⁶⁾ Van Vliet, M. T. H., et al. (2016b), 'Multi-model assessment of global hydropower and cooling water discharge potential under climate change'.

⁽²⁸⁷⁾ Van Vliet, M. T. H., et al. (2016c). 'Power-generation system vulnerability and adaptation to changes in climate and water resources.

⁽²⁸⁸⁾ JRC (2018). Seasonal impacts of climate change on electricity production : JRC PESETA IV project

⁽²⁸⁹⁾ Moemken, J. et al. (2018). Future changes of wind speed and wind energy potentials in EURO-CORDEX ensemble simulations

⁽²⁹⁰⁾ Scott Hosking, J., et al., (2018). Changes in European wind energy generation potential within a 1.5 °C warmer world'

⁽²⁹¹⁾ Jerez, S., et al. (2015). The impact of climate change on photovoltaic power generation in Europe

⁽²⁹²⁾ Yang et al. (2021). Climate Change and Renewable Energy Generation in Europe—Long-Term Impact Assessment on Solar and Wind Energy Using High-Resolution Future Climate Data and Considering Climate Uncertainties

spatial and temporal distribution of variations of wind availability and solar irradiance, which can generate higher variation of PV and wind potential at the local level.

The spatial availability of biomass supply for bioenergy is also impacted by climate change: climate change allows warm-adapted tree species and warm-season crops to expand northwards in Europe, whereas southern Europe is projected to experience a decline in its suitability for forest growth as a result of increasing heat and water stress and scarcity⁽²⁹³⁾.

The electricity grid, which will increase in size and importance as increasing renewables leads to wider distribution of electricity supply, will be significantly impacted by extreme weather events: heavy snowfall and icing can create ice sleeves around power line conductors, windstorms, wildfires can cause trees to fall on overhead lines, heatwaves can create electric faults in electricity cables⁽²⁹⁴⁾. Due to climate change alone, and in the absence of adaptation, analysis shows that damages could triple by the 2020s, multiply six-fold by mid-century, and amount to more than 10 times by the end of the century⁽²⁹⁵⁾, considerably increasing the cost of the energy system.

Climate change will also modify the final energy demand in the building sector. An increase in temperature reduces the demand for heating, while increasing the demand for cooling⁽²⁹⁶⁾. Given that in the EU, heating demand is larger than cooling demand, the overall energy demand will decrease, with this change being minor (5%) in the short term and becoming more prominent only in the second half of the century⁽²⁹⁷⁾. In cold countries, a decrease of total energy demand occurs, while warm countries will experience an increase of overall energy demand and an increase in peak electricity demand due to cooling⁽²⁹⁸⁾.

The overall impact of climate change on the energy system will not simply be the sum of the impacts applied to each energy technology separately. It will result from the interactions between the extreme events and long-term trends applied to a dynamic system.

Accounting for the impact of climate change in the design of power plants and energy infrastructure is an appropriate adaptation measure to limit potential future damage, minimise costs, and ensure the security of power supply. Projections that include adaptation options, such as faster development of wind and PV, extension of transmission lines and flexibilities, and innovation in cooling technology have shown to increase the share of EU power capacities that are unaffected by climate change, and decrease the cost of electricity for customers⁽²⁹⁹⁾.

⁽²⁹³⁾ EEA (2017). *Climate change adaptation and disaster risk reduction in Europe: enhancing coherence of the knowledge base, policies and practices*

⁽²⁹⁴⁾ Khatoun, N. (2023). Heatwave Triggers Unprecedented Power Cuts in Malta: A Deep Dive. Accessed on 26-7-2023

⁽²⁹⁵⁾ Forzieri et al (2018), Escalating impacts of climate extremes on critical infrastructures in Europe, *Global Environmental Change* 48, 97–107

⁽²⁹⁶⁾ EEA (2019). Heating and cooling degree days (CLIM 047).

⁽²⁹⁷⁾ JRC (2019). Assessment of the impact of climate change on residential energy demand for heating and cooling

⁽²⁹⁸⁾ Damm, A., et al. (2017) “Impacts of +2 °C global warming on electricity demand in Europe”.

⁽²⁹⁹⁾ JRC (2018). Seasonal impacts of climate change on electricity production: JRC PESETA IV project.

An integrated approach involving the private sector and EU and national policymakers will be crucial to strengthen the energy market and policy framework to limit the impact of climate change on the power system and ensure the development of a decarbonised, secure, climate-resilient and cost-efficient EU energy system.

2.3.4.2 Transport

Climate change affect the transport sector through multiple impacts, including heatwaves, sea level rise, floodings, wildfires, changes in precipitation, and other extreme weather events, all of which impact transport infrastructures, operations and travel behaviour (Figure 17). Climate change is also projected to impact passenger and freight transport due to shifts in tourism and agricultural production ⁽³⁰⁰⁾⁽³⁰¹⁾.

In Europe, the transport sector has already been affected by heatwaves, which caused road melting and railway asset failures, and by extreme precipitation, floods and landslides which damaged roads, railways and other infrastructure. With increasing warming, the risks are projected to increase. In Northern Europe the higher number of freezing and thawing cycles of construction materials increases risks to transport infrastructure ⁽³⁰²⁾.

Railway transport can be affected by climate change in a variety of ways, which cause disruption of railway operations and damage to infrastructure. Negative impacts of climate-related events on railways include railway rail buckling, rail flooding, expansion of swing bridges, damage to electrical equipment due to overheating, bridge scour, pavement deterioration, damage related to coastal erosion and damage of sea walls ⁽³⁰³⁾.

Port operations in parts of Northern, Western and Central Europe might be disrupted by sea level rise, while ports in the Mediterranean could be affected by changes in wave agitation, particularly beyond 2°C global warming level ⁽³⁰⁴⁾.

⁽³⁰⁰⁾ Gossling S., Neger C., Steiger R., and Bell R. (2023). Weather, climate change, and transport: a review. *Natural Hazards*. DOI: 10.1007/s11069-023-06054-2

⁽³⁰¹⁾ Koetse and Rietvelds (2009). The impact of climate change and weather on transport: An overview of empirical findings. *Transport Research Part D: Transport and Environment*. 14(3): 205-221.

⁽³⁰²⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽³⁰³⁾ Kostianaia E.A. and Kostianoy A. 2023. Railway Transport Adaptation Strategies to Climate Change at High Latitudes: A Review of Experience from Canada, Sweden and China. *Transport and Telecommunication*. 24(2):180-194.

⁽³⁰⁴⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

Climate change impacts inland waterways, which are vulnerable to extreme events including drought and flooding ⁽³⁰⁵⁾. Low-water-level days present the most significant disruption in inland navigation in Europe and cause significant economic impacts ⁽³⁰⁶⁾.

Road traffic can be affected by high temperatures causing degradation of road surfaces, flooding of infrastructure, closure of roads due to wildfire and wildfire smoke, and other extremes ⁽³⁰⁷⁾.

Air travel could be affected by climate change through multiple pathways, including poor visibility, strong winds, and heavy precipitation. Airports are also impacted by inundation from sea level rise and storm surges. Raising temperatures could reduce lift generation in planes and affect air travel in Europe, ⁽³⁰⁸⁾ and reduce maximum take-off total weight, payload and climb rate. The projected changes in the North Atlantic jet stream could increase clear-air turbulence in the transatlantic flight corridor, and impact flight times and fuel consumption. Changing weather patterns might result in the need to increase maintenance intervals and improve inspection methods to detect risks ⁽³⁰⁹⁾.

⁽³⁰⁵⁾ Koetse and Rietvelds. 2009. The impact of climate change and weather on transport: An overview of empirical findings. *Transport Research Part D: Transport and Environment*. 14(3): 205-221.

⁽³⁰⁶⁾ A. Christodoulou, P. Christidis, B. Bisselink. Forecasting the impacts of climate change on inland waterways. *Transportation Research Part D: Transport and Environment*; Volume 82, May 2020.

⁽³⁰⁷⁾ Gossling S., Neger C., Steiger R., and Bell R. 2023. Weather, climate change, and transport: a review. *Natural Hazards*. DOI: 10.1007/s11069-023-06054-2

⁽³⁰⁸⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015

⁽³⁰⁹⁾ Gossling S., Neger C., Steiger R., and Bell R. 2023. Weather, climate change, and transport: a review. *Natural Hazards*. DOI: 10.1007/s11069-023-06054-2

Figure 17: Examples of climate change impacts on transport

Some examples of climate change impacts on transportation infrastructure and operations

	 Road	 Rail	 Waterways and ports
Temperature - Higher mean temperatures; heat waves/droughts; changes in the numbers of warm and cool days - Reduced snow cover and arctic land and sea ice; permafrost degradation and thawing	- Thermal pavement loading and degradation - Asphalt rutting - Thermal damage to bridges - Increased landslides - Increased needs for cooling - Reduced integrity of winter roads and shortened operating seasons - Slope instability	- Track buckling - Infrastructure and rolling stock overheating/failure - Slope failures - Signaling problems - Speed restrictions - Asset lifetime reduction - Higher needs for cooling - Shorter maintenance windows - Higher construction and /maintenance costs - Demand changes	- Damage to infrastructure, equipment and cargo - Higher energy consumption for cooling - Potential reductions in snow/ice removal costs - Extension of the construction season - Occupational health and safety issues during extreme temperatures
Precipitation Changes in the mean values; changes in intensity, type and/or frequency of extremes	- Inundation, damage and wash-outs of roads and bridges - Increased landslides - Impacts on bridges	- Flooding, damage and wash-outs of bridges - Problems with drainage systems and tunnels - Delays	- Infrastructure inundation - Navigation restrictions in inland waterways due to river water levels changes
Sea levels/storm surges - Mean sea level rise - Increased extreme sea levels	- Erosion of coastal roads - Flooding, damage and wash-outs of roads and bridges	- Bridge scour, catenary damage at coastal assets - Disruption of coastal train operation	- Asset inundation - Navigation channel sedimentation - Maintenance costs

Source: UNECE-WMO ⁽³¹⁰⁾

2.3.4.3 Tourism

The tourism industry in Europe is a significant contributor to GDP and it is already affected by the impacts of climate change, particularly by changes in snow-cover duration and depth, and hotter summers. It is estimated that Southern Europe is already experiencing economic losses, while the rest of Europe is experiencing smaller gains from the impact of climate change on tourism.

Increasing global warming will affect mountain resorts due to increasing need for snowmaking and decreasing stability of ropeway transport due to permafrost degradation in high altitude areas. Summer tourism could be positively affected by higher temperatures in Northern Europe, with the opposite trend in southern Europe. Coastal erosion and inundation risk due to sea-level rise could decrease the amenity of European beaches ⁽³¹¹⁾. A JRC study ⁽³¹²⁾ also finds a clear north-south pattern in future tourism demand changes, with northern regions experiencing gains and southern regions experiencing significant reductions. This trend is projected to increase with increasing global warming.

⁽³¹⁰⁾ UNECE-WMO. Climate Change Impacts and Adaptation for Transport Networks and Nodes. https://unfccc.int/sites/default/files/resource/2.12UNECE-WMO_CCImpact_Transport.pdf (accessed in July 2023)

⁽³¹¹⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015

⁽³¹²⁾ Matei, N.A., García-León, D., Dosio, A., Batista e Silva, F., Ribeiro Barranco, R., Císcar Martínez, J.C., Regional impact of climate change on European tourism demand, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/899611, JRC131508

2.3.5 *Impact of Climate Change on the Land system*

Agriculture and forestry sectors are highly exposed to climate change but also crucial for providing essential services. Decreasing the negative impacts of agriculture, forestry and fisheries on the environment, and enhancing sustainable production and management of natural resources that is resilient to climate change has become a priority across European policies, including the Common Agricultural Policy (CAP) (European Commission 2021; Alliance 2018), and the European Green Deal ⁽³¹³⁾.

The future development of the land sector is afflicted with large uncertainties. Future conditions will be affected by climate change and natural disturbances. Climate change impacts agriculture and forestry sectors, predominantly negatively (e.g., from lower rainfall, increasing variability, extreme heat and pests) but also with some positive impacts (e.g. from CO₂ fertilisation, extended growing seasons and new crops in some latitudes), which however, do not counterbalance the negative impacts. Extreme events affect production of biomass and food both directly and indirectly, as well as negatively impact the potential to mitigate climate change.

Effects of climate change on agriculture and forestry have been studied extensively although models that have still severe limitations, as many aspects are not included. Yet an overall picture emerges. European agriculture is already affected by climate change, including by water stress and scarcity, heat, dry conditions, and extreme weather. Increasing global warming will increase the risk of crop failure and decreased pasture quality, as well as making production increasingly unpredictable. The effects differ strongly depending on the types of crops or forests and depending on the region. Southern, Western and Central Europe are projected to be most negatively affected. Agricultural zones are projected to shift, with overall losses in maize and wheat yields, which are not compensated by regional gains in wheat. Grassland biomass production is projected to decline, and a reduction in pollination is also foreseen ⁽³¹⁴⁾. Climatic drivers interact with non-climatic ones, including unsustainable practices, exacerbating the impacts on ecosystems and biodiversity. The use of chemicals in agriculture, for example, importantly contributes to the reduction in pollination.

With climate change, disturbances in forests are increasing in frequency. European forests are exposed in particular to wind disturbances, wildfires, and insect and fungus infestations. This negatively impacts forest functions, including carbon sequestration and provision of wood materials. The impacts of climate change on forests vary regionally and locally. Climate change increases the frequency and magnitude of wildfires. In contrast to landscape fires, which are critical to the healthy functioning of many ecosystems, wildfires are linked to extreme fire weather and burn out of control, harming human and natural systems. According

⁽³¹³⁾ Siddi, Marco. 2020. "The European Green Deal: Assessing Its Current State and Future Implementation," 14.

⁽³¹⁴⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børshiem, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

to the IPCC ⁽³¹⁵⁾ hot weather conditions that provoke wildfires, increased throughout Europe in the past decades and are projected to further increase and expand with increasing global warming levels, particularly affecting Southern, Western and Central Europe.

Wildfires pose risk to people and ecosystems and result from complex interactions between changing climate conditions such as increased drought, heat, and decreased humidity, and human factors such as demographic trends, land-use, and land management practices. While certain risks such as man-made ignition of wildfires (the main source of wildfires) can be reduced with appropriate management, including ecosystem restoration, the risk posed by wildfires cannot be entirely eliminated. Wildfires affect the global carbon cycle by releasing CO₂ into the atmosphere, further exacerbating global warming. They can cause loss of lives and livelihoods, impact health, devastate ecosystems and degrade watersheds. The impacts of wildfires can be long-lasting, including in biodiversity hotspots, which might never fully recover. Moreover, frequent fires can eliminate woody plant species which are replaced with herbaceous and often annual species, or invasives weeds, change soil properties and increases soil erosion ⁽³¹⁶⁾. Like in the case of pollinators decline, unsustainable forestry practices affect negatively the resilience of forests ecosystems. Scientific literature shows that more biodiverse forests more resilient, multifunctional, productive, deliver more ecosystem services and even capture more carbon ⁽³¹⁷⁾ ⁽³¹⁸⁾ ⁽³¹⁹⁾ ⁽³²⁰⁾ ⁽³²¹⁾ ⁽³²²⁾.

In addition to agriculture and forests, climate change is already impacting other ecosystems in Europe and, interacting with non-climatic pressures such as intensive land use, and land use change, it further reduces their resilience. Driven by global warming, the boundaries of today's biogeographical regions have started to shift. Modelling studies in the field suggest that terrestrial ecosystems on up to half of Europe's land area will experience major climate-change shifts during this century, including many of today's protected areas ⁽³²³⁾ ⁽³²⁴⁾. Many

⁽³¹⁵⁾ IPCC (2022) AR6 WGII Climate Change 2022: Impacts, Adaptation and Vulnerability, pp. 1817–1927.

⁽³¹⁶⁾ United Nations Environment Programme (2022). Spreading like Wildfire – The Rising Threat of Extraordinary Landscape Fires. A UNEP Rapid Response Assessment. Nairobi

⁽³¹⁷⁾ Lewis, S.L., Wheeler, Ch.E.; Mitchard, E.T.A. and Kock, A. (2019) “Restoring natural forests is the best way to remove atmospheric carbon, in *Nature*, 68, 25-28, <https://doi.org/10.1038/d41586-019-01026-8>

⁽³¹⁸⁾ Van der Plas, F., Manning, P., Allan, E. et al. (2016) “Jack-of-all-trades effects drive biodiversity–ecosystem multifunctionality relationships in European forests”, in *Nature Communication* 7, 11109. <https://doi.org/10.1038/ncomms11109>

⁽³¹⁹⁾ Peura, M., Burgas, D., Eyvindson, K., Repo, A. & Mönkkönen, M. (2018). Continuous cover forestry is a cost efficient tool to increase multifunctionality of boreal production forests in Fennoscandia. *Biological Conservation* 217; 104-112; <https://www.sciencedirect.com/science/article/pii/S0006320717308170>

⁽³²⁰⁾ Liang, J. et al. (2016) “Positive biodiversity-productivity relationship predominant in global forests”, in *Science*, Vol 354, Issue 6309, [doi: 10.1126/science.aaf8957](https://doi.org/10.1126/science.aaf8957)

⁽³²¹⁾ Pukkala, T. 2016. Which type of forest management provides most ecosystem services? *Forest Ecosystems* 3:9; <https://forestecosyst.springeropen.com/track/pdf/10.1186/s40663-016-0068-5>

⁽³²²⁾ Mori, A.S., Dee, L.E., Gonzalez, A. et al. Biodiversity–productivity relationships are key to nature-based climate solutions. *Nat. Clim. Chang.* **11**, 543–550 (2021). DOI: 10.1038/s41558-021-01062-1

⁽³²³⁾ Samuel Hoffmann, Severin D. H. Irl & Carl Beierkuhnlein (2019) Predicted climate shifts within terrestrial protected areas worldwide. *Nature Communications* vol 10 N° 4787

⁽³²⁴⁾ Hickler et al. (2012) Projecting the future distribution of European potential natural vegetation zones with a generalized, tree species-based dynamic vegetation model. In: *Global Ecology and Biogeography*, 21, 50–63.

terrestrial species may not be able to keep up with the speed of northwards and uphill range shifts, especially when suitable habitats are fragmented (no migration corridors), or for habitat specialists and species with low mobility and reproduction rates. In fact, even though we are only at the beginning of a period of rapid global warming, researchers are already demonstrating its negative impacts on Europe's nature and biodiversity, from the landscape level down to the genetic diversity of individual species ⁽³²⁵⁾. Relevant studies in the field also indicate that the *direct* effects of changing climate conditions on nature will likely be exacerbated *indirectly* by human land use change in response to global warming such as further agricultural and forestry intensification (to compensate for projected productivity losses or the expected greater virulence of pests) and growing competition for land and water resources ⁽³²⁶⁾. Together, all these effects risk exacerbating the rate of local and regional habitat loss and species extinctions world-wide and also in Europe.

2.3.5.1 Forests and other ecosystems

2.3.5.1.1 Forests

Forests are highly dependent on and determined by the prevailing climatic conditions. It goes beyond the climatic requirements and tolerances of individual tree species, as biodiverse forests have developed as communities of species interdependent between them, with their soils and hydrological conditions. Climatic zones are often identified by dominant tree species of typical forest types, and the climatic characteristics of these zonal forest types tend to be very narrow compared to the shifts in local climate due to climate change, with an increasing share of otherwise natural forest becoming maladapted already.

Forest management in Europe has a long history of planting species outside their natural ranges, most often conifers like Norway spruce, and usually in monoculture plantation. This has been done mainly for commercial reasons, but also for ease of management or the rapid re-establishment of vegetation in degraded/abandoned areas, often on soils heavily damaged by agriculture, such as grazing. In all such cases short-term growth and/or success of reestablishment took precedent over long-term site suitability and ecological stability. Today, 74% of EU forest area consists of even-aged stands, and one third of the forests comprise of only one tree species ⁽³²⁷⁾. Whilst forest stands with these characteristics are more vulnerable to stress and disturbances, forest-based industries and many forest managers preferred them over more site-adapted and resilient mixed stands, for economic reasons: by standardizing trees, they reduce management and harvesting costs and produce economies of scale, but at the cost of more vulnerability and biodiversity and soil quality loss. With increasing impacts of climate change, these land use and forest management choices start going awry. Rapidly changing climatic conditions are having near-immediate effects (less than 20-40 years) with abrupt shifts in tree abundances and forest composition ⁽³²⁸⁾. During the last few years, across

⁽³²⁵⁾ Exposito-Alonso, M., Exposito-Alonso, M., Gómez Rodríguez, R. et al. Natural selection on the *Arabidopsis thaliana* genome in present and future climates. *Nature* 573, 126–129 (2019) doi:10.1038/s41586-019-1520-9

⁽³²⁶⁾ See notably the IPCC special report on climate change and land and also the IPBES global assessment.

⁽³²⁷⁾ [FISE - Forest Information System for Europe \(2023\) Forest biodiversity](#)

⁽³²⁸⁾ J.W. Williams and K.D. Burke (2019) Past abrupt changes in climate and terrestrial ecosystems. In: T.E. Lovejoy and L. Hannah (Eds.) *Biodiversity and Climate Change*. Yale University Press, New Haven & London.

Europe, clear signals indicate that tree health is deteriorating⁽³²⁹⁾ ⁽³³⁰⁾, forest zones and tree ranges shift, and forested landscapes are beginning to transform.

2.3.5.1.1.1 Assessment of present and past impacts on forests

Analysis of both satellite retrievals and surface inventories of disturbance events are confirming the increasing frequency and increasing overall area affected by the various types of natural disturbances, with a relevant rise of wind disturbances⁽³³¹⁾, wildfires and bark-beetle infestations, the latter particularly in central-European spruce forests⁽³³²⁾. The JRC PESETA IV study⁽³³³⁾ investigated the vulnerability of European forests to natural disturbances and found that due to climate-driven disturbances, key forest functions, including carbon sequestration and provision of wood materials could be seriously affected. In the 2000-2017 period, windstorms caused the largest biomass loss in both relative and absolute terms (~38%, ~17 t ha⁻¹), followed by fires (~24%, ~12.5 t ha⁻¹) and insect outbreaks (~21%, ~9 t ha⁻¹), with Northern and Mediterranean regions disproportionately affected. The vulnerability of forests to natural disturbances depends more on a forest's structural properties than on climate and landscape features, however, changes in temperature and precipitation patterns in the past decades increased the vulnerability of European forests to natural disturbances in general and particularly to insect outbreaks.

Some of the notable climate-related disturbances in the past years include:

- The unprecedented droughts experienced since 2018 have triggered significant tree dieback in many parts of Europe. For instance, satellite images of Germany show a canopy cover loss of 501,000 ha between 2018-2021 (corresponding to 4.9% of the total forest area) following the 2018-2019 drought⁽³³⁴⁾.
- Weakened by the droughts, Norway spruce stands crumbled under unprecedented bark beetle attacks in Northern and Central Europe, with the Czech Republic becoming Europe's epicentre of these outbreaks. In 2017–2019, over 5% of the Czech growing stock of Norway spruce was damaged each year, causing the total depletion of spruce in some regions. The 2018-2020 drought years lead to the largest documented outbreak of bark beetles in Sweden, which killed 17 million m³ of spruce trees in the southern part of the country.

⁽³²⁹⁾ ICP Forests Brief No 5. <http://icp-forests.net/page/icp-forests-briefs>.

⁽³³⁰⁾ Institut national de l'information géographique et forestière (IGN): Résultats 2022 de l'Inventaire forestier national : une forêt française confrontée aux dérèglements climatiques. <https://www.ign.fr/espace-presse/resultats-2022-de-linventaire-forestier-national-une-foret-francaise-confrontee-aux-dereglements>. Accessed on 25/07/2023.

⁽³³¹⁾ Senf, C. and Seidl, R.: Storm and fire disturbances in Europe: Distribution and trends, *Glob. Chang. Biol.*, (November 2020), 1–15, doi:10.1111/gcb.15679, 2021.

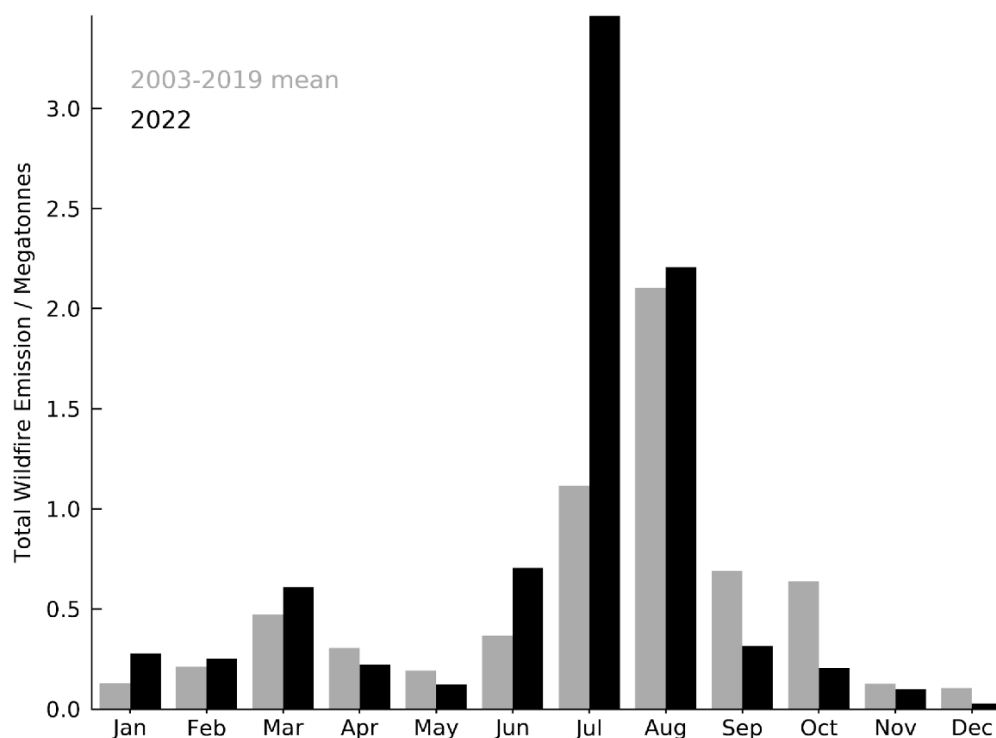
⁽³³²⁾ Sebal, J., Senf, C. and Seidl, R.: Human or natural? Landscape context improves the attribution of forest disturbances mapped from Landsat in Central Europe, *Remote Sens. Environ.*, 262(May), 112502, doi:10.1016/j.rse.2021.112502, 2021.

⁽³³³⁾ Forzieri G., Girardello M., Ceccherini G., Mauri A., Spinoni J., Beck P., Feyen L. and Cescatti A. Vulnerability of European forests to natural disturbances, EUR 29992 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-13884-6, doi:10.2760/736558, JRC118512

⁽³³⁴⁾ Thonfeld et al. 2022. A First Assessment of Canopy Cover Loss in Germany's Forests after the 2018–2020 Drought Years. *MDPI AG in Remote Sensing*. doi.org/10.3390/rs14030562

- Some 40% of the fires registered in 2022, the hottest summer and the second worst wildfire season on record in Europe, affected central and northern European countries. Fire danger for Europe as a whole was higher for most of that year than the 1991–2020 average (Figure 18) ⁽³³⁵⁾. Total wildfire emissions from the EU plus the UK from 1 June to 31 August 2022 were estimated at 6.4 Mton of carbon, the highest level for these months since the summer of 2007 ⁽³³⁶⁾.

Figure 18: Wildfire carbon emissions from EU



Note: Estimated total monthly wildfire carbon emissions from European Union countries (black bars) compared to the average for the 2003–2019 reference period (grey bars).

Source: CAMS GFASv1.2 wildfire data record. Credit: CAMS/ECMWF

Reported data of the 34 member countries of the ‘Forest Europe’ process show a significant increase in forest disturbances between 1950 and 2019, causing on an average of 43.8 million m³ of disturbed timber volume per year. In the last 20 years, disturbances on average accounted for 16% of the mean annual harvest in Europe. Whereas wind was statistically the most important damaging agent, accounting for almost half of the damage during the study period, bark beetle outbreaks – driven by warming and droughts - doubled their share in the last 20 years (Figure 19) ⁽³³⁷⁾.

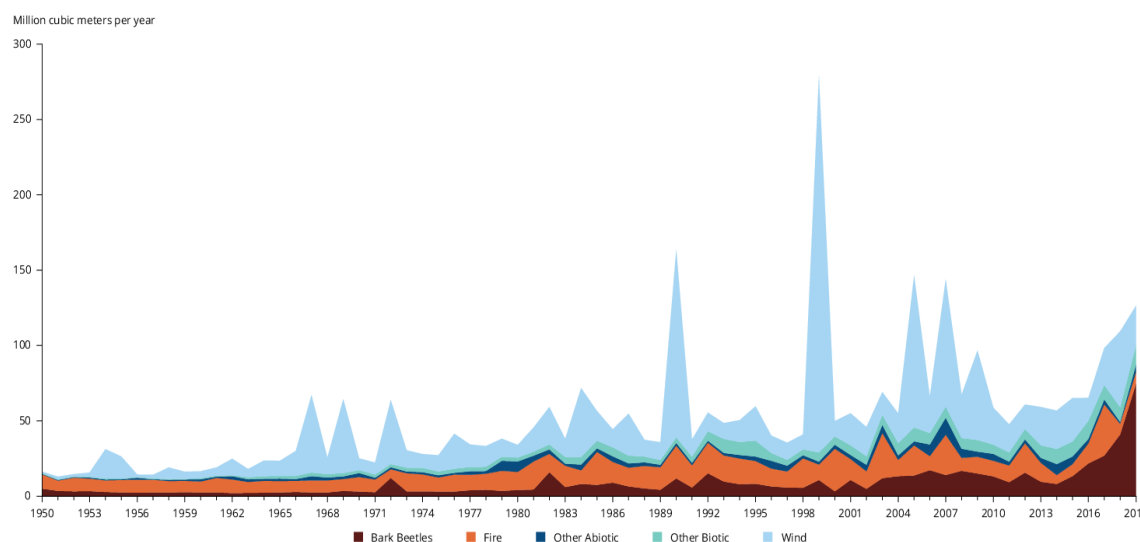
⁽³³⁵⁾Copernicus (2022) European State of the Climate 2022 <https://climate.copernicus.eu/esotc/2022/wildfires>

⁽³³⁶⁾Copernicus (2022) CAMS: monitoring extreme wildfire emissions in 2022 <https://atmosphere.copernicus.eu/cams-monitoring-extreme-wildfire-emissions-2022>

⁽³³⁷⁾ Patacca, M. et al. (2023). Significant increase in natural disturbance impacts on European forests since 1950. *Global Change Biology*, 29, 1359– 1376. <https://doi.org/10.1111/gcb.16531>. See also McDowell, N. G., Allen, C. D., Anderson-Teixeira, K., Aukema, B. H., Bond-Lamberty, B., Chini, L., ... & Xu, C. (2020). Pervasive shifts in forest dynamics in a changing world. *Science*, 368(6494), eaaz9463.

Climate change must be expected to continue to expose Europe's forests to growing risks from wildfires, outbreaks of biotic agents, wind throws, or a combination of these three. More than 60% of the biomass in European forests is exposed to these risks - over 33 billion tonnes in total - putting the future role of forests for wood provision or carbon sequestration under growing uncertainty (³³⁸).

Figure 19: Reported forest damage in Europe by disturbance until 2019



Source: Patacca et al. (2023). Graph: EEA

2.3.5.1.1.2 Projections of future climate change impacts on forests

The effects of global warming on forest growth and productivity in today's boreal zone may, on balance, be positive, as tree growth in these regions should benefit from increasing temperatures, longer growth seasons, and higher atmospheric CO₂ levels (³³⁹)(³⁴⁰). At the same time, even modest climate change may lead to major transitions in boreal forests (³⁴¹), and the changing climate also incorporates great uncertainties with regard to the frequency and magnitude of natural disturbances. These disturbances may become a major driver of

(³³⁸) Forzieri G. et al (2020) Vulnerability of European forests to natural disturbances. JRC PESETA IV project – Task 12. Luxembourg: Publications Office of the European Union / Forzieri, G., Girardello, M., Ceccherini, G. et al. (2021) Emergent vulnerability to climate-driven disturbances in European forests. Nat Commun 12, 1081.

(³³⁹) Lindner, M., Fitzgerald, J. B., Zimmermann, N. E., Reyer, C., Delzon, S., van Der Maaten, E., ... & Hanewinkel, M. (2014). Climate change and European forests: what do we know, what are the uncertainties, and what are the implications for forest management?. Journal of environmental management, 146, 69-83.

(³⁴⁰) Forzieri, G., Dakos, V., McDowell, N.G., Ramdane, A. and Cescatti, A. (2022) Emerging signals of declining forest resilience under climate change. Nature, 608, 534–539. Available from: <https://doi.org/10.1038/s41586-022-04959-9>

(³⁴¹) Reich, P.B., Bermudez, R., Montgomery, R.A. et al. Even modest climate change may lead to major transitions in boreal forests. Nature 608, 540–545 (2022). <https://doi.org/10.1038/s41586-022-05076-3>

forest dynamics and mediate changes in productivity⁽³⁴²⁾. Artificial spruce plantations are suffering under unprecedented droughts and bark beetle infestations. But also beech - a naturally dominant tree species across large regions of Europe's forests - may experience a progressive decrease of growth ranging from -20% to more than -50% by 2090, depending on the region and climate change scenario⁽³⁴³⁾. Conversely, in Mediterranean forests where water is the limiting factor, the future drier conditions in the region are expected to deteriorate the productivity capacity and even existence of forests and increase tree mortality and wildfire occurrence.

Importantly, whilst climate change impacts on forests do vary regionally and locally, depending on a variety of factors, any projection is difficult and fraught with significant uncertainty. In addition to the complex interplay of factors in regional exposure and vulnerability to climate impacts, much depends also on the general evolution of climate change itself, and the speed and scale at which its hazards come into force. The IPCC emphasized that for any given level of warming, many climate-related risks are higher than previously estimated⁽³⁴⁴⁾. In other words, current projections about the size of the climate change impacts on nature and people could be underestimated and worse case scenarios cannot be excluded. For example, a recent global assessment⁽³⁴⁵⁾ shows that statistically implausible heatwaves have occurred in 31% of the world's regions between 1959 and 2021, with no apparent spatial or temporal pattern, and that therefore 'impossible extremes' could occur anywhere and at any time.

Using the GLOBIOM model (see Annex 6, section 1.2 for description) to project natural disturbances in Europe, wind is the most important disturbance agent, in terms of the total damage, especially in Central and Northern Europe. Wind is predicted to still account for approximately 50% of the total damage by the end of the century even though its increase in disturbance activity due to climate change is less pronounced than other disturbances. In Mediterranean regions, wildfires are the dominant agent and the projected increase in temperature and reduction in precipitation in the region are expected to increase their frequency and severity⁽³⁴⁶⁾.

Figure 20 shows the distribution of wind damage expected in the EU. The areas most prone to damage are those located in the mountain forests of Central Europe, especially in France, Germany, Austria, Czechia and Slovakia, while wind damages for the Mediterranean region would be limited. Apart from mountain forests in Central Europe, the expected vulnerability to wind damage is high in Sweden. Countries in Eastern Europe would display intermediate damage caused by windstorms.

⁽³⁴²⁾ Reyer, C., Lasch-Born, P., Suckow, F., Gutsch, M., Murawski, A., & Pilz, T. (2014). Projections of regional changes in forest net primary productivity for different tree species in Europe driven by climate change and carbon dioxide. *Annals of forest science*, 71(2), 211-225.

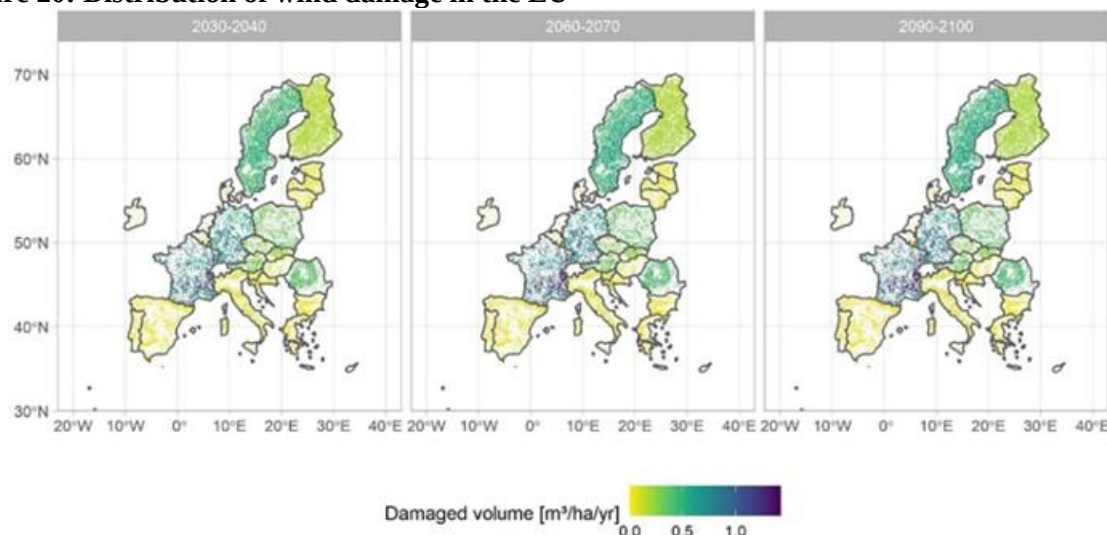
⁽³⁴³⁾ Martinez del Castillo, E., Zang, C.S., Buras, A. et al. Climate-change-driven growth decline of European beech forests. *Commun Biol* 5, 163 (2022). <https://doi.org/10.1038/s42003-022-03107-3>

⁽³⁴⁴⁾ IPCC (2022) AR6 WGII Climate Change 2022: Impacts, Adaptation and Vulnerability

⁽³⁴⁵⁾ Thompson, V., Mitchell, D., Hegerl, G.C. et al. The most at-risk regions in the world for high-impact heatwaves. *Nat Commun* 14, 2152 (2023). <https://doi.org/10.1038/s41467-023-37554-1>

⁽³⁴⁶⁾ See as well IPCC (2022) AR6 WGII Climate Change 2022: Impacts, Adaptation and Vulnerability. In the long term, lack of precipitation and heat will also reduce tree growth and possibly even make forest regrowth impossible in some parts of the Mediterranean region.

Figure 20: Distribution of wind damage in the EU



Note: The figure shows the yearly expected damage in m³/ha/year, caused by windstorms in the EU forest area, as an average over three periods (2030-2040, 2060-2070 and 2090-2100).

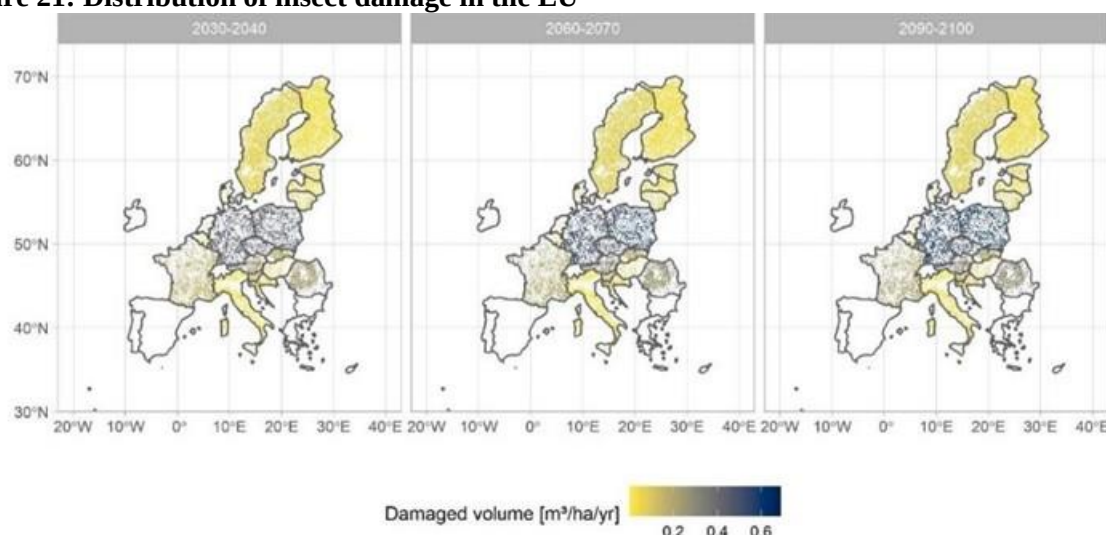
Source: GLOBIOM.

Insect damage is expected to occur mostly in temperate forests of Central Europe, where European spruce bark beetle is the most important biotic disturbance agent. Insect damage is expected to cause the second largest impact of disturbances, accounting for about 25% to 30% of the total damage at the end of the century ⁽³⁴⁷⁾. Similar to wind damage, the vulnerability to insects is according to GLOBIOM modelling highest in Germany, Poland, Austria, Czechia and Slovakia as shown in Figure 21. No major differences across forest types in relation to the predicted insect damage were found in the models, however scientific literature traditionally alerts about the lower resilience to pests and plagues of monoculture plantations ⁽³⁴⁸⁾.

⁽³⁴⁷⁾ It should be noted that modelling damage by biotic agents for the medium and long term bears considerable uncertainty due to many different drivers, complex interdependencies and non-linear relations.

⁽³⁴⁸⁾ Liu, C. L. C., Kuchma, O., & Krutovsky, K. V. 'Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future', *Global Ecology and conservation*, 15, 2018.

Figure 21: Distribution of insect damage in the EU

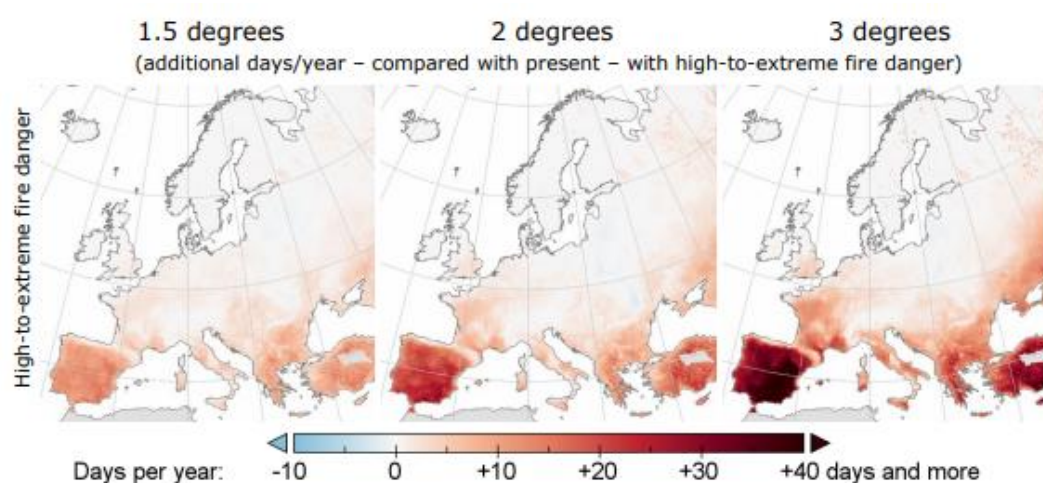


Note: The figure shows the yearly expected damage in m³/ha/year, caused by insect outbreaks in the EU forest area, as an average over three periods (2030-2040, 2060-2070 and 2090-2100).

Source: GLOBIOM

The JRC PESETA IV study⁽³⁴⁹⁾ assessed the wildfire danger and vulnerability for Europe and found that the number of days with high-to-extreme wildfire danger is expected to significantly increase in the future through climate change, particularly in Mediterranean Europe (Figure 22) due to drier and warmer conditions.

Figure 22: High-to-extreme fire danger by different levels of global warming



Note: Additional days per year with high-to-extreme fire danger, with reference to the situation in the control period 1981-2010, for different levels of global warming compared to pre-industrial times.

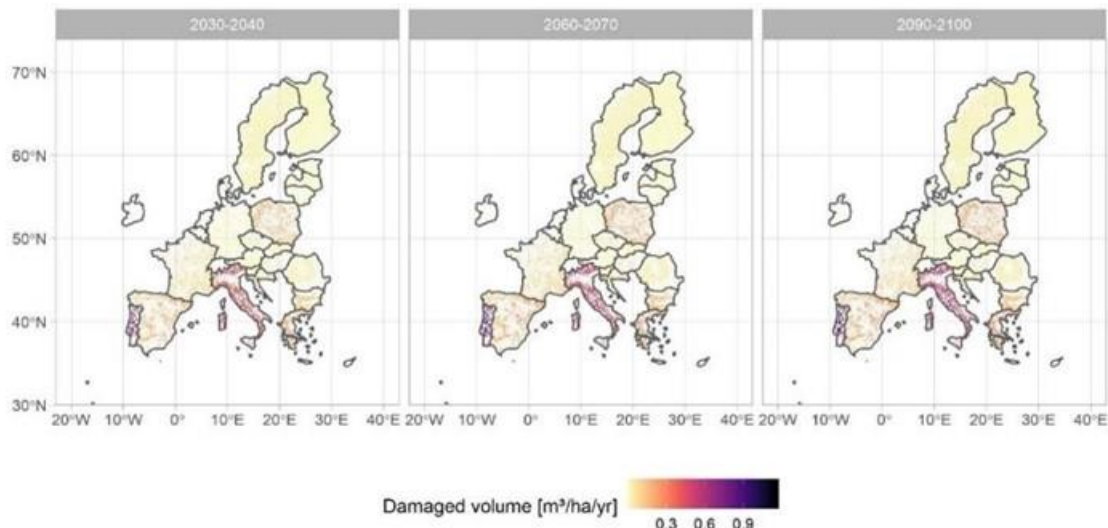
Source: JRC PESETA IV⁽³⁵⁰⁾

⁽³⁴⁹⁾ Costa, H., de Rigo, D., Libertà, G., Houston Durrant, T., San-Miguel-Ayanz, J., 2020. European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions. Publications Office of the European Union, Luxembourg, 59 pp. ISBN:978-92-76-16898-0 , <https://doi.org/10.2760/46951>

⁽³⁵⁰⁾ Costa, H., et al. 2020. European wildfire danger and vulnerability in a changing climate: towards integrating risk dimensions. Publications Office of the European Union, Luxembourg, 59 pp

GLOBIOM modelling projects wildfires to account for roughly 15-20% of the total damage at the end of the century and to occur mostly in the Mediterranean region with hotspots in Portugal, Spain Italy and Greece as shown in Figure 23. Other projections ⁽³⁵¹⁾⁽³⁵²⁾ estimated similar results for regional hotspots of natural disturbances but showed sharper increase in damaged volumes.

Figure 23: Distribution of wildfire damage in EU



Note: The figure shows the yearly expected damage in m³/ha/year, caused by wildfires in the EU forest area, as an average over three periods (2030-2040, 2060-2070 and 2090-2100).

Source: GLOBIOM

In general, hotspots of damage to forests were observed in Scandinavia and mountain forests of Central Europe. A driving factor for the disturbances in these areas might be related to the large share of conifer forests. Spruce forests, which is the dominant species of montane forests in central Europe, are particularly vulnerable to wind damage, due to the shallow root system of the species.

Adaptation measures may increase the resilience of the forests and thereby the carbon sinks and stocks, making it less vulnerable to natural disturbances and climate change. These measures can play a key role in mitigating wind damage in European forests and aim at increasing forest resilience towards environmental pressures on forest ecosystems. Particularly, future species selection must take into consideration the risks of wind damage and promote groups with higher stability ⁽³⁵³⁾. Similarly, the selection of species plays an important role in the resistance to fire occurrence ⁽³⁵⁴⁾. Importantly, ambitious adaptation measures for forests may prevent more dramatic sink losses in the future but require decades

⁽³⁵¹⁾ Gregor, K., Knoke, T., Krause, A., Reyer, C. P., Lindeskog, M., Papastefanou, P., ... & Rammig, A. (2022). Trade-offs for climate-smart forestry in Europe under uncertain future climate. *Earth's Future*, e2022EF002796.

⁽³⁵²⁾ Seidl, R., Schelhaas, M. J., Rammer, W., & Verkerk, P. J. (2014). Increasing forest disturbances in Europe and their impact on carbon storage. *Nature climate change*, 4(9), 806-810.

⁽³⁵³⁾ Albrich, K., Rammer, W., Thom, D., & Seidl, R. (2018). Trade-offs between temporal stability and level of forest ecosystem services provisioning under climate change. *Ecological Applications*, 28(7), 1884-1896.

⁽³⁵⁴⁾ Adámek, M., Jankovská, Z., Hadincová, V., Kula, E., & Wild, J. (2018). Drivers of forest fire occurrence in the cultural landscape of Central Europe. *Landscape Ecology*, 33(11), 2031-2045.

of implementation. The rate of deliberate forest renewal and transformation is slow, and hence most of today's forest ecosystems, with their specific structural and functional traits, will still be in place in 2040, exposed throughout the years to the rapidly changing climatic drivers. Hence their effect between 2030 and 2040 will be limited. Adaptation to climate change may therefore play a minor role for the achievement of the 2040 climate targets, but urgent action is nevertheless needed.

Adaptation might also provide a challenge for forest management. Traditional forestry systems and methods provide only limited direction for future forest management under changing conditions. Climate change may result in forest types that are unfamiliar and unprecedented, hence information on historical tree species compositions may often be of little value for adaptive forest management. This lack of predictability calls for adaptive, diversified and resilience-enhancing forest management systems with a preference for 'no regret' practices which work under any climate scenario.

2.3.5.2 Agriculture

2.3.5.2.1 Water management

Water scarcity exacerbated by climate change (see section 2.3.2) is threatening agriculture in particular, as 24% of Europe's water abstraction is due to agriculture⁽³⁵⁵⁾. Analysis of impacts of droughts on agriculture show reduced productivity on annual and perennial crops, reduced availability of irrigation water and impacts on livestock farming. In turn, the extraction of water for irrigation amplifies pressure on water resources. Hence the high consumption of water contributes to decreasing groundwater levels and severe lack of water availability in some European regions.

The share of irrigated agricultural land varies among European regions, with 60% of all irrigated areas being located in Southern Europe, where 85% of all irrigation abstraction takes place⁽³⁵⁶⁾. Southern Europe is also projected to experience less precipitation in the future and more frequent and severe droughts, reducing the availability of water for irrigation. At the same time, increased evapotranspiration rates due to increasing temperatures will further increase crop water requirements. With increasing global warming irrigation water demand is projected to increase in most irrigated regions in Europe, putting additional pressure on water resources⁽³⁵⁷⁾.

While irrigation may look like a suitable adaptation option to avoid production losses, large-scale or ground-water reliant irrigation can be a form of maladaptation, as it reduces groundwater availability, reduces long-term potential for hydropower, and can increase salinization, cost of water and reduce availability of water for aquaculture. It can also increase expenses for farmers, affecting small-scale farmers the most⁽³⁵⁸⁾⁽³⁵⁹⁾.

⁽³⁵⁵⁾ European Court of Auditors, 'Sustainable water use in agriculture', *Special Report*, 20, 2021.

⁽³⁵⁶⁾ European Environment Agency, 2021. Water resources across Europe — confronting water stress: an updated assessment.

⁽³⁵⁷⁾ European Environment Agency, 2019. Climate change adaptation in the agriculture sector in Europe.

⁽³⁵⁸⁾ Bezner Kerr, R., T. Hasegawa, R. Lasco, I. Bhatt, D. Deryng, A. Farrell, H. Gurney-Smith, H. Ju, S. Lluich-Cota, F. Meza, G. Nelson, H. Neufeldt, and P. Thornton, 2022: Food, Fibre, and Other Ecosystem Products. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the*

2.3.5.2.2 Impacts on crops

Climate change is already affecting agriculture through warming and precipitation changes, which has resulted in the northward movement of agro-climatic zones in Europe, earlier onset of the growing season, and the changes in crop yields, forest productivity and livestock. While for many years in Europe crop yields have been increasing, several studies suggest an important role of climate change in the observed flattening of yield levels in Western Europe. The combination of heat, drought and excessive rain have caused increased costs and economic losses in annual and permanent crops ⁽³⁶⁰⁾. Weather extremes due to compound effect of cold winters, excessive autumn and spring precipitation and summer drought have already caused production losses in the past years.

Climate change impacts agricultural crop productivity in various ways. The temperature requirements of the crop, lower rainfall, increasing variability, the length of the growing season and agronomic limitations such as whether a crop is cultivated under rainfed or irrigated systems play an important role. An increase in CO₂ concentration in the atmosphere has an important impact on the photosynthesis of plants, which on average leads to an increase in biomass productivity for crops, known as the CO₂ fertilisation effect, which can for some crops (e.g., wheat and barley) counterbalance some of the negative impacts of drought and warming ⁽³⁶¹⁾.

The JRC PESETA IV study ⁽³⁶²⁾ assessed the impact of climate change on crop yields in Europe, assuming no enhanced yield from CO₂ fertilization, and found that grain maize is projected to be most affected with substantial yield reductions for most of the producing countries in Europe. At 1.5°C global temperature increase, maize yield would decrease by 3% in Northern Europe and 7% in Southern Europe, and under 2.0°C by 5% in Northern Europe and 11% in Southern Europe (see Figure 24). Few Northern European countries could experience low gains in yield of grain maize. Overall yield reductions are lower at lower levels of warming. As grain maize is irrigated in most of Europe, these projections of impacts

Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 713–906, doi:10.1017/9781009325844.007

⁽³⁵⁹⁾ Some municipalities in the EU have already increased their prices for water use from agriculture to due water scarcity. Though many Member States apply different exemptions from the requirement for water abstraction and have water pricing levels for agriculture that do not take recovery costs for water services into account.

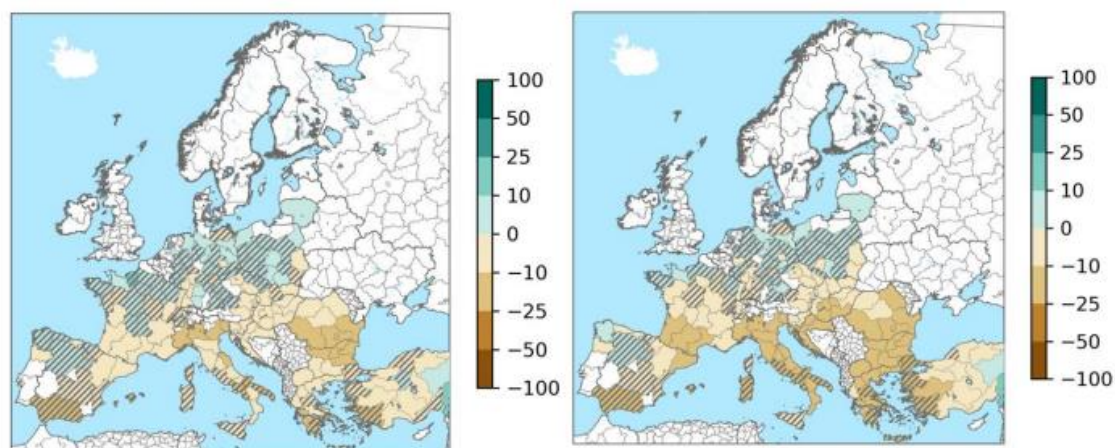
⁽³⁶⁰⁾ Stahl et al. 2016

⁽³⁶¹⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽³⁶²⁾ Hristov, J., Toret, A., Pérez Domínguez, I., Dentener, F., Fellmann, T., Elleby C., Ceglar, A., Fumagalli, D., Niemeyer, S., Cerrani, I., Panarello, L., Bratu, M., Analysis of climate change impacts on EU agriculture by 2050, EUR 30078 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10617-3, doi:10.2760/121115, JRC119632.

of climate change on yields assume sufficient irrigation water being available. However, under rain-fed conditions (see Figure 25), European maize production is projected to collapse around 2050, with yield losses higher than 23% in all EU countries and exceeding 80% in some, rendering maize production unviable in regions with unsustainable water use and projected decrease in precipitation.

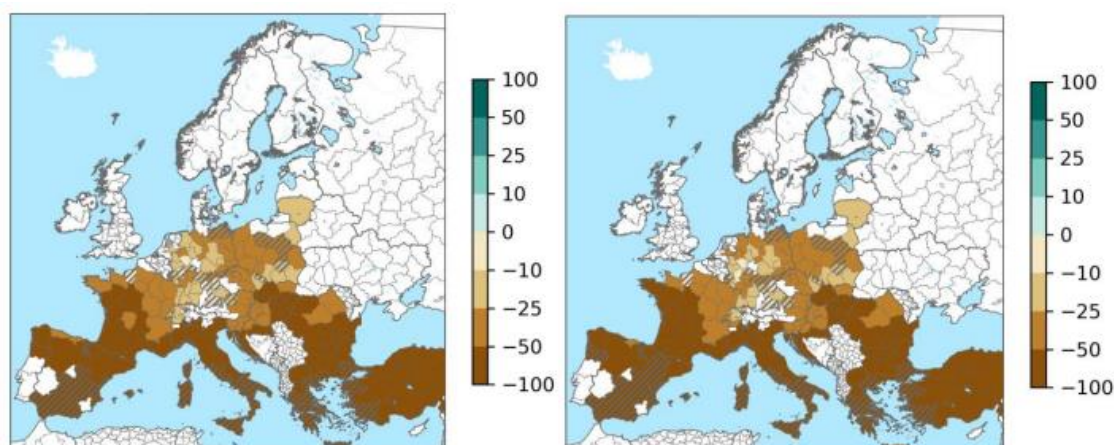
Figure 24: Changes in grain maize yield from Climate Change impacts with irrigation



Note: Graph shows impacts under RCP8.5 for 1.5°C (left panel) and 2°C (right panel) under irrigated conditions ⁽³⁶³⁾. Ensemble mean changes of grain maize yield (% relative to the historical period) projected under the RCP8.5 for 1.5°C (left panel) and 2°C (right panel) warming conditions, and assuming irrigated conditions. Hatching denotes areas with low models' agreement (i.e. less than 66% of models agree in the sign of estimated changes).

Source: JRC PESETA IV

Figure 25: Changes in grain maize yield from Climate Change impacts without irrigation



Note: Impacts are assuming rainfed conditions without irrigation. Ensemble mean changes of grain maize yield (% relative to the historical period) projected under the RCP8.5 for 1.5°C (left panel) and 2°C (right panel) warming conditions, assuming that no irrigation will be possible (i.e. rain-fed). Hatching denotes areas with low models' agreement (i.e. less than 66% of models agree in the sign of estimated changes)

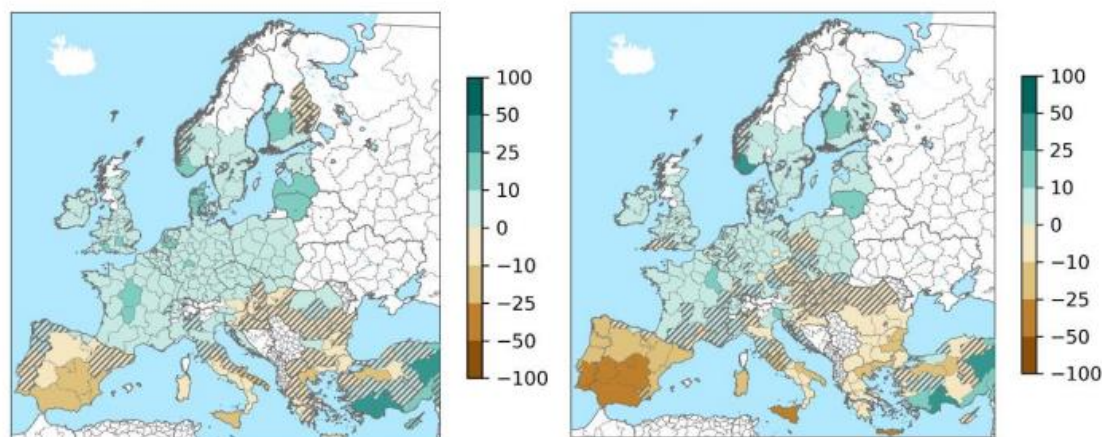
Source: JRC PESETA IV

Regarding yield of wheat in Europe, JRC PESETA IV found large uncertainties in the impact of climate change, mainly deriving from variable projections of precipitation, as wheat is mostly rain-fed. Projections under RCP8.5 show increases of 5-16% in yield for Northern Europe and losses of up to -49% in Southern Europe by 2050. Losses are slightly lower under 1.5°C compared to 2°C, most visible in the Iberian Peninsula and Italy (Figure 26). It is

⁽³⁶³⁾ In the cited PESETA IV report, the main results are obtained from the RCMs projections analysed for a 20-year period when the mean global temperature increases reach 1.5 °C and 2 °C. In the ten RCP8.5 model realisations the central year of these two periods ranges from 2018 to 2029 for the 1.5 °C warming conditions, and from 2030 to 2044 for the 2 °C global warming conditions.

important to note that the impacts of extreme weather events including heat stress and droughts are likely underestimated in these projections.

Figure 26: Changes in wheat yield from climate change



Note: Ensemble mean changes of wheat yield (% relative to the historical period) projected under the RCP8.5 for 1.5°C (left panel) and 2°C (right panel) warming conditions under rain-fed (no irrigation) conditions. Hatching denotes areas with low models' agreement (i.e. less than 66% of models agree in the sign of estimated changes).

Source: JRC PESETA IV

2.3.5.2.3 Regional differences

There are growing regional differences in agricultural production in Europe due to climate change, and they are projected to further increase. With increasing warming, growing regions for certain crops will shift or expand, and warming is projected to increase yields of some crops. Southern Europe is projected to be most negatively affected, and reduced irrigation water availability, heat and drought stress could lead to reduced profitability and abandonment of farmland⁽³⁶⁴⁾.

The JRC PESETA IV study⁽³⁶⁵⁾ finds climate change could trigger yield losses and shocks to European agriculture markets, with Southern Europe being the most negatively affected. The increasing divergence of production between Southern (declining) and Northern (potentially increasing) could impact the mutual reliance and trade patterns across EU countries, without appropriate adaptation strategies. Overall, at 1.5°C global warming, wheat yields could increase by 5% in Northern Europe and decrease by 7% in Southern Europe. At 2°C global warming, yields of maize in Southern Europe could decline by more than 10%. With a reduction in available irrigation water, crop losses could be much larger, and with no

⁽³⁶⁴⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børshiem, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽³⁶⁵⁾ Feyen L., Ciscar J.C., Gosling S., Ibarreta D., Soria A. (editors) (2020). *Climate change impacts and adaptation in Europe. JRC PESETA IV final report. EUR 30180EN*, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18123-1, doi:10.2760/171121, JRC119178

irrigation (rain-fed conditions) maize yield losses could reach 20% for all EU countries, and up to 80% for some Southern European countries (for more detailed projections see 2.3.5.2.2).

In the GLOBIOM model, impacts of climate change were modelled for different regions in the EU taking both negative as well as positive effects like CO₂ fertilisation into account. On average, crop yields decrease under all levels/scenarios of global warming, but this decrease is disproportionately larger as global temperatures get higher. Under an RCP2.6 scenario, average crop yields decrease by -2.2% in 2050, under an RCP7.0 scenario this has further increased to -2.6%. The North of Europe is the only region experiencing an increase in productivity because of climate change. Under RCP2.6 this is 1%, under RCP7.0 2.8%. The other regions in Europe all experience a decrease in crop productivity, which is largest in the Southern region (between -2.6% and -4.6% depending on the RCP). In the Central-East it ranges between -1.4% and -1.8% and in the West, crop productivity decreases with an increasing degree of warming, from -2.4% under RCP2.6 to -2.7% under RCP7.0. However, these impacts of climate change on agriculture productivity for most regions can be considered low, particularly in comparison with studies such as PESETA IV that find significantly higher losses.

As a significant caveat to the reported results concerning the agricultural sector, the increase in the risk of global synchronous crop failure of key staple crops will pose a risk that could affect EU economies through food price inflation and potentially through food insecurity domestically and globally, also impacting political stability. To illustrate, the probability of an over 10% reduction of maize yield in top four major exporting countries (accounting for 87% of global maize exports) may rise from zero in 2020 to 7% under 2 °C warming and 86% under 4 °C warming ⁽³⁶⁶⁾

2.3.5.3 Biodiversity and other ecosystems

Climate change is already impacting land ecosystems in Europe, many of which are also exposed to non-climatic hazards such as habitat loss and fragmentation, overexploitation, altered hydrological regimes and pollution. Climate change mitigation can limit the likelihood of larger climate change impacts on biodiversity and such actions can also help to increase resilience and adaption to climate change ⁽³⁶⁷⁾.

With increasing warming, risks for terrestrial ecosystems will continue to increase. Climate change has resulted in local losses and range shifts of thermosensitive species including insects, freshwater organisms, amphibians, reptiles, and birds. Amongst the most affected

⁽³⁶⁶⁾ Tigchelaar M. et al. 2018. Future warming increases probability of globally synchronized maize production shocks. PNAS. 115 (26) 6644-6649. doi.org/10.1073/pnas.1718031115

⁽³⁶⁷⁾ Smith, P., J. Nkem, K. Calvin, D. Campbell, F. Cherubini, G. Grassi, V. Korotkov, A.L. Hoang, S. Lwasa, P. McElwee, E. Nkonya, N. Saigusa, J.-F. Soussana, M.A. Taboada, 2019: Interlinkages Between Desertification, Land Degradation, Food Security and Greenhouse Gas Fluxes: Synergies, Trade-offs and Integrated Response Options. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.- O. Portner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. <https://doi.org/10.1017/9781009157988.008>

groups of animals are insects, central components of many ecosystems⁽³⁶⁸⁾. In the last three decades, the flying insect population in German protected areas has decreased by 76%. This data is considered to be representative of what is happening in Europe as a whole⁽³⁶⁹⁾. Flying insects include pollinators, key not only for biodiversity, but for food provision: pollinator-dependent crops contribute to 35% of global crop production volume⁽³⁷⁰⁾. Progressive subtropicalization is projected to occur in Southern Europe at 1.5°C and in Western and Central Europe at 3°C global warming level. Permafrost thawing and degradation in European Alps and Scandinavia has been observed and is projected to continue. Similar to forests, inland wetlands and peatlands, which hold important carbon stocks, will continue to be negatively affected by drought and warming. High latitude ecosystems are vulnerable to heat, and loss of mass has occurred in most mountain glaciers particularly in the past two decades⁽³⁷¹⁾. The years 2022 and 2023 saw a record loss of glacier ice from European Alps, mainly due to lack of snow, which contributed to summer drought conditions. In Switzerland, glaciers lost around 10% of their remaining volume⁽³⁷²⁾⁽³⁷³⁾.

The Alpine tundra occurs in high elevation zones of some of Europe's mountain ranges, and represents an important reservoir of freshwater resources and provides a habitat to unique species. Most of it is located in the Pyrenees, the Alps and the Scandes. It is projected to be greatly affected by global warming due to the tight ecological-climatic bands in the mountains⁽³⁷⁴⁾. The JRC PESETA study assesses that under 3°C of warming it would shrink by over

⁽³⁶⁸⁾ Harvey, J. A., Tougeron, K., Gols, R., Heinen, R., Abarca, M., Abram, P. K., Basset, Y., Berg, M., Boggs, C., Brodeur, J., Cardoso, P., de Boer, J. G., De Snoo, G. R., Deacon, C., Dell, J. E., Desneux, N., Dillon, M. E., Duffy, G. A., Dyer, L. A., ... Chown, S. L. (2023). Scientists' warning on climate change and insects. *Ecological Monographs*, 93(1). <https://doi.org/10.1002/ecm.1553>

⁽³⁶⁹⁾ Hallmann CA, Sorg M, Jongejans E, Siepel H, Hofland N, Schwan H, et al. (2017) More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE* 12(10): e0185809. <https://doi.org/10.1371/journal.pone.0185809>

⁽³⁷⁰⁾ IPBES (2016): Summary for policymakers of the assessment report of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services on pollinators, pollination and food production. S.G. Potts, et al. (eds.). Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany.

⁽³⁷¹⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børshheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

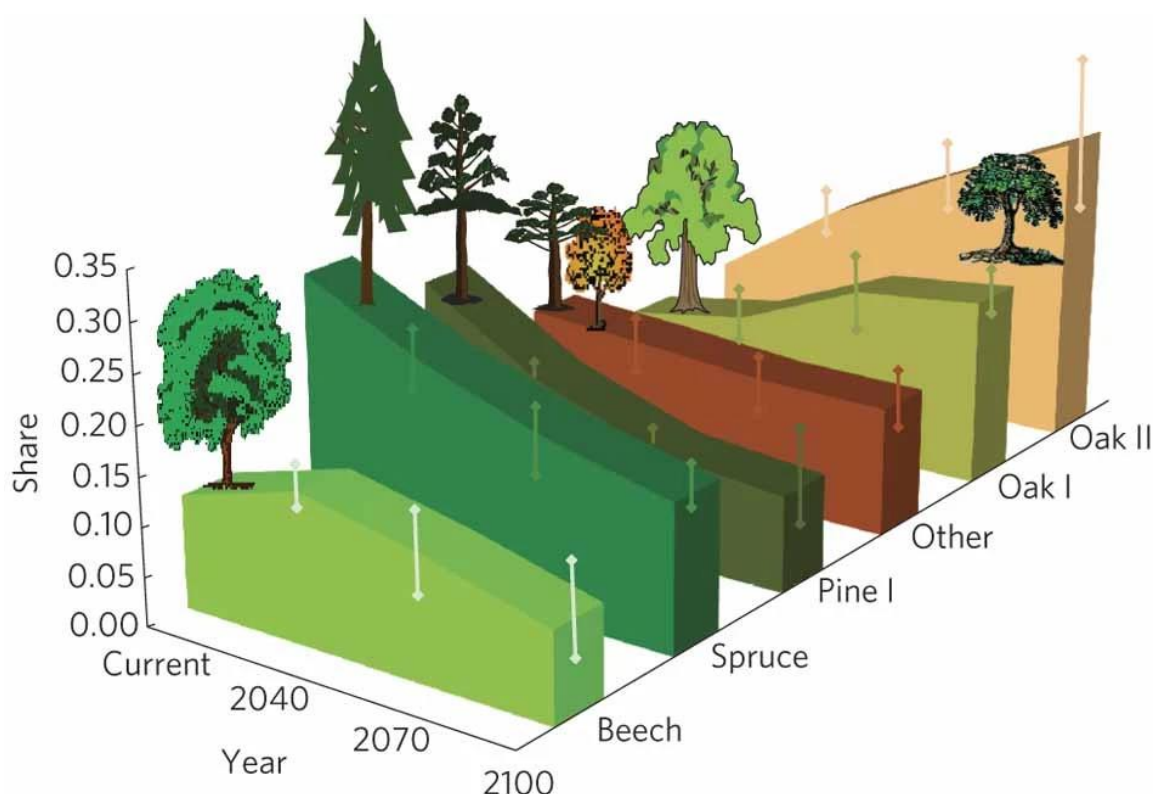
⁽³⁷²⁾ COPERNICUS, European State of the Climate 2022. [European State of the Climate 2022 Summary | Copernicus](#)

⁽³⁷³⁾ <https://wmo.int/files/provisional-state-of-global-climate-2023>

⁽³⁷⁴⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børshheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

75% compared to the reference period (1981-2010), with treeline moving by up to 8 meters upwards per year. It is projected to be most affected in the Pyrenees, where it would virtually disappear at 3°C global warming level, while in the Scandes and Alps it would shrink by around 87% and 75%, respectively. At 1.5°C and 2°C of global warming level, the overall loss of extent would be 31-36% and 50% respectively, with Pyrenees most affected, losing 74% at 1.5°C and above 90% at 2°C. The advance of treeline and shrinking of alpine tundra will impact high mountain ecosystems including through changes in snowpack accumulation, which will change mountain hydrology and affect low elevation biota. Cold-adapted species of plants will decline, and warm-adapted species will increase. Cold mountain habitats and their biota are projected to progressively decline, which will lead to extirpation of alpine plant species ⁽³⁷⁵⁾. To illustrate the massive shift of species due to climate change, Figure 27 shows the change in forest types expected to occur in Europe until the end of the century based on a moderate warming scenario.

Figure 27: Development of major tree species in Europe until 2100



Note: Projections are based on a moderate warming scenario A1B (IPCC 2007, AR4, WG 1)

Source: Hanewinkel et al. 2013 ⁽³⁷⁶⁾

Freshwater ecosystems are vulnerable to climate change and are projected to be affected by the reduced river flow (made worse by increasing pressures on hydromorphology, e.g. construction of new reservoirs), low oxygen, salinity incursion, eutrophication and

⁽³⁷⁵⁾ Barredo, J.I., Mauri, A., Caudullo, G., Impacts of climate change in European mountains — Alpine tundra habitat loss and treeline shifts under future global warming, EUR 30084 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10717-0, doi:10.2760/653658, JRC115186.

⁽³⁷⁶⁾ Hanewinkel, M., Cullmann, D., Schelhaas, M.J. et al. 'Climate change may cause severe loss in the economic value of European forest land' *Nature Climate Change*, 3, 203–207, 2013.

spread of invasive species. These will lead to loss of species, especially molluscs, fish and insects. In line with the global trend, European lakes have been warming in the past decades. Globally, the year 2022 was the warmest year on records for lakes, and the fourth warmest for European lakes, which are warming at a rate of 0.33°C per decade, which is faster than the global rate of 0.23°C per decade ⁽³⁷⁷⁾.

Changes to the ocean, including sea warming, ocean acidification, deoxygenation and more frequent marine heatwaves will affect both ocean ecosystems and the people relying on them and will continue through the rest of this century ⁽³⁷⁸⁾. Sea surface warming between 0.25°C and 1°C has already been observed over the past decade and is projected to continue increasing, along with changes to salinity and pH. In 2022, sea surface temperatures across Europe's seas were the warmest on record. Record temperatures were observed in the Mediterranean Sea, the Bay of Biscay, the English Channel and Irish Sea and in the Norwegian Sea ⁽³⁷⁹⁾. In the summer 2023 sea surface temperatures in the Mediterranean Sea were again exceptionally high, locally exceeding 30°C, and reached more than 4°C above average in most of western Mediterranean ⁽³⁸⁰⁾.

Habitat loss and northward distribution shifts of species have been observed, and marine heatwaves have had severe impacts on marine ecosystems. Along with redistribution and alterations in community composition, biodiversity decline has also been observed in some sub-regions. With increasing global warming, risks to marine and coastal ecosystems will further increase ⁽³⁸¹⁾.

In the Black Sea basin, climate change is recognised as an important pressure of the Environment of the Black Sea (2009-2014/5). One of the consequences of temperature rise due to climate change is the invasion of the Black Sea by Mediterranean-originated species ⁽³⁸²⁾.

Europe hosts some biodiversity hotspots, including Fenno-Scandia Alpine tundra and taiga, European Mediterranean montane forests, Mediterranean forests, woodlands, scrub, Danube

⁽³⁷⁷⁾ COPERNICUS, European State of the Climate 2022. [European State of the Climate 2022 Summary | Copernicus](#)

⁽³⁷⁸⁾ IPCC, 2022: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844

⁽³⁷⁹⁾ COPERNICUS, European State of the Climate 2022. [European State of the Climate 2022 Summary | Copernicus](#)

⁽³⁸⁰⁾ [Heatwaves, wildfires mark summer of extremes | World Meteorological Organization \(wmo.int\)](#)

⁽³⁸¹⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015.

⁽³⁸²⁾ Oguz T. 2005. Long-Term Impacts of Anthropogenic Forcing on the Black Sea Ecosystem. *Oceanography* 18(2):112-121.

River delta, Balkan rivers and streams, Northeast Atlantic shelf marine and Mediterranean Sea. Those are areas with exceptionally high species richness, including rare and endemic species, where historic climatic variability was moderate. Biodiversity hotspots are projected to be especially vulnerable to climate change due to limited geographic ranges of their endemic species. Climate change will impact species abundance, diversity, area, physiology and fisheries catch potential ⁽³⁸³⁾.

Identifying and protecting climatic refugia, which are microhabitats that components of biodiversity retreat to, is crucial for the survival, persistence and eventual expansion of biota under anthropogenic climate change ⁽³⁸⁴⁾.

3 ECONOMIC COST OF CLIMATE CHANGE

3.1 Evidence from recent events

The increase in the frequency and scale of extreme climate-related events in past decades is well-documented, as is the causality with the global rise in temperatures. The global economic losses and fatalities associated with such events are well documented, including by global insurance and re-insurance companies.

Allianz reports, that the heatwave of 2023 which affected Southern Europe, the United States and China may have cost 0.6% of GDP ⁽³⁸⁵⁾. AON ⁽³⁸⁶⁾ reports that direct economic losses resulting from natural disasters amounted to US\$ 313 billion in 2022 (in current prices). All but US\$ 9 billion of these costs were related to climate events. Since the beginning of the century, AON estimates direct losses at an average of about US\$ 300 billion. Looking back further, the data indicates a clear rising trend in direct economic losses, starting around the 1980s (Figure 28).

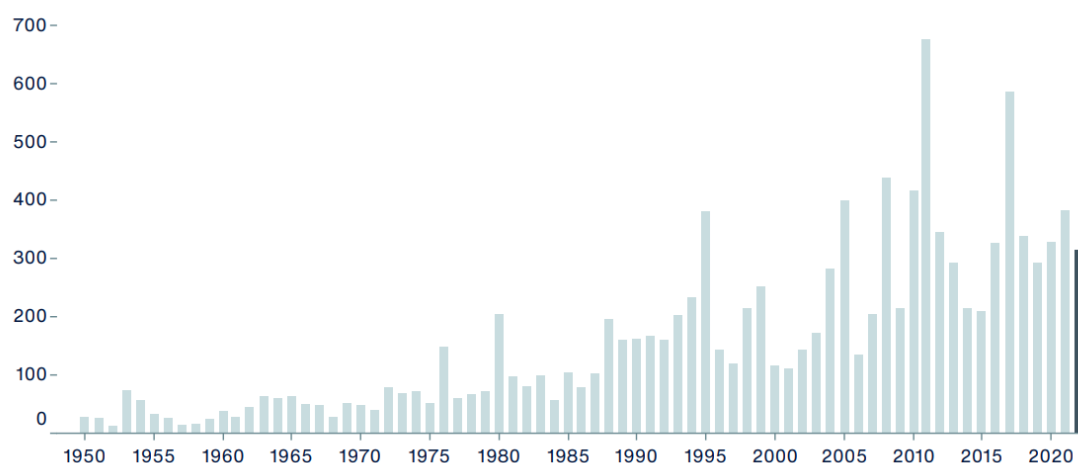
⁽³⁸³⁾ Costello, M.J., M.M. Vale, W. Kiessling, S. Maharaj, J. Price, and G.H. Talukdar, 2022: Cross-Chapter Paper 1: Biodiversity Hotspots. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2123–2161, doi:10.1017/9781009325844.018.

⁽³⁸⁴⁾ Keppel et al. 2011. Refugia: identifying and understanding safe havens for biodiversity under climate change. *Global Ecology and Biogeography*. doi.org/10.1111/j.1466-8238.2011.00686.x

⁽³⁸⁵⁾ Subran L., Groschl J. and Zimmer M. 2023. Global boiling: Heatwave may have cost 0.6pp of GDP. Allianz Research. URL: https://www.allianz.com/en/economic_research/publications/specials_fmo/global-heatwave-implications.html

⁽³⁸⁶⁾ AON. 2023. Weather, Climate and Catastrophe Insight.

Figure 28: Global economic losses from natural disasters since 1950

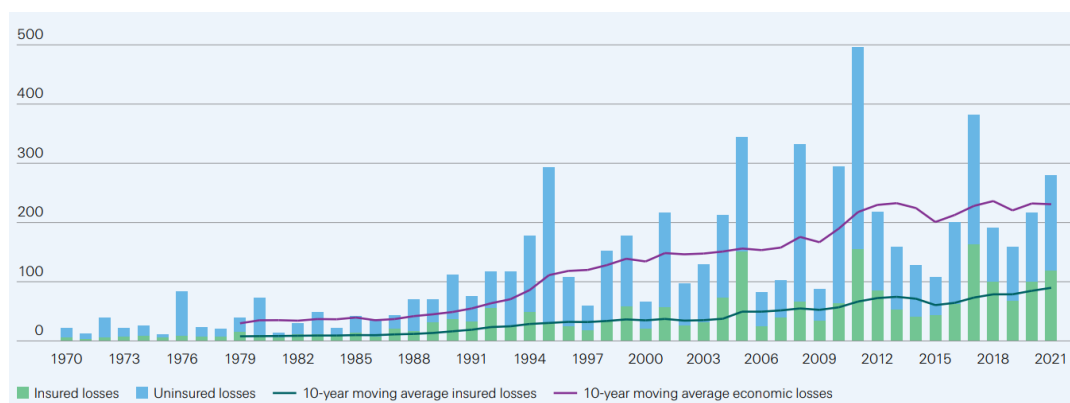


Note: Losses shown in billion US\$ 2021

Source: AON (2023).

While the precise data differ according to the sources used and the methodologies used or the scoped covered, the rising trend in climate-related economic damages is an unequivocal finding across the board. The Swiss Re Institute ⁽³⁸⁷⁾ estimates that natural catastrophes, mainly climate-related, generated world-wide losses of US\$ 270 billion in 2021 (Figure 29), equivalent to 0.29% of global GDP. This compares to estimated losses of 0.23% of GDP on average in the past decade. Of these losses, Swiss Re estimates that about US\$ 110 billion were covered by insurance. Globally, uninsured losses represent a large proportion of direct losses.

Figure 29: Insured and uninsured losses from catastrophes (billion US\$ 2021)



Source: Swiss Re Institute (2023).

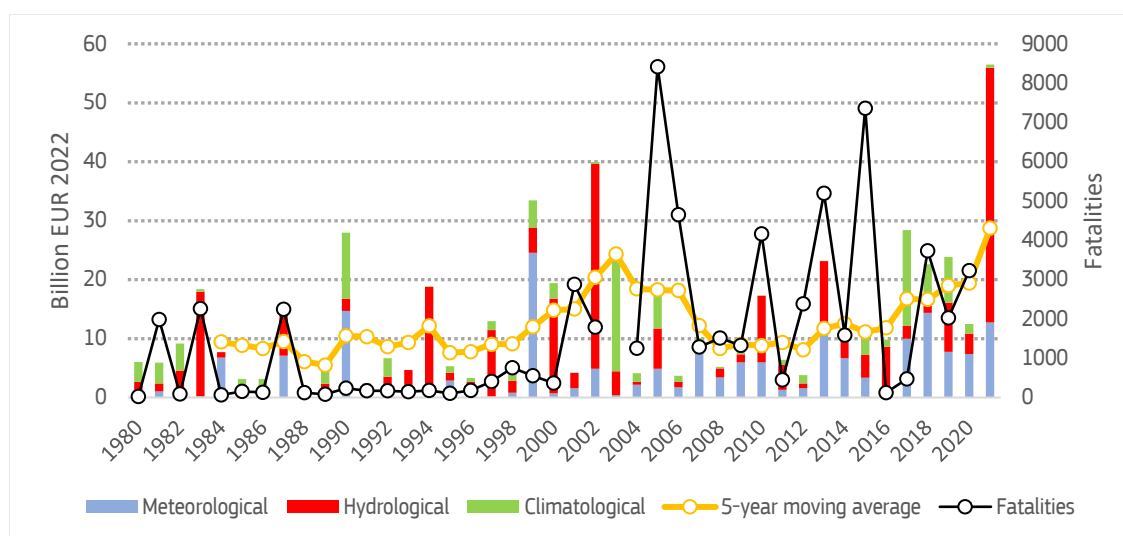
A rising trend in direct economic losses from climate-related events is also observed in the EU, particularly since the beginning of the 2010s. EEA reports that weather- and climate-related extremes caused economic losses estimated at EUR 560 billion in the EU between 1980 and 2021, of which only EUR 170 billion (30%) were insured. Nearly 195,000 fatalities have been caused by floods, storms, heat- and coldwaves, wildfires and landslides in that time ⁽³⁸⁸⁾. Hydrological and meteorological events are the main sources of direct losses in the

⁽³⁸⁷⁾ Swiss Re Institute. Sigma. Natural Catastrophes in 2021: the floodgates are open.

⁽³⁸⁸⁾ <https://www.eea.europa.eu/ims/economic-losses-from-climate-related>

EU, with the costliest single events arising mainly from riverine floods (Figure 30). For example, the floods in the summer of 2021 in Belgium and Germany are estimated to have caused economic losses of close to EUR 50 billion, in addition to more than 200 casualties⁽³⁸⁹⁾. Meteorological events, mainly heatwaves, are nevertheless the biggest climate-related source of excess fatalities (abstracting from premature deaths related to atmospheric pollution, as discussed in section 2.3.1). It is estimated that there were about 74 000 excess fatalities in the EU due to the heatwave of 2003, and around 60 000 excess fatalities again during the heatwave of 2022⁽³⁹⁰⁾.

Figure 30: Direct economic costs and fatalities from climate-related events in the EU



Source: EEA and Eurostat.

Economic costs of climate change are also being seen and felt at the individual level and the increasing frequency and magnitude of impact are raising questions on the capacity of the insurance sector to handle such risks in the future. For instance, insurance companies are not offering home insurance to an increasing number of homes in the USA due to rapidly growing exposure to extreme weather events like wildfires⁽³⁹¹⁾. Difficulties in adequately insuring homes is also set to increase in Australia due to flooding, with analysis suggesting one in every seven homes in high-risk areas will see their home insurance become unaffordable or unavailable already by 2030⁽³⁹²⁾.

Europeans are currently underinsured in relation to weather events that will increase due to climate change. Currently only a quarter of the total losses caused by extreme weather and climate-related events across Europe are insured, indicating that there is an insurance

⁽³⁸⁹⁾ <https://climate.copernicus.eu/esotc/2021/flooding-july>

⁽³⁹⁰⁾ Ballester, J., Quijal-Zamorano, M., Méndez Turrubiates, R.F. et al. Heat-related mortality in Europe during the summer of 2022. *Nat Med* (2023).

⁽³⁹¹⁾ <https://www.axios.com/2023/05/29/state-farm-home-insurance-california-wildfires>

⁽³⁹²⁾ https://www.climatecouncil.org.au/wp-content/uploads/2022/05/CC_Report-Uninsurable-Nation_V5-FA_Low_Res_Single.pdf

protection gap in Europe (³⁹³). The protection gaps vary significantly among Member States, and vary by climatic events, covering coastal floods, river floods, wildfires and windstorms.

3.2 Analyses on global economic impacts

Estimating global aggregate economic costs of climate change is challenging due to uncertainties that characterize the impacts of climate change (see section 3.4).

Diverse methodologies are used in the literature for the assessment of costs of climate change (³⁹⁴), including biophysical process models, structural economic models, econometrics, hybrid approaches (³⁹⁵) and semi-qualitative methods based on expert elicitation (³⁹⁶). Econometric estimates tend to produce higher damage estimates than models. Further, studies use different impact categories and different spatial and temporal scope.

Differences derive also from evaluation methods applied to assess climate impacts. Monetizing mortality/morbidity from climate change for example can be done through estimating macroeconomic impacts of loss of labour productivity, or through the value of statistical life. There are ethical concerns to putting monetary value to non-economic losses, such as loss of human life, loss of species, or intangible heritage. Quantification of costs of climate change is nonetheless useful as it provides at least a partial picture of ranges of economic damages, the impact categories, and differences between direct and indirect costs.

Costs can be presented as:

- Aggregate or systemic costs (aggregate GDP losses from climate change)
- Direct costs of climate change impacts: (method for economic costs that does not consider market adjustments)
- Indirect costs (such as weakening economic growth, lower asset values)
- Transmission mechanisms (e.g., trade effects: can exacerbate or smoothen losses from climate change)

The IPCC Special Report on Global Warming of 1.5°C (2018) (³⁹⁷) states that 2°C degrees of warming is projected to lead to lower aggregated economic growth due to climate change in

(³⁹³) EIOPA, “The dashboard on insurance protection gap for natural catastrophes in a nutshell”, <https://www.eiopa.europa.eu/system/files/2022-12/dashboard-on-insurance-protection-gap-for-natural-catastrophes-in-a-nutshell.pdf>

(³⁹⁴) Bosello F. and Leon C.J. 2022. Climate change impacts in the EU: new evidence from recent research. EAERE Magazine, 16 Spring 2022 – Climate Impacts and Adaptation.

(³⁹⁵) O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Key Risks Across Sectors and Regions. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2411–2538, doi:10.1017/9781009325844.025.

(³⁹⁶) Bosello F. and Leon C.J. 2022. Climate change impacts in the EU: new evidence from recent research. EAERE Magazine, 16 Spring 2022 – Climate Impacts and Adaptation.

(³⁹⁷) Hoegh-Guldberg, O., D. Jacob, M. Taylor, M. Bindi, S. Brown, I. Camilloni, A. Diedhiou, R. Djalante, K.L. Ebi, F. Engelbrecht, J. Guiot, Y. Hijioka, S. Mehrotra, A. Payne, S.I. Seneviratne, A. Thomas, R. Warren, and G. Zhou, 2018: Impacts of 1.5°C Global Warming on Natural and Human Systems. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to

2100 compared to 1.5°C of warming. The mean net present value of the costs of damages from global warming in 2100 for 1.5°C is US \$54 trillion, and US \$69 trillion for 2°C, relative to 1961–1990. This includes costs associated with climate change-induced market and non-market impacts, impacts due to sea level rise, and impacts associated with large-scale discontinuities.

The IPCC AR6 Working Group II report (2022) ⁽³⁹⁸⁾ confirms that global aggregate economic impacts generally increase with higher degree of global warming. However, due to the wide range of damage estimates and lack of comparability between methodologies, the report does not provide a robust range of estimates but recognizes that global aggregate economic impacts could be higher than estimated in the previous report.

The latest IEA Net Zero Roadmap report ⁽³⁹⁹⁾ finds that without increasing policy ambition by 2030, limiting global average temperature to 1.5°C by 2100 will become much harder, as higher levels of CO₂ removal from the atmosphere will be necessary after 2050. Such delay in climate action would cost the world an additional US \$1.3 trillion per year.

A recent study by van der Wijst et al. (2023) ⁽⁴⁰⁰⁾ estimates that global damages from climate change would reach 10–12% of GDP by 2100 under a 3°C global warming scenario, and 2% of GDP under a well below 2°C global warming scenario. With increasing warming losses increase rapidly (Figure 31), and after the mid-century the economic benefits of climate action become increasingly apparent. They conclude that the economic benefits of reduced damages from climate change substantially outweigh the cost of climate change policy, even when some climate damages, such as impacts on health and biodiversity, are not accounted for (Figure 32).

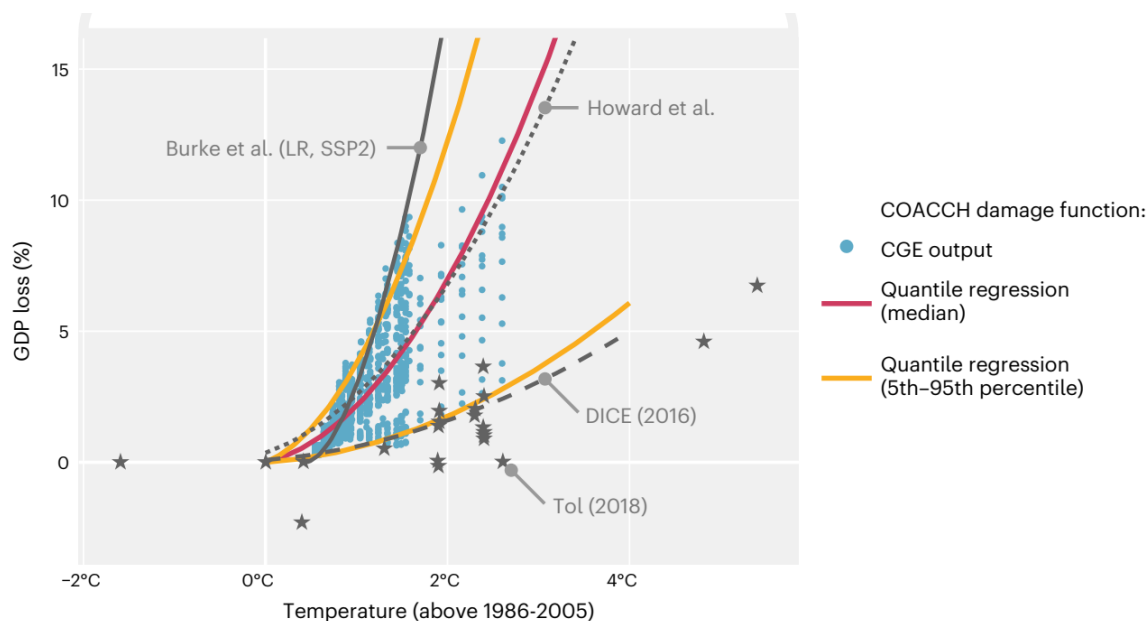
the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 175–312. <https://doi.org/10.1017/9781009157940.005>.

(398) O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Key Risks Across Sectors and Regions. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2411–2538, doi:10.1017/9781009325844.025.

(399) International Energy Agency. 2023. Net Zero Roadmap: A Global Pathway to Keep 1.5°C Goal in Reach. URL: <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>

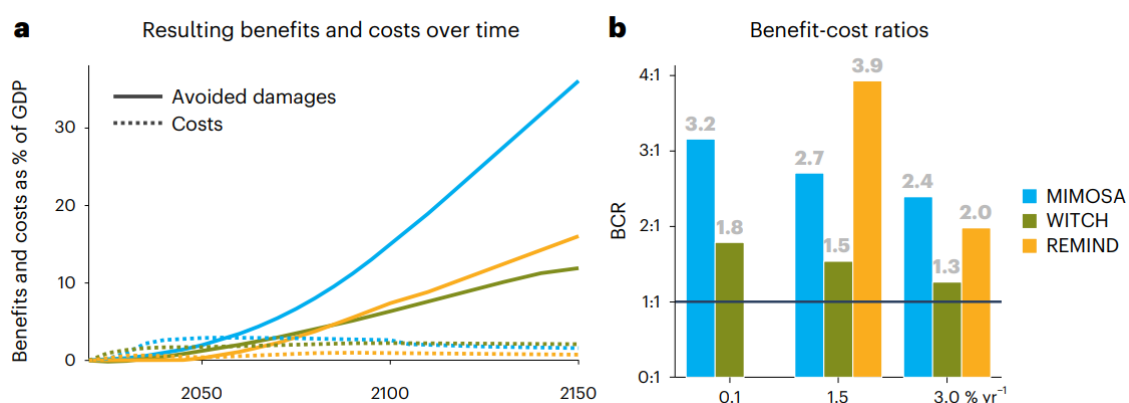
(400) van der Wijst, KI., Bosello, F., Dasgupta, S. et al. New damage curves and multimodel analysis suggest lower optimal temperature. *Nature Climate Change*, **13**, 434–441 (2023). <https://doi.org/10.1038/s41558-023-01636-1>

Figure 31: Example of damage functions as used in Integrated Assessment Models



Note: Model using quantile regression, showing 5th (low estimate), 50th (medium) and 95th (high) percentiles.
Source: van der Wijst et al. (2023).

Figure 32: Benefit-cost ratios for the Cost-benefit analysis



Note: Benefit-cost ratios for the cost-benefit analysis scenario using the medium damage function (50th percentile):
a, Policy costs (dotted lines) and avoided damages (benefits, solid lines) over time for the scenario with medium discounting. b, BCR: total discounted avoided damages divided by the total discounted mitigation costs. REMIND is not calibrated for the lowest discount rate. The numbers above the bars correspond to the exact value of the benefit-cost ratio.

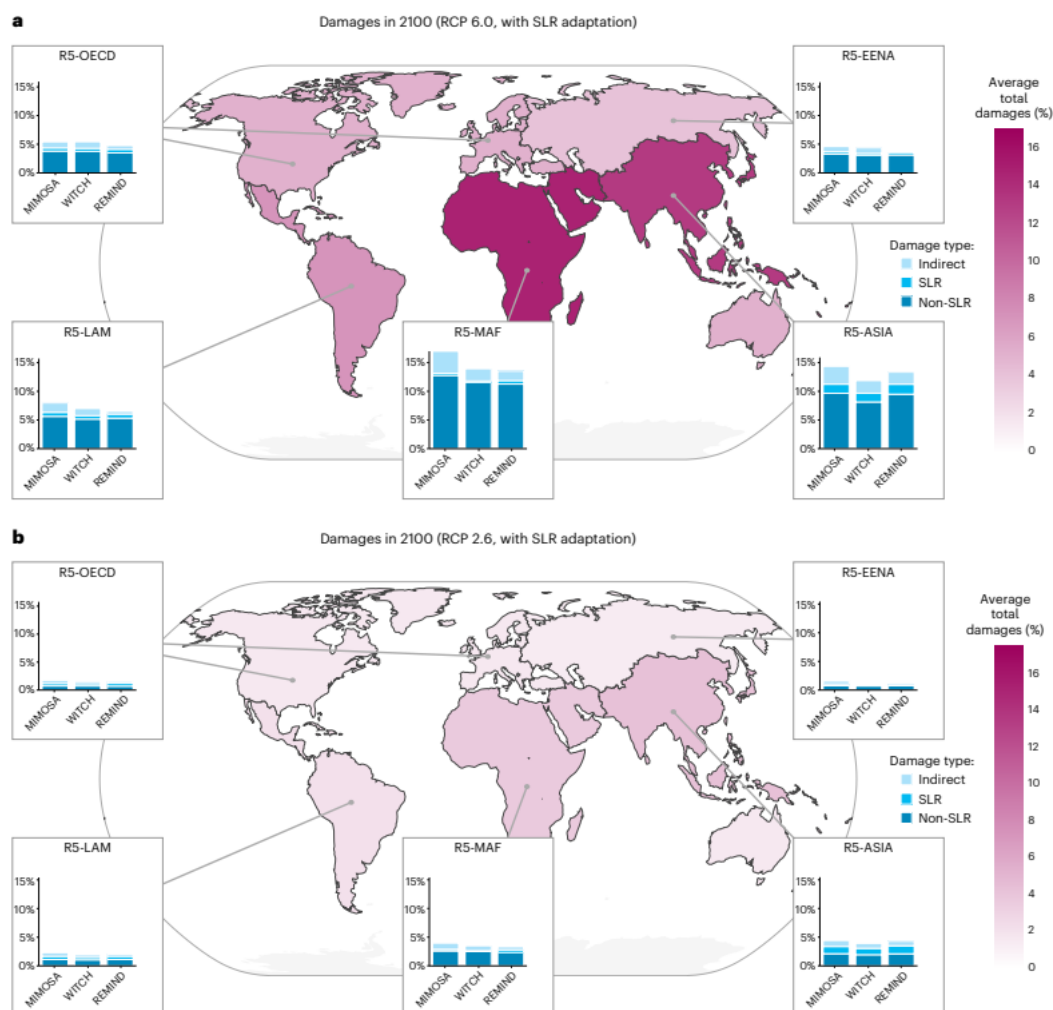
Source: van der Wijst et al. (2023).

The economic impacts vary between region and social groups (Figure 33). With increasing global warming levels, Africa and the Middle East are projected to experience the highest damages from climate change, followed by Asia and Latin America ⁽⁴⁰¹⁾. While economic

⁽⁴⁰¹⁾ van der Wijst, KI., Bosello, F., Dasgupta, S. et al. New damage curves and multimodel analysis suggest lower optimal temperature. *Nature Climate Change*, 13, 434–441 (2023). <https://doi.org/10.1038/s41558-023-01636-1>

impacts on poorer countries and households account for a smaller share of aggregate losses in GDP terms, the impact on welfare and wellbeing can be substantial ⁽⁴⁰²⁾.

Figure 33: End of century damages for the five macro-regions for two scenarios



Note: The damages are split into three types (direct temperature-related damages, direct sea-level-rise damages and indirect damages from GDP loss accumulation). The damages are shown for the year 2100 in the RCP6.0 scenario (a) and the RCP2.6 scenario (b). Both scenarios assume optimal sea-level-rise adaptation. This figure does not show intra-regional differences; only the population-weighted average per macro-region is shown.

Source: van der Wijst et al. (2023).

3.3 Sectoral economic impacts in the EU

3.3.1 The PESETA study

The impacts of climate change will also affect European economies. The JRC PESETA IV study assessed the impacts of climate change in broader economic terms for seven impact

⁽⁴⁰²⁾ O'Neill, B., M. van Aalst, Z. Zaiton Ibrahim, L. Berrang Ford, S. Bhadwal, H. Buhaug, D. Diaz, K. Frieler, M. Garschagen, A. Magnan, G. Midgley, A. Mirzabaev, A. Thomas, and R. Warren, 2022: Key Risks Across Sectors and Regions. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2411–2538, doi:10.1017/9781009325844.025.

categories: river floods, coastal floods, agriculture, energy supply, droughts, windstorms and human mortality. They used a static approach, assuming current size and structure of the economy. The full economic impacts of climate change were not assessed, and the assessment also did not consider the impact of passing climate tipping points. It finds that exposing present economy to 1.5°C, 2°C and 3°C global warming would result in annual welfare loss of, respectively, EUR 42 billion/year (0.33% of GDP), EUR 83 billion/year (0.65% of GDP) and EUR 175 billion/year (1.38% of GDP). In this study human mortality from extreme heat accounts for the dominant part of economic climate impacts, however, it strongly depends on the monetary value that is put on human life. River flood damage is projected to increase six-fold at 3°C global warming, reaching EUR 43 billion per year by the end of the century, compared to the current losses estimated at EUR 7.8 billion per year (EU + UK), and exposing 500 000 people to river flooding per year, compared to 170 000 today. Limiting warming to 1.5°C would decrease the number of people exposed by 230 000 and halve the economic impacts. Without strong adaptation action, coastal flood losses would rise sharply due to sea level rise, and at 3°C global warming level, annual economic damages in the EU+UK would reach EUR 240 billion by 2100, compared to EUR 1.4 billion per year today. 2.2 million people would be exposed to coastal flooding compared to 0.1 million today. Moderate mitigation action would reduce economic losses by half (to EUR 111 billion per year) and people exposed to 1.4 million per year. Even with strong mitigation, adaptation will continue to be necessary to limit impacts from flooding. The benefits of adaptation are long-lasting and avoided damage grows in time and with increasing global warming levels. At 3°C global warming, losses from drought would increase from EUR 9 billion per year today to EUR 45 billion per year in 2100. Current annual losses from drought are estimated to be around EUR 9.4 billion (EU+UK), with Spain, Italy and France being the most impacted. The largest share of the losses comes from agriculture, followed by the energy sector and public water supply. At 1.5°C global warming level, losses from drought in EU+UK could reach EUR 25 billion per year by the end of the century, EUR 31 billion at 2°C global warming and EUR 45 billion at 3°C global warming ⁽⁴⁰³⁾ ⁽⁴⁰⁴⁾.

3.3.2 Other recent analyses

Bosello and Leon (2022) ⁽⁴⁰⁵⁾ review recent studies on the economic costs of climate change for the EU and find that macroeconomic losses can be higher than previously estimated. Extreme events and impacts on infrastructure are the main drivers, as well as health impacts on mortality and impacts on labour productivity. In the literature they assess, coastal damages from sea-level rise and riverine floods account to more than 70% of GDP market losses, stressing the importance of infrastructural adaptation. They conclude that staying within the Paris Agreement temperature range would greatly reduce the macroeconomic and welfare losses compared to higher global warming scenarios.

⁽⁴⁰³⁾ Feyen L., Ciscar J.C., Gosling S., Ibarreta D., Soria A. (editors) (2020). Climate change impacts and adaptation in Europe. JRC PESETA IV final report. EUR 30180EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18123-1, doi:10.2760/171121, JRC119178

⁽⁴⁰⁴⁾ Cammalleri C., Naumann G., Mentaschi L., Formetta G.(a), Forzieri G., Gosling S.(b), Bisselink B., De Roo A., and Feyen L., Global warming and drought impacts in the EU, EUR 29956 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-12947-9, doi:10.2760/597045, JRC118585.

⁽⁴⁰⁵⁾ Bosello F. and Leon C.J. 2022. Climate change impacts in the EU: new evidence from recent research. EAERE Magazine, 16 Spring 2022 – Climate Impacts and Adaptation.

The COACCH project ⁽⁴⁰⁶⁾, ⁽⁴⁰⁷⁾ (Co-designing the Assessment of Climate Change Costs) considers the economic costs of climate change in Europe for the following categories: energy demand and supply, labour productivity, agriculture, forestry, fisheries, transport, sea-level rise, and riverine floods. The study finds that the economic cost of climate change for Europe is high even for central scenarios in the mid-century, and with higher warming the costs increase significantly later in the century. Ambitious climate mitigation will therefore provide major economic benefits in Europe by reducing climate damages, and those benefits are projected to be more pronounced later in the century. In the next two decades some impacts are unavoidable and can be reduced with adaptation action, which can deliver high benefit to cost ratio.

The Swiss Re Institute ⁽⁴⁰⁸⁾ explicitly simulated for some of the uncertainties that are often unaccounted-for in the literature. It attempted to factor in impact variables such as the impact of supply chain disruptions, migration and biodiversity. It also treated the potential for tail risk parameter uncertainty by applying multiplicative factors to the accumulated economic impact from the quantified and proxied risk channels. While basing a multiplicative factor itself on anything other than expert judgement is difficult, excluding tail risk parameter uncertainty altogether amounts to a de facto choice to apply a multiplicative factor of 1. The results suggest up to 8% of GDP loss by mid-century in Europe on a path of 2-2.6°C global warming, and up to 10.5% of GDP loss on a path to 3.2°C of global warming, as against up to 2.8% of GDP loss in a well below 2°C scenario.

All of the assessed studies find large regional disparities within Europe. The magnitude of welfare losses in Southern Europe and South-Eastern Europe are estimated to be several times larger than in Northern Europe.

3.3.3 Bottom-up analysis with the NEMESIS model

3.3.3.1 Approach

An evaluation of the macro-economic costs of a range of climate hazards was carried out for this impact assessment, using the NEMESIS macro-econometric model. ⁽⁴⁰⁹⁾ The study builds on a comprehensive review of the literature that assesses the impact of individual impacts/hazards. It integrates 9 different types of hazards or sectors affected: (1) coastal floodings; (2) river floodings; (3) droughts; (4) labour productivity; (5) agriculture; (6) forests; (7) fisheries; (8) energy demand; (9) energy supply. These are integrated into the model via capital destruction, changes in production or input availability, changes in productivity and changes in consumption. As far as capital destruction is concerned, the modelling assumes that 30% of damages are supported by the insurance sector, and that no public support is provided for uninsured damages. Such damages therefore increase costs for firms and/or imply income losses for households.

⁽⁴⁰⁶⁾ COACCH (2021a). The Economic Cost of Climate Change in Europe: Report on The Macro-Economic Cost of Climate Change in Europe. Policy brief by the COACCH project. Published September, 2021.

⁽⁴⁰⁷⁾ COACCH (2021b). COACCH (2021). The Economic Cost of Climate Change in Europe: Synthesis Report on Interim Results. Policy brief by the COACCH project. Editors: Paul Watkiss, Jenny Troeltzsch, Katriona McGlade, Michelle Watkiss. Published July 2021.

⁽⁴⁰⁸⁾ Swiss Re Institute (2021) [The economics of climate change | Swiss Re](#)

⁽⁴⁰⁹⁾ <https://www.erasme-team.eu/en/the-nemesis-model/>

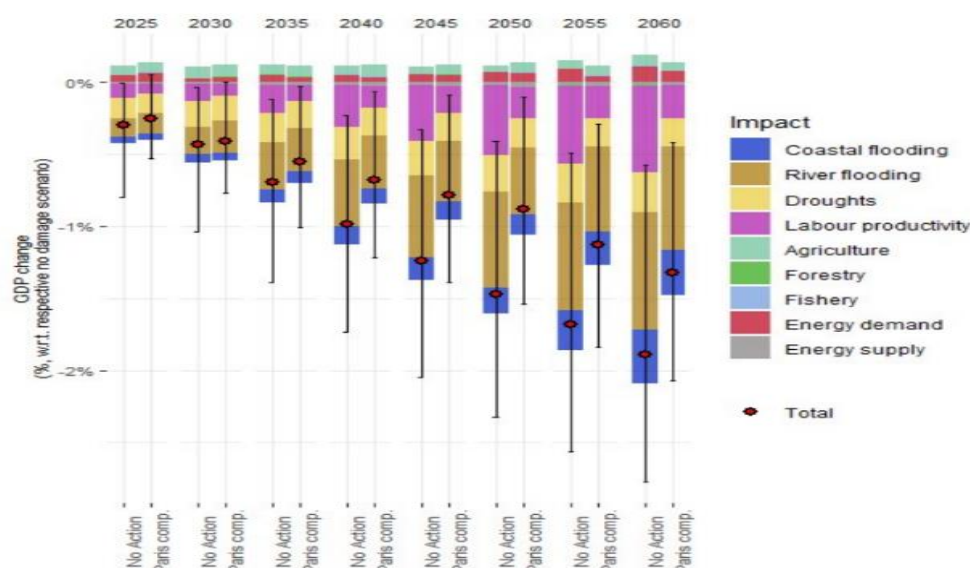
The “climate damage” scenarios assess the 9 types of hazards / sectoral impacts individually and combined. The macro-economic impacts are evaluated in comparison with a baseline where no climate hazards are taken into account. Two damage scenarios were modelled, each with its respective baseline: (1) a “net zero emissions” scenario, where the EU achieves climate neutrality by 2050 and the rest of the world implements measures so as to align with the IPCC’s RCP1.9 pathway, which reaches an increase in global temperatures of 1.6°C around 2050 and 1.4°C around 2090; and (2) a “no action” scenario where the EU acts in accordance with the Reference 2020 scenario and the world develops along the IPCC’s RCP7.0 pathway, which reaches an increase in global temperature of 2.1°C around 2050 and 3.6°C around 2090.

While the literature on the bottom-up assessment of impacts of individual hazards or sectoral effects is relatively rich, including specifically on the EU and its Member States, there are also divergences on the scale of the impacts. The integration of the bottom-up impacts into NEMESIS was therefore carried out based on three levels: (1) the bottom quartile of the literature; (2) the average; and (3) the top quartile. As the literature tends to be relatively conservative in terms of impacts, the results described herein are mainly those based on the top quartile of impacts.

3.3.3.2 Shorter term

Looking at the shorter time horizon of the IPCC’s RCPs to 2050-2060, the difference between the no action and the net zero emissions scenarios is significant from a macro-economic perspective, but not extremely stark. Under the no action scenario, climate damages are estimated to reduce EU GDP by up to 1% by 2030 (top quartile), with damages increasing to 1.7% by 2040 and 2.3% by 2050. Losses under the net zero emissions scenario are more limited at 0.8% by 2030 (top quartile) and increasing less over time than under the no action scenario with a negative impact of 1.2% by 2040 and 1.5% by 2050. This is related to the fact that the trajectories in terms of global warming are very similar up to 2050. Looking over this period, the modelling shows that GDP losses – which fully abstract from human impacts – are moderate and similar under the two scenarios at first, but that they become much more significantly over time as the climate warms further. This generates a widening divergence of impacts across the two scenarios over time, with rising cumulative negative impacts from a higher degree of warming. The main drivers for the negative impacts are labour productivity, river floodings, droughts and coastal floodings in a longer time horizon (Figure 34). Looking beyond GDP, the macro-economic modelling also highlights that the cost of a warming climate in terms of employment would be large. By 2050, employment under the “no action” scenario (top quartile) is projected to be close to 1.3% below baseline, which is equivalent to a loss of about 2.4 million jobs.

Figure 34: EU GDP losses under SSP1-1.9 (RCP1.9) and SSP3-7.0 (RCP7.0) (2020-2060)



Source: NEMESIS model.

3.3.3.3 Higher degrees of global warming

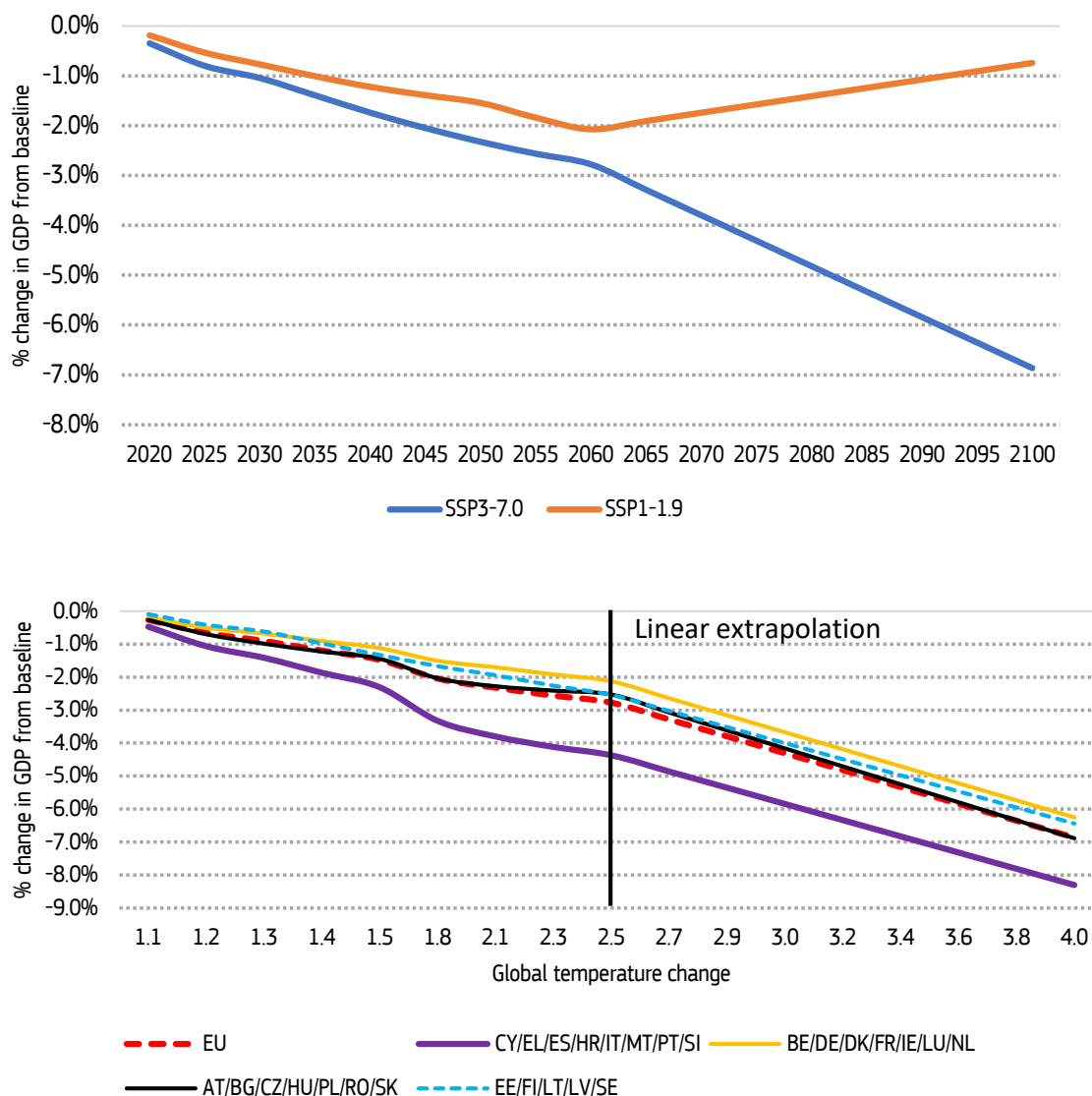
The difference in temperatures between the RCP1.9 and RCP7.0 become stark in the second half of the century: by around 2050, the global temperature increase of the two explored pathways differs only by 0.5°C, while in the subsequent decades that gap significantly increases to about 2.2°C before the end of the century (see Table 6 in this Annex).

The impact on GDP of such temperature difference was therefore estimated with a simple linear extrapolation of the full modelling results between 2020 and 2060, building on the estimated impacts for given temperature increases between these two points of time in the explored SSPs. This approach thus provides a rough estimation that is likely on the conservative side given that it assumes a linear relationship between warming levels and economic impacts. It nevertheless provides an estimate of economic impacts under higher increases in global temperatures.

Assuming a linear extrapolation of damages to 2100 would yield a loss of employment of almost 4% under the “no action” scenario, with only a small loss of about 0.4% under the “net zero emissions” scenario. The relative loss in terms of employment is smaller than the impact in terms of GDP as the labour market is expected to adjust to some extent, including with a reduction in real wages that would limit the fall in terms of total employment. This would nevertheless have additional negative welfare impacts, which are not measured here.

Looking beyond that time frame, however, the cost of failing to keep the global warming trend to within the Paris Agreement’s most ambitious objective of 1.5°C become very large. By around 2090, with a global warming level of around 3.6°C, the EU economy could face costs of about 7% of GDP (top quartile, Figure 35). This estimate is in line with global analyses for similar temperature increase.

Figure 35: EU GDP losses from climate hazards under different SSPs



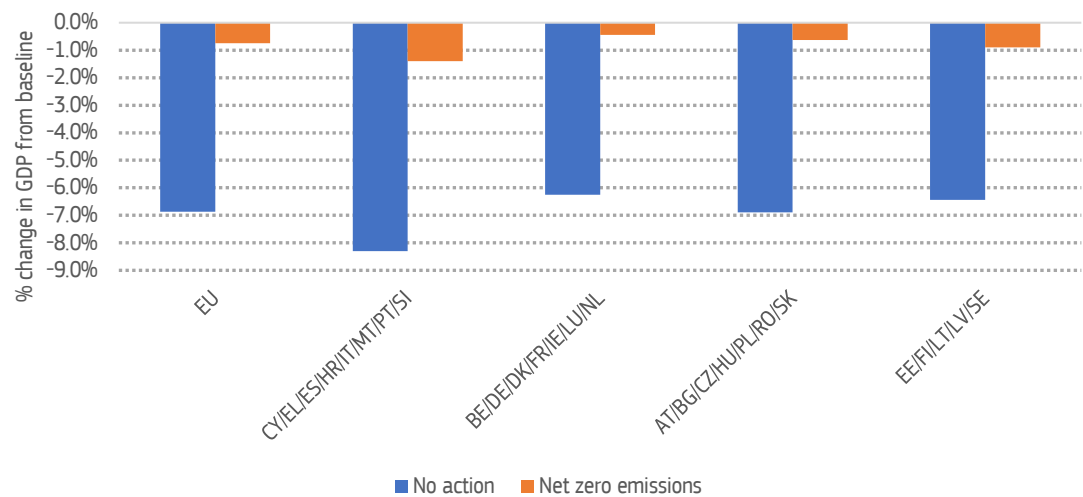
Note: Different shared socioeconomic pathways (SSP) implemented SSP1-1.9 and SSP3-7.0 Upper illustrates the timeline change per SSP, lower illustrates different warming levels per different areas.

Source: NEMESIS model and own extrapolation.

In addition, this estimate is likely very conservative for the reason mentioned above (linear extrapolation of results up to 2060), because the bottom-up literature tends to be conservative itself, and because a range of factors are not taken into consideration in this analysis, including the impacts of climate change on ecosystem services (including access to water) or the effects on tourism. Further, it must be noted that this analysis focuses strictly on macro-economic indicators and that it does not take into accounts impacts on health and mortality.

The modelling also shows that regions of the EU will be affected in contrasted manners, even if all face large overall costs arising from some hazards or others, and from broad economic interactions across the EU. The region most affected includes Southern and Mediterranean countries, while those facing somewhat smaller impacts are mostly in the north of Europe (Figure 36).

Figure 36: GDP losses by 2100 under the SSP1-1.9 and SSP3-7.0 pathways



Source: NEMESIS model and own extrapolation.

3.4 The limitations of economic valuation with economic models

What we know from science about the scale of the physical changes that can be expected at different levels of global warming also provides a check for the plausibility of economic impact projections. The difference in average global temperatures between pre-industrial times (mid-19th century) and the peak of the last ice age (the Last Glacial Maximum) is estimated to have been around 5°C. Policies implemented by the end of 2020 are projected to result in 3.2°C , with a range of 2°C – 3.3°C global warming by 2100 ⁽⁴¹⁰⁾, and such degree of warming could result in a very different world from the one we know today. The nature and the scale of changes in the natural systems are such that the exact socio-economic impacts on the global economy and societies are shrouded with uncertainty. Further, uncertainties in predicting the physical and socio-economic impacts of climate change increase significantly with higher degrees of warming, which makes it difficult to extrapolate on the basis of the impacts of lower levels of warming.

Extrapolating historical trends has limitations in predicting how economies would fare under climatic conditions that may depart radically from those that characterised the past centuries and millennia. As economic damage functions are calibrated with observations that relate to relatively small historical temperature changes and even weather variations, it is natural that large uncertainty concerns any extrapolation of damages from stronger temperature variations.

Assessing economic costs of climate change also involves challenges due to the global and long-term nature of climate change, involvement of non-market values, gaps in the ability to quantify impact channels involving ecosystem services, the interaction of risk drivers in complex or cascading risks, non-linearity and irreversibility of phenomena, and climate, socioeconomic and system response uncertainties. Most studies do not account for the

⁽⁴¹⁰⁾ IPCC, 2023: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, 36 pages. (in press).

probability of high-impact events. These considerations further reinforce the likelihood that, as a rule, the literature tends to underestimate the economic impacts of global warming.

Despite their potential catastrophic effects, some impacts of climate change, such as climate tipping points (see section 2.1.2) are characterized by the level of uncertainty that prevents them from being considered in economic models with precision, and so they are often not accounted for. This results in the underestimation of economic impacts of climate change, which could be several-fold larger than currently estimated.

Table 7 provides a snapshot of the range of damages in terms of % of GDP that are estimated in the literature, employing different methods and functional forms and a range of geographical coverage. Direct comparability is therefore limited, but it is nevertheless interesting to note the very substantial variation of estimates in scenarios of global warming that are roughly in the same class.

Table 7: Examples of climate related damage functions

Model (author)	dT (°C)(a)	damage (% of GDP) (b)	Method	Remarks
Tol (2018)	1 2 6	-0.7 0.6 6.3	Estimated on the basis of point estimates from a literature survey	
PESETA IV (Feyen et al, 2020)	1.5 2 3	0.3 0.7 1.4	several impact channels modelled	Estimate for EU
PESETA III (Ciscar et al. 2018)	4	1.9	several impact channels modelled	Estimate for EU
PAGE 09 (Hope, 2011a)	3	Just under 2%	several impact channels modelled	Estimate for EU
DICE 2016R (Nordhaus, 2016)	3 6	2.0 8.2	estimated on the basis of point estimates from a literature survey	
ENV-Linkages (OECD, 2015)	1.5 4.5	1.0 3.3	examination of different sectoral impacts	Damages by 2060
COACCH (Watkiss et al, 2019)	2.4 4.3	3 10	Multi-model examination of so far 3 sectors: coastal floods, river floods, transport infrastructure	Estimates for EU. RCP 4.5 (0.7 trn EUR pa) and RCP 8.5 (2.6 trn EUR p.a). %age for 2085 based on 1.5% GDP growth
Howard and Sterner (2017)	3 3	7-8 9-10	Literature survey, adjusting for duplication and omitted variable bias	Global. For the first estimate catastrophic damages are excluded, and for the second catastrophic risks are included
Burke et al (2017)	2 4	18 43	Impact of observed temperature variations on labour and agriculture	Global. Long-run, differentiated response scenario as reported.

Note: (a) global mean surface temperature change compared to pre-industrial level; (b) loss of GDP compared to no-climate-change baseline by 2100 (unless otherwise stated).

Source: adapted from Dimitrijevic et al (2021) ⁽⁴¹¹⁾

4 IMPACTS OF CLIMATE CHANGE ON BUSINESSES

The vulnerability of European businesses to climate change depends on the region, type of risk, sector and business characteristics. Climate related events including floods, droughts, heatwaves, heavy precipitation, sea level rise and changing rainfall patterns can seriously affect business assets. They can lead to business interruptions and job losses, they can impact working conditions, occupational safety and health, labour productivity and even induce short-term and long-term migration of workers ⁽⁴¹²⁾. A study by S&P Global ⁽⁴¹³⁾ finds, that by 2050s over 90% of the world's largest companies will see at least one asset financially exposed to climate risks, and for more than a third of these companies at least one asset will

⁽⁴¹¹⁾ Dimitrijevic et al. 2021. Quarterly Report on the Euro Area (QREA), Vol. 20, No. 1

⁽⁴¹²⁾ International Labour Organization. Frequently Asked Questions on Climate Change and Jobs. URL: https://www.ilo.org/global/topics/green-jobs/WCMS_371589/lang--en/index.htm

⁽⁴¹³⁾ Ritchie G. 2022. 90% of World's Biggest Firms Will Have at Least One Asset Exposed to Climate Risk, Fresh Data Show. Bloomberg, 15th of September 2022.

lose at the minimum 20% of its value. An extensive study by the European Central Bank ⁽⁴¹⁴⁾ assessed the resilience of non-financial corporates (NFCs) and euro area banks to climate risks, under various assumptions in terms of future climate policies over the next 30 years. It found that the effects of climate change would increase over time and would disproportionately affect certain geographies and sectors. The increased frequency and intensity of natural disasters would affect the production plants located in the areas exposed to natural hazards and could cause significant damage, interrupt production process, and potentially lead to business failure. Early transition to a zero-carbon economy comes with clear benefits, as short-term costs of the transition are smaller than the costs of climate change in the medium- to long-term. Without climate action, the impacts of climate change on corporates and banks most exposed to climate risks would become very significant, and significantly and negatively affect their creditworthiness.

European industrial and service sectors are affected by climate change in multiple ways, both directly and indirectly, though damage to assets, increased insurance costs, increased operating and maintenance costs, disruptions in transport, and reduced revenues. European businesses are affected by climate hazards both inside the EU and internationally through impacts on supply chains ⁽⁴¹⁵⁾. While all segments of the EU economy are and will continue to be affected by climate change, some sectors are more exposed than others, notably agriculture (see section 2.3.5.2), tourism (see section 2.3.4.3), fisheries and forestry (see section 2.3.5.1.1).

Smaller businesses have relatively higher capital constraints and hence less resources than larger companies to face such risks. They are less able to react to climate events and implement efficiency changes ⁽⁴¹⁶⁾. Small companies have started to experience the impact of climate change on their operation, as reported by the European Investment Bank in its 2022 overview on SMEs. Collier and Rajin ⁽⁴¹⁷⁾ indicate that the higher frequency of extreme events due to climate change will imply higher costs for small businesses. According to the International Labour Organization, SMEs are less equipped than large companies to plan and invest in adaptation measures ⁽⁴¹⁸⁾.

Climate change already affects the construction, agriculture, manufacturing, transportation, banking and insurance sectors through reduced productivity, losses from floods, water scarcity and droughts. Pulp and paper, chemical and plastic manufacturing are also impacted, as well as sectors relying on shipping, hydropower and water supply. The financial and insurance sector is affected through impacts in the customer and financial markets. Many

⁽⁴¹⁴⁾ Alogoskoufis S. et al. 2021. ECB economy-wide climate stress test. Occasional Paper Series, No 281 / September 2021.

⁽⁴¹⁵⁾ COACCH (2021). The Economic Cost of Climate Change in Europe: Business Policy brief by the COACCH project. Published November 2021. Copyright: COACCH, 2021.

⁽⁴¹⁶⁾ World Trade Organization. 2022. Small Businesses and climate change. MSME Research note 3. World Trade Organization Centre William Rappard, Rue de Lausanne 154, CH-1211 Geneva 21, Switzerland

⁽⁴¹⁷⁾ Collier B. and M. Rajin, "As climate risk grows, so will costs for small businesses". Harvard Business Review, August 2022.

⁽⁴¹⁸⁾ Enabling business mitigation and adaptation to climate change Green policies and the role of Employer and Business Membership Organization. International Labour Organization. December 2022

sectors will be exposed to multiple risks, and through indirect effects through supply chains, transport, and electricity networks ⁽⁴¹⁹⁾.

While currently damages are mainly related to floods and storms, heat and drought will become major drivers in the future. Floods represent one of the most important risks with large economic impact for businesses, both from damage and loss of assets, and from costs of disruption, lost time and lost production. Floods can also disrupt transport, leading to travel delays and costs, and affecting supply chains. As the risk of floods is projected to increase in many parts of Europe (see section 2.3.3), damages to business are also projected to increase. This is expected to impact the insurance premiums for floods, translating into higher costs for businesses.

Heatwaves negatively affect work and labour productivity and can lead to health risks for workers. The COACCH (Co-designing the Assessment of Climate Change Costs) project estimated that in Europe the loss of labour productivity in industrial and construction sector due to higher temperatures could reach 3% at RCP4.5. However, there are significant regional differences across Europe, with southern Europe being disproportionately affected, while some colder regions could see gains in labour productivity.

Climate change related events in one country can propagate along the supply chain and indirectly lead to adverse economic impacts in another country. COACCH study found that due to the increased frequency of extreme climate events and associated productivity shocks, export performance can be significantly reduced in the future. It is projected that tropics and sub-tropics will experience the largest impacts on exports due to stronger climate impacts. As Europe is strongly integrated in global production networks, it has less concentrated supply chains compared to some other regions, however, it is nonetheless vulnerable to supply chain shocks which can lead to reduced export performance. The impacts vary between countries and sectors, with largest impacts on the sectors with least diversified supply chains, including the food sector, mining and quarrying and electricity, gas and water sectors ⁽⁴²⁰⁾.

In a survey carried out by the European Central Bank ⁽⁴²¹⁾ in 2022, respondents -including from 90 large and mostly multinational companies - mentioned a range of physical risks from climate change for their companies. They were related to the sourcing of raw materials, integrity of production facilities, infrastructure, supply chains, logistics and labour conditions. Damage to physical assets and infrastructure is of particular concern to the companies dependent on or operating in the agricultural sector, manufacturing sector with potentially vulnerable supply chains, construction and the transport sectors.

⁽⁴¹⁹⁾ Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. Børsheim, J. Carnicer, E. Georgopoulou, M. Haasnoot, G. Le Cozannet, P. Lionello, O. Lipka, C. Möllmann, V. Muccione, T. Mustonen, D. Piepenburg, and L. Whitmarsh, 2022: Europe. In: *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1817–1927, doi:10.1017/9781009325844.015

⁽⁴²⁰⁾ COACCH (2021). *The Economic Cost of Climate Change in Europe: Business Policy brief* by the COACCH project. Published November 2021. Copyright: COACCH, 2021.

⁽⁴²¹⁾ Kuil F., Morris R. and Sun Y. 2022. The impact of climate change on activity and prices – insights from a survey of leading firms. URL: https://www.ecb.europa.eu/pub/economic-bulletin/focus/2022/html/ecb.ebbox202204_04~1d4c34022a.en.html

5 IMPACTS OF CLIMATE CHANGE ON SOCIETY AT LARGE

One of the largest uncertainties in climate science is the crossing of climate tipping points (see section 2.1.2 of this Annex). Tipping point impacts will cascade through socio-economic and ecological systems over timeframes that are short enough to defy the ability and capacity of human societies to adapt, leading to severe effects on human and natural systems ⁽⁴²²⁾. For example, rapidly and permanently altered growing conditions could impact crop yields, which can affect local food availability and global food prices.

Multiple tipping point impacts can be far reaching, leading to never seen before climatic conditions emerging. The interaction of reductions in glacial melt from the Himalayan icecap which provides drinking and irrigation water for downstream communities, in combination with rising sea level, could lead to water shortages and flooding. These impacts, together with anticipated heat spikes, could make living conditions for hundreds of millions of people in low lying areas such as Bangladesh and Vietnam untenable, leading to mass migration ⁽⁴²³⁾.

Climate change could impact many areas of society, and lead to cascading and interacting impacts, ranging from migration and conflict to health and mortality impacts, political instability, to food, fuel and water shortages ⁽⁴²⁴⁾. Climate change is a growing concern for European Union security and defence, affecting military infrastructure, military capabilities, missions and operations ⁽⁴²⁵⁾.

Climate models often do not capture many of the most severe impacts from climate change, such as tipping points. There are certain challenges and limitations that these tools might never be able to overcome because of the uncertainty of climate change or because of the limitations of modelling and data ⁽⁴²⁶⁾. The inability to capture all interactions between sectors affected by climate change and the interaction between climate change impacts themselves, suggests that modelling results are currently on the conservative side ⁽⁴²⁷⁾.

The warming levels at which elements such as the polar ice sheets, the Atlantic Meridional Overturning Circulation, or the Amazon rainforest, might tip to alternative states are largely unknown. Progress is being made to couple individual earth system models, but substantial further work is required to accurately represent tipping point interactions and to predict when individual subsystems might cross tipping points ⁽⁴²⁸⁾. Given that much progress is required to

⁽⁴²²⁾ OECD, Climate Tipping Points – Insights for Effective Policy Action. 2022. <https://doi.org/10.1787/abc5a69e-en>

⁽⁴²³⁾ S. Trust, et al., The Emperor's New Climate Scenarios, The Institute and Faculty of Actuaries, <https://actuaries.org.uk/media/qeydewmk/the-emperor-s-new-climate-scenarios.pdf>

⁽⁴²⁴⁾ L. Kemp et al., Climate Endgame: Exploring catastrophic climate change scenarios: <https://www.pnas.org/doi/pdf/10.1073/pnas.2108146119>

⁽⁴²⁵⁾ European Commission, Joint Research Centre, Tavares da Costa, R., Krausmann, E., Hadjisavvas, C., Impacts of climate change on defence-related critical energy infrastructure, Publications Office of the European Union, 2023, <https://data.europa.eu/doi/10.2760/03454>

⁽⁴²⁶⁾ The United Nations Environment Program Finance Initiative (UNEP FI), 2023 Climate Risk Landscape: <https://www.unepfi.org/themes/climate-change/2023-climate-risk-landscape/>

⁽⁴²⁷⁾ S. Trust, et al., The Emperor's New Climate Scenarios, The Institute and Faculty of Actuaries, <https://actuaries.org.uk/media/qeydewmk/the-emperor-s-new-climate-scenarios.pdf>

⁽⁴²⁸⁾ Key findings and Recommendations from the H2020 projects on Tipping Points: TiPES, COMFORT, TiPACCs

improve the representation of tipping points, it is possible that their impact is currently underestimated, and they may be crossed earlier than anticipated.

As a consequence of climate models not capturing tipping points and potentially underestimating risks, the users of these models in other sectors are thus also underestimating the impacts of climate change. Climate modelling is increasingly being used in the financial services sector to inform investment decisions and manage risk, as such, there is a risk that financing decisions being taken today are not as climate-change resilient as they should be ⁽⁴²⁹⁾.

Along with physical climate tipping points, the field of socio-economic tipping points and social tipping processes has been receiving increasing attention in the past years. Climate-induced socio-economic tipping points have been defined as “a climate change induced, abrupt change of a socio-economic system, into a new state of fundamentally different quality, beyond a certain threshold that stakeholders perceive as critical” ⁽⁴³⁰⁾. Examples include potential collapse of insurance markets due to extreme weather risks, migration from coastal areas due to extreme sea level rise or a major climatic shock, and land abandonment and price spike due to climate induced agriculture shocks ⁽⁴³¹⁾.

6 CONCLUSIONS

Anthropogenic climate change is a threat to humans and nature, and it is already causing widespread and adverse impacts, which disproportionately affect the most vulnerable people and systems. The only way to lessen the impacts is by strong mitigation and adaptation action. Insufficient climate action will lead to increasing global warming, which will result in even more severe negative impacts, some of which will be irreversible. In the next decades, climate risks could become multiple times higher than currently observed. One of the biggest concerns is the triggering of climate tipping points, which could lead to sudden and substantial impacts, too short for societies and ecosystems to adapt. Potential impacts include extreme sea-level rise, extreme temperatures, droughts and wildfires, and release of significant amount of greenhouse gases, accelerating global warming.

Globally, communities the most vulnerable to climate change are located in Africa, Asia, Central and South America, Small Islands and Arctic.

Europe is warming twice as fast as the global average and all its regions have already been affected by the impacts of climate change. Droughts, floods and wildfires have increased in frequency and intensity, and affected the health and wellbeing and the economy, and impacted ecosystems. With increasing warming, the impacts of climate change are projected to intensify, and they will differ between different regions, with Southern regions experiencing the most negative impacts. Climate change also affects different social groups differently, disproportionately affecting the poorer households. Climate change is projected to result in

⁽⁴²⁹⁾ S. Trust, et al., The Emperor’s New Climate Scenarios, The Institute and Faculty of Actuaries, <https://actuaries.org.uk/media/qeydewmk/the-emperor-s-new-climate-scenarios.pdf>

⁽⁴³⁰⁾ COACCH (2021). The Economic Cost of Climate Change in Europe: Report on Climate and Socio-Economic Tipping Points. Policy brief by the COACCH project, page 3.

⁽⁴³¹⁾ Kees C H van Ginkel et al 2020 *Environmental Research Letters* 15 023001 DOI: 10.1088/1748-9326/ab6395

substantial economic damages in Europe, which will increase with higher degrees of warming.

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PART 3/5

COMMISSION STAFF WORKING DOCUMENT

IMPACT ASSESSMENT REPORT

Part 3

Accompanying the document

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS**

Securing our future

**Europe's 2040 climate target and path to climate neutrality by 2050 building a
sustainable, just and prosperous society**

{COM(2024) 63 final} - {SEC(2024) 64 final} - {SWD(2024) 64 final}

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Annex 8: Detailed quantitative analysis of GHG pathways

1 KEY TRANSFORMATIONS TO CLIMATE NEUTRALITY BY 2050

The impact assessment explores different GHG emission pathways in the 2030-2050 period, building on the Fit-for-55 and REPowerEU policy package for 2030 and beyond, and achieving climate neutrality by 2050. The first section below describes the evolution of GHG emissions in the various pathways explored, looking at their reduction and the contribution of carbon removals. The following sections provide details on the associated transformation in various sectors: the energy system, with dedicated analysis on the energy supply, buildings, industry, transport, as well as non-CO₂ emissions, agriculture and LULUCF emissions.

The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

1.1. GHG emissions

1.1.1. GHG budgets and net GHG emissions

1.1.1.1. GHG budgets

The target options provide different remaining GHG budgets for the period 2030-2050: 21 GtCO₂-eq for the linear option, 18 GtCO₂-eq for option 2 (at least 85% up to 90%) and 16 GtCO₂-eq for option 3 (at least 90% up to 95%) (see section 5.2 in the main document).

The ESABCC analyses a (intra-EU) range of 11-16 GtCO₂-eq for the EU to contribute to limiting global warming to 1.5°C with no or limited overshoot ⁽¹⁾. The ESABCC report highlights that scaling-up of energy technologies beyond challenging levels is required to achieve the more ambitious end of this range: not overcoming such technological deployment challenge moves the range to 13-16 GtCO₂-eq. ESABCC also recommends a range of 11-14 GtCO₂-eq ⁽²⁾.

1.1.1.1. Net GHG emissions

The scenarios achieve net GHG reductions in line with the budgets associated to each target option.

Table 1 shows the 2040 and 2050 net GHG emissions in S1, S2, S3, and LIFE (see Annex 6 for their description), as well as the corresponding reductions compared to 1990. The values are provided for Union-wide GHG emissions and removals regulated in Union law, in accordance with the climate neutrality target scope ⁽²⁾. With the fit-for-55

⁽¹⁾ The ESABCC provides ranges for intra-EU emissions which do not take into account international emissions under Union Law as in the European Climate Law and analysed in this impact assessment.

⁽²⁾ Regulation (EU) 2021/1119, Article 2

package ⁽³⁾, this covers all domestic net emissions (in the sense of the UNFCCC inventories), international intra-EU aviation, international intra-EU maritime, and 50% of international extra-EU maritime from the Monitoring Reporting and Verification (MRV) scope ⁽⁴⁾. The table also provides a range to illustrate the uncertainties on the future evolution of LULUCF net removals, considering a lower level and an upper level depending on the effect of policies or other factors (See 1.8 of this Annex for more details).

Table 1: Net GHG emissions and reductions compared to 1990

	2040				2050	
	S1	S2	S3	LIFE	S3	LIFE
Total Net GHG - MtCO₂-eq	1051 [1051 to 893]	578 [681 to 520]	356 [458 to 298]	353 [469 to 302]	-38 [90 to -100]	-70 [85 to -117]
Reduction vs 1990 - %	-78% [-78% to -81%]	-88% [-86% to -89%]	-92% [-90% to -94%]	-93% [-90% to -94%]	-101% [-98% to -102%]	-101% [-98% to -102%]

Note: Main values reported correspond to the LULUCF net removals considered in the scenarios, with net GHG emissions with lower and upper level of LULUCF net removals are in brackets. S1 and S2 values for 2050 are similar to S3.

Source: PRIMES, GLOBIOM, GAINS.

While all scenarios achieve climate neutrality in 2050, in 2040, the net GHG emissions are clearly different across scenarios.

S1 leads to total net GHG emissions reaching about 1050 MtCO₂-eq (ranging down to 890 MtCO₂-eq depending on the behaviour of the LULUCF net removals), representing a reduction of 78% compared to 1990. This scenario focuses on strengthening the existing trends with limited contribution of more advanced mitigation options supported by novel technologies ⁽⁵⁾ by 2040 and fits a linear trajectory of net GHG emissions between 2030 and climate neutrality in 2050.

The S2 scenario deploys the full potential of existing decarbonisation solution, such as electrification and renewable and relies upon novel technologies such as carbon capture and a higher uptake of e-fuels using fossil free carbon (see sections 1.1.3 and 1.2 in this Annex), as well as further abatement in the agriculture sector (see 1.1.4 and 1.7). It reaches about 580 MtCO₂-eq in 2040, or 88% reduction compared to 1990 (ranging between 86% and 89%).

The S3 scenario foresees early implementation of novel technologies to attain net GHG emissions levels of around 360 MtCO₂-eq in 2040, and a reduction level of -92%, with a range between -90% and -94%.

LIFE implements additional circular economy and sufficiency actions in industry, transport and agriculture, achieving similar reduction as per S3, but with a different sectoral distribution of emission (see 1.1.2 in this Annex). This setting illustrates the

⁽³⁾COM/2021/550 final

⁽⁴⁾ Regulation (EU) 2015/757 (amended by Regulation (EU) 2023/957)

⁽⁵⁾ Not yet commercially available at large scale, such as carbon capture and renewable hydrogen

important role of demand-side policies and measures to reduce GHG emissions, and to enhance the environmental performance of mitigation actions by limiting the consumption of natural resources, including raw materials and land or further improving some direct environmental benefits of climate action (see sections 1.4, 1.7.5 and 1.9.1).

The levels of emission reductions achieved in the different scenarios are in line with ranges found in the literature, spanning from 84% to 89% ⁽⁶⁾, from 87% to 91% ⁽⁷⁾, around 89% ⁽⁸⁾ and from 88 to 95% by the ESABCC ⁽⁹⁾.

The distribution of emissions between CO₂, non-CO₂ gases and GHGs coming from LULUCF sector is reported in Table 2. A more detailed analysis of the sectoral reduction for S1, S2, S3 and LIFE is described in the following sections.

Table 2: CO₂, non-CO₂ and emissions from LULUCF sector.

	2040				2050	
	S1	S2	S3	LIFE	S3	LIFE
Total Net GHG - MtCO₂-eq	1051	578	356	353	-38	-70
<i>CO₂ (excl. LULUCF) * - MtCO₂</i>	815	521	331	432	5	83
<i>Non-CO₂ (excl. LULUCF) ** - MtCO₂-eq</i>	454	373	342	281	291	236
<i>LULUCF*** - MtCO₂-eq</i>	-218	-316	-317	-360	-333	-389

*Note: *includes CO₂ from fossil fuel combustion (category 1 in inventories), industrial processes and product use (category 2) and agriculture under category 3. **Includes non-CO₂ emissions under categories 1, 2, 3 and 5 of the inventories. ***Only main values are reported.*

1.1.2. GHG emissions and role of removals

According to the IPCC, reductions in gross GHG emissions, nature-based and industrial carbon removals are all needed to reach net zero ⁽¹⁰⁾. While gross GHG emissions need to decrease significantly, the deployment of carbon removals is unavoidable to counterbalance hard-to-abate residual emissions and replace residual fossil fuels. However, relying primarily on carbon removals without intervening in gross GHG emissions may be unrealistic since the potential for removals is limited by land constraints, feasibility, cost-efficiency, public acceptance and technological consideration ⁽¹¹⁾.

⁽⁶⁾ ECEMF (2023), ECEMF Policy Brief: Insights on EU2040 targets based on a model intercomparison exercise of EU Climate Neutrality Pathways. DOI 10.5281/zenodo.8337667. <https://zenodo.org/record/8337668> Full model range, including international bunkers.

⁽⁷⁾ Rodrigues et al., (2023). 2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal, *Nature Communication*, Under Review. Intra-EU scope.

⁽⁸⁾ Graf, A., et al. (2023). Breaking free from fossil gas. A new path to a climate-neutral Europe. Agora Energiewende.

⁽⁹⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 9, Table 12. The range spans from 88-92% and up to 95% if technological challenges can be overcome.

⁽¹⁰⁾ IPCC (2022): *Climate Change 2022: Mitigation of Climate Change*. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change.

⁽¹¹⁾ CLG Europe (2023). Raising European Climate Ambition for 2040 A CLG Europe position paper.

The increasing role of carbon removals is also highlighted in the public consultation questionnaire, where majority of respondents (around 65%, including all categories) calls for 2040 carbon removal targets separate from net emission, and experts from the academic, economic and public sectors are in favour of an important role of the carbon removals. 61% of the papers analysed also comment on carbon removals, with most of them indicating removals instrumental to reach climate neutrality, if complementary to GHG emission reduction at source. There is no clear preferred pathway indicating the contribution of nature-based vs industrial removals. In position papers, the emphasis of forests as carbon sink is underlined, while carbon capture for industrial removals plays an important role for energy-intensive industries to reduce hard-to-abate emissions within the sector. The public consultation indicates a general slight inclination for relying on nature-based removals (around 30% of respondents) or a balanced approach between nature-based and industrial removals (around 27% of respondents). This preference is confirmed also when looking individually at the different stakeholder groups, except for large businesses and SMEs, who expressed by majority a preference for either a balance between nature-based and industrial removals or a stronger reliance on industrial removals.

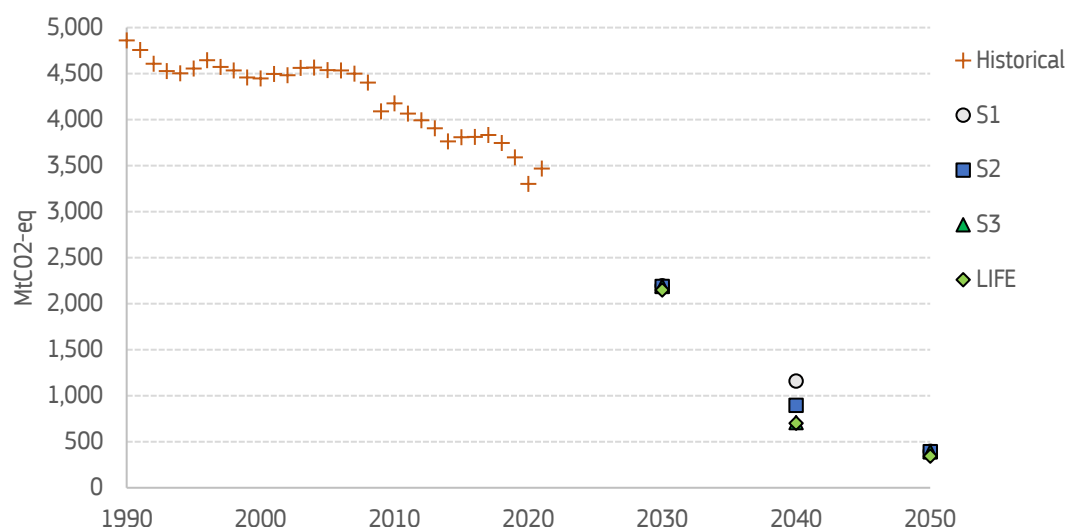
1.1.2.1. Gross GHG Emissions

The “gross GHG” emissions are defined as the actual GHG emissions excluding the contribution of industrial removals and net LULUCF removals that are part of the computation of “net GHG” emissions meeting EU’s climate objectives for 2030 and 2050.

Figure 1 shows the evolution of EU gross GHG emissions over 1990-2050. In 2021, EU gross emissions achieved around 3570 MtCO₂-eq, with a reduction of around 28% compared to 1990 ⁽¹²⁾. The trajectory until 2030 is consistent with the Fit-for-55 policy package, where emissions reach around 2300 MtCO₂-eq. Post-2030, these emissions keep decreasing in all scenarios, albeit at difference pace by 2040 and beyond. They reach about 400 MtCO₂-eq in 2050, when they are compensated by industrial and LULUCF net carbon removals to converge to climate neutrality.

(12) EEA Greenhouse Gases Data Viewer. DAS-270-en Published on 18 Apr 2023

Figure 1: Domestic Gross GHG emissions



Note: Gross GHG emissions represented here include only domestic emissions and excludes industrial carbon removals and the LULUCF net removals.

Source: PRIMES, GAINS.

Table 3 summarises the gross GHG emission by sector. In S1 gross GHG emissions decrease following a linear profile over 2031-2050, reaching around 1270 MtCO₂-eq in 2040, which correspond to a decrease of around 75% compared to 1990 levels. Most sectors undergo significant emissions reductions already over 2031-2040, with emissions ranging from around -70% in the domestic transport sectors to about -10% in agriculture. The S2 scenario achieves further reductions of gross GHG emissions by 2040, reaching around 940 MtCO₂-eq or 80% reduction compared to 1990. Significant additional reductions with respect to S1 take place notably in power and heat, industry and agriculture. The S3 scenario achieves a reduction of around 85% in 2040, driven by extra reductions to S2 in all sectors, including the industry sector, where they are triggered by higher recourse to carbon capture and storage of fossil fuels (see section 1.1.3.2), the power system, buildings and transport. LIFE, which aims at the same overall reduction as S3, redistributes gross emissions across the different sectors. While energy and industry sectors reduce to a level intermediate between S2 and S3, mostly due to a lower use of e-fuels and DACC, agriculture emissions reduce more than in S3.

Table 3: Gross GHG emissions

MtCO ₂ -eq		2005	2015	2030	2040				2050			
					S1	S2	S3	LIFE	S1	S2	S3	LIFE
Total Gross GHG Emissions		4641	3914	2301	1273	943	748	740	416	413	411	360
Power and district heating		1300	1012	339	123	42	23	34	21	22	19	15
Other Energy sectors*		277	237	133	71	59	53	57	39	39	38	36
Industry (Energy)		469	360	232	126	94	75	86	6	6	9	11
Domestic Transport		822	772	583	190	143	120	134	10	8	7	9
Residential and Services**		648	514	221	119	92	75	92	20	19	19	29
Industry (Non-Energy)		343	233	157	139	88	14	13	7	7	7	7
Other Non-Energy sectors***		101	130	56	33	26	25	25	23	22	22	22
International transport (target scope)	Intra-EU aviation	35	38	43	31	29	28	14	14	12	11	10
	Intra-EU navigation	31	27	25	7	6	4	0	0	0	0	0
	50% extra-EU maritime MRV	50	42	44	14	11	9	0	0	0	0	0
Agriculture****		390	385	361	351	302	271	209	249	249	249	194
Waste		155	118	87	68	55	55	55	32	32	32	32
CO ₂ calibration		15	43	24	3	-1	-1	-1	0	0	0	0
Non-CO ₂ calibration		5	2	-3	-3	-3	-3	-3	-3	-3	-3	-3
Memo Items												
International aviation (Intra-EU and Extra-EU)		96	103	117	83	80	78	73	38	34	31	27
International maritime (Intra-EU and Extra EU)		152	129	134	41	33	25	33	0	0	0	0

Note: Calibration of total to inventory 2023. *Includes emissions from energy branch and other non-CO₂ emissions from the energy sector; **Includes fossil fuel combustion in the agriculture/fishery/forestry sector; ***Includes CO₂ fugitive emissions and non-CO₂ emissions from direct use or specific products (e.g., aerosols, foams, etc). **** Excludes fossil fuel combustion in the sector, but includes "category 3" CO₂ emissions, assumed constant at 10 MtCO₂.

Source: PRIMES, GAINS.

Sectors that reduce little in 2031-2040 accelerate their decarbonisation in the 2041-2050 decade, while sectors that have already reached low emissions levels by 2040, maintain or slow down the reduction rate by 2050, leading to a balanced contribution to climate neutrality for all sectors across 2030-2050. Overall, gross GHG emissions in 2050 reduce to -92% vs 1990 across all scenarios.

1.1.2.2. Nature-based carbon removals

Table 4 shows the LULUCF net removals in the different scenarios. The central level for 2040 is close to -320 MtCO₂-eq in all scenarios by 2040, slightly above the target for 2030 (-310 MtCO₂-eq). The differences between S1, S2 and S3 are driven by the different bioenergy needs in the energy systems underpinning the scenarios (see section 1.8 in this Annex). LIFE is characterised by a different food system that frees up land for carbon farming activities such as afforestation.

The table also provides a range (from lower level to upper level) to illustrate the uncertainties on the future evolution of LULUCF net removals, depending on the effect of policies or other factors (see section 1.8 in this Annex).

Table 4: LULUCF net removals by scenarios in 2040 and 2050

MtCO ₂ -eq	2040				2050			
	S1	S2	S3	LIFE	S1	S2	S3	LIFE
Lower level	-218	-213	-215	-243	-213	-202	-206	-234
Central level	-319	-316	-317	-360	-341	-332	-333	-389
Upper level	-376	-374	-376	-410	-403	-394	-396	-436

*Note: The 'Central level' is derived from applying in the modelling the same policy intensity as the one necessary to meet the 2030 target, except for S1 in 2040. The 'Lower level' is derived from assuming no additional cost as the lower boundary of the LULUCF net removals level. The 'Upper level' is derived from the maximum mitigation potential as the upper boundary of the LULUCF net removals level. The **numbers in bold** are used to compute the overall net GHGs for the different scenarios.*

Source: GLOBIOM

The expected contribution of LULUCF to the 2040 climate target stays within the boundaries of the ESABCC, which discusses an upper bound of 400 MtCO₂-eq in 2040⁽¹³⁾ and describes three iconic scenarios that display a larger range from 323 MtCO₂-eq to 601 MtCO₂-eq in 2040 and from 312 MtCO₂-eq to 669 MtCO₂-eq in 2050⁽¹⁴⁾.

Section 1.8 in this Annex provides more details on the LULUCF sector and the related GHG emissions and removals.

1.1.2.3. Industrial carbon removals

Industrial carbon removals, together with nature-based removals, are projected to play an increasing role in the EU economy in the next decades⁽¹⁵⁾, in the view of balancing EU GHG emissions by 2050, and achieving negative emissions thereafter⁽¹⁶⁾.

Industrial removals can contribute to compensate residual GHG emissions from hard-to-abate sectors. They can also progressively replace fossil carbon feedstock in processes like the production of plastics or e-fuels⁽¹⁷⁾,⁽¹⁸⁾ and become the main source of (fossil-free) carbon in sectors where carbon will still be needed in the long-term.

Figure 2 shows the industrial removals projected by PRIMES and differentiated by their source. The total amount of carbon removed until 2040, whether captured from the atmosphere, from biomass combustion or from biogas upgrading, varies across scenarios. Removals are projected to remain marginal in the S1 scenario by 2040, to reach

⁽¹³⁾ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Section 7.7.1. This risk level was based on research by Pilli et al. (2022) who provide as a probable range of -100 to -400 MtCO₂-eq for the LULUCF sink in 2050 taking future climate change impacts based on RCP 2.6 into account. Scenarios exceeding the upper bound of -400 MtCO₂-eq may rely on implausibly high LULUCF sink levels.

⁽¹⁴⁾ Ibid. Table 15

⁽¹⁵⁾ COM(2021) 800 final

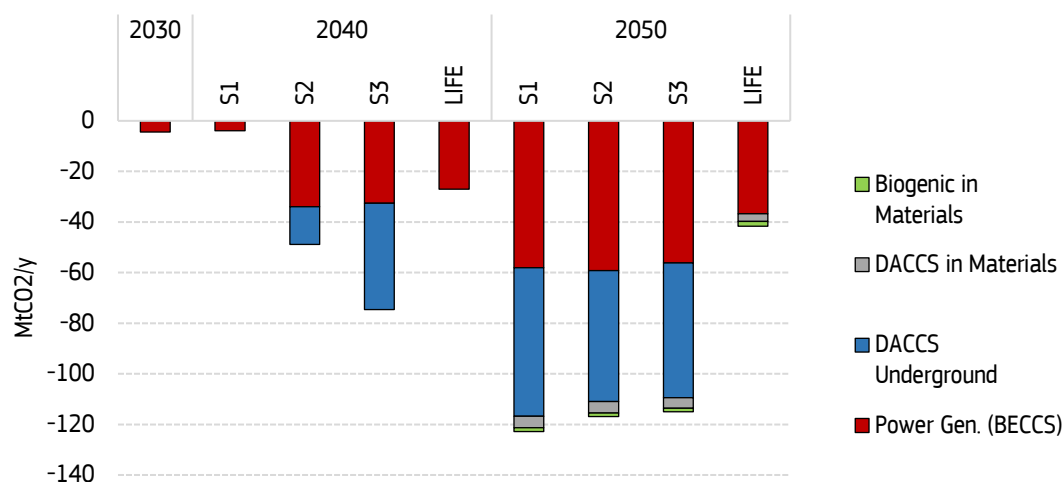
⁽¹⁶⁾ European Climate Law (Regulation (EU) 2021/1119), Article 2.

⁽¹⁷⁾ The Global CO₂ Initiative (2016). Global Roadmap for Implementing CO₂ Utilization.

⁽¹⁸⁾ CEFIC (2021). Shining a light on the EU27 chemical sector's journey toward climate neutrality.

50 MtCO₂ in S2 and up to 75 MtCO₂ in S3. Removals deploy progressively from S1 to S3 and allow for higher reductions of net GHG emissions (see also Figure 7). LIFE models lower carbon removals: demand-side actions and enhanced LULUCF net removals can reduce the need for industrial removals, and, in this projection, eliminate the recourse to DACC in 2040.

Figure 2: Carbon removals by source and use



Source: PRIMES.

The amount of carbon removed by industrial means in 2050 is similar across scenarios and reaches around 120 MtCO₂/y, suggesting the need for significant carbon removals to achieve climate neutrality. While most of the storage takes place in underground sites, limited storage in permanent materials also appears in the last decade. The slightly higher values for S1 are required to compensate for delayed climate action in 2031-2040.

While the modelling shows a similar share of BECCS and DACCS by 2040 in S3 and beyond by 2050, their actual relative deployment will depend on a number of factors, e.g.: high costs and technological uncertainty (DACCS ⁽¹⁹⁾ ⁽²⁰⁾), cost and competition on biomass resource and possible negative impact on LULUCF (BECCS ⁽²¹⁾ ⁽²²⁾ ⁽²³⁾), see

⁽¹⁹⁾ Motlaghzadeh, K., Schweizer, V., Craik, N., & Moreno-Cruz, J. (2023). Key uncertainties behind global projections of direct air capture deployment. *Applied Energy*, 348, 121485. <https://doi.org/10.1016/j.apenergy.2023.121485>.

⁽²⁰⁾ Lehtveer, Mariliis & Emanuelsson, Anna. (2021). BECCS and DACCS as Negative Emission Providers in an Intermittent Electricity System: Why Levelized Cost of Carbon May Be a Misleading Measure for Policy Decisions. *Frontiers in Climate*. 647276. 10.3389/fclim.2021.647276.

⁽²¹⁾ Slade, R., Bauen, A., and Gross, R. (2014). Global bioenergy resources. *Nat. Clim. Change* 4:99. doi: 10.1038/nclimate2097

⁽²²⁾ Creutzig, F., et al. (2015). Bioenergy and climate change mitigation: an assessment. *GCB Bioenergy* 7, 916–944. doi: 10.1111/gcbb.12205

⁽²³⁾ Directive (EU) 2018/2001 (amendment to be published)

section 1.8 in this Annex), creation of the transport and storage infrastructure, public acceptance and equitable and sustainable technology scale up ⁽²⁴⁾.

Both technologies add requirements on the ambitious and challenging industrial sectors' decarbonisation plans, and these needs to be coupled effectively with feasibility analysis and supporting measures as appropriate. While the scenarios filtered by the ESABCC attribute a minor role to carbon captured from the atmosphere ⁽²⁵⁾, the IEA indicates that more efforts are needed to fully develop DACCS ⁽²⁶⁾. The demand side, with the amount of e-fuels required by other sectors and the need to compensate residual emissions, will also influence the deployment of each technology.

Given the lack of predictability for the uptake of one removal technology over another by 2040, a comparison between different deployment pathways is performed.

Figure 3 compares the industrial carbon removals obtained in 2040 with the PRIMES model, with deployment pathways projected by the POTEnCIA model. In PRIMES (Figure 3, left) BECCS tends to come first, and considerations of sustainable biomass availability limits its expansion. The remaining needs for removals are fulfilled by DACCS, which appears as complementary to BECCS. The POTEnCIA model (Figure 3, right), where the cap on the amount of sustainable biomass supply for bioenergy is relaxed (see also Annex 6), illustrates a stronger deployment of BECCS, reaching up to around 80 MtCO₂ in 2040 in S3, complemented by storage of biogenic carbon from biogas upgrade and very limited development of DACCS. Higher recourse to BECCS leads to an increase of bioenergy demand, with a possible negative impact on the LULUCF net removals (see 1.8.2).

Both pathways modelled provide an amount of total industrial removals in 2040 lower than the estimated maximum in the scenarios considered by the ESABCC, corresponding to 214 MtCO₂ ⁽²⁷⁾, and consistent with ranges of 10-220 MtCO₂ that can be found in the literature ⁽²⁸⁾, ⁽²⁹⁾, ⁽³⁰⁾, ⁽³¹⁾.

⁽²⁴⁾ Liebling K., et al. (2023). International Governance of Technological Carbon Removal: Surfacing Questions, Exploring Solutions.

⁽²⁵⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 16.

⁽²⁶⁾ IEA (2023), Tracking Direct Air Capture. Accessed on 14-08-23

⁽²⁷⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 16 summing DACCS and BECCS.

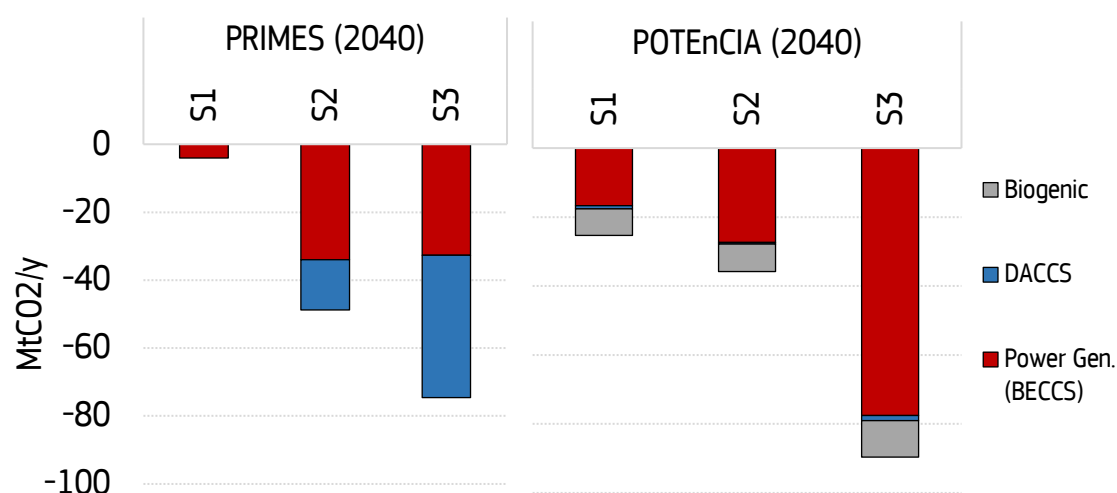
⁽²⁸⁾ Rodrigues et al., (2023). 2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal, *Nature Communication*, Under Review.

⁽²⁹⁾ Kalcher, L. et al., (2023). The post-2030 climate target debate starts now, *Strategic Perspectives and Climact*. <https://strategicperspectives.eu/the-post-2030-climate-target-debate-starts-now/>

⁽³⁰⁾ Graf, A., et al. (2023). Breaking free from fossil gas. A new path to a climate-neutral Europe. *Agora Energiewende*.

⁽³¹⁾ Climate Analytics (2022). 1.5°C National Pathways Explorer. *Climate Analytics*.

Figure 3: Industrial carbon removals in PRIMES and POTEnCIA in 2040



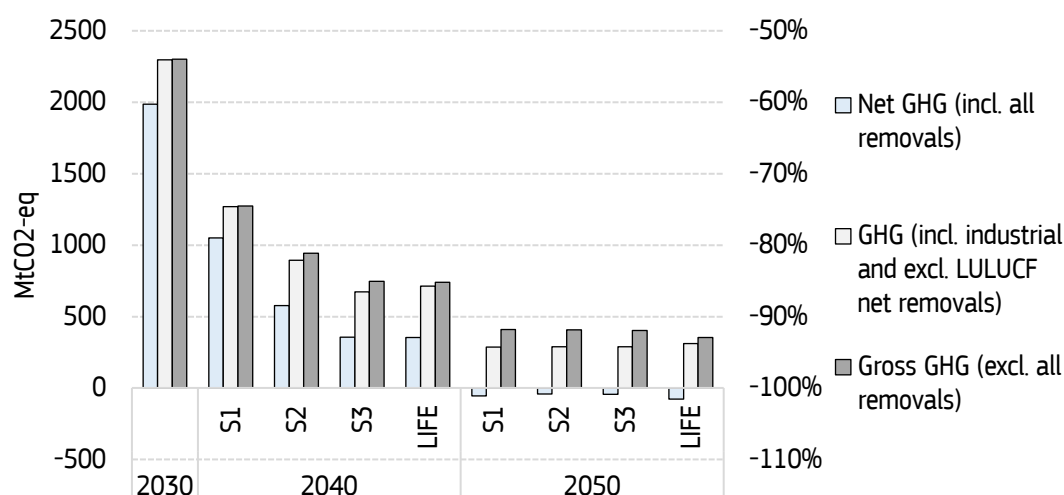
Source: PRIMES, POTEnCIA.

1.1.2.4. Balancing emissions and removals

In Figure 4, gross GHG emissions (excluding all removals) only reduce between 75% and 85% in 2040 and around 92% in 2050 (vs 1990⁽³²⁾). In comparison, net GHG emissions (including all removals) reduce more and achieve net-zero in 2050. This suggests that removals complete other mitigation options and are needed to achieve climate neutrality. In 2040, the PRIMES modelling analysis shows that total (industrial and LULUCF net) removals range from around 220 MtCO₂-eq in S1 to around 390 MtCO₂-eq in S3 (with upper level of LULUCF net removals). Around 360 MtCO₂-eq are needed to achieve net reductions of 90% and beyond in 2040 (considering the lowest level of gross emissions projected in S3), with this value increasing in the range of 430-460 MtCO₂-eq in 2050 to attain net-zero.

⁽³²⁾ In line with the remaining gross emissions without counting compensation from removals analysed by the ESABCC and corresponding to around 390 MtCO₂.

Figure 4: Net and Gross GHG Emissions and % reductions vs 1990



Note: "Net GHG" includes domestic emissions, international intra-EU aviation and maritime transport and 50% of extra-EU maritime transport (as per MRV). "Excl. LULUCF" subtracts the LULUCF net removals from net GHG. "Excl. all removals" subtracts industrial removals and LULUCF net removals from net GHG, resulting in gross GHG emissions.

Source: PRIMES, GAINS.

Table 5 summarises the model projections on different type of removals and show that nature-based and industrial removals play different roles. While LULUCF net removals contribute significantly in 2030 and along until 2050, the role of industrial removals becomes more relevant from 2040 in pathways with the lowest carbon budget (S3) and by 2050 in all cases. LIFE always shows a relative higher contribution of LULUCF net removals compared to industrial removals, and a slightly more moderate recourse to overall removals in 2050. This means that all pathways need a strong LULUCF net removals, which needs to be complemented by industrial solutions.

Table 5: LULUCF net removals and industrial carbon removals

	2030	2040				2050			
		S1	S2	S3	LIFE	S1	S2	S3	LIFE
Total Removals (MtCO2-eq)	-314	-222 [-222 to -380]	-365 [-262 to -423]	-391 [-290 to -450]	-387 [-270 to -437]	-462 [-334 to -525]	-447 [-318 to -510]	-447 [-319 to -509]	-428 [-274 to -476]
Net LULUCF sink (MtCO2-eq)	-310	-218 [-218 to -376]	-316 [-213 to -374]	-317 [-215 to -376]	-360 [-243 to -410]	-341 [-213 to -403]	-332 [-202 to -394]	-333 [-206 to -396]	-389 [-234 to -436]
Industrial Removals (MtCO2)	-4	-4	-49	-75	-27	-121	-115	-114	-40
BECCS	-4	-4	-34	-33	-27	-58	-59	-56	-37
DACCS	0	0	-15	-42	0	-63	-56	-57	-3

Source: PRIMES, GLOBIOM.

The 36 scenarios selected by the ESABCC⁽³³⁾ offer an overview of the possible balances between removals and emission reductions: for 2040, the level of gross emission lies

⁽³³⁾ The range refers to the 36 filtered scenarios, including also scenarios not complying with environmental risk that led to an emission reduction for 2040 between 83% and 96%.

between 1596 and 697 MtCO₂-eq ⁽³⁴⁾ and the contribution of removals is split into land-based removals (range between -100 and -400 MtCO₂-eq, with majority between -300 and -400 MtCO₂-eq) and industrial removals (BECCS and DACCS ranging between -46 and -214 MtCO₂, with majority around -200 MtCO₂) ⁽³⁵⁾.

In the modelling analysis, the amount of projected gross GHG emissions in 2040 and the contribution of nature-based removals lies within the range of the 36 ESABCC scenarios studied by the ESABCC. Instead, while the industrial removals in the main scenarios lie in the lower end of the range of the 36 scenarios analysed, achieving reductions up to 90% and beyond in 2040 cannot rely only on LULUCF net removals and needs to be complemented by development of industrial removals.

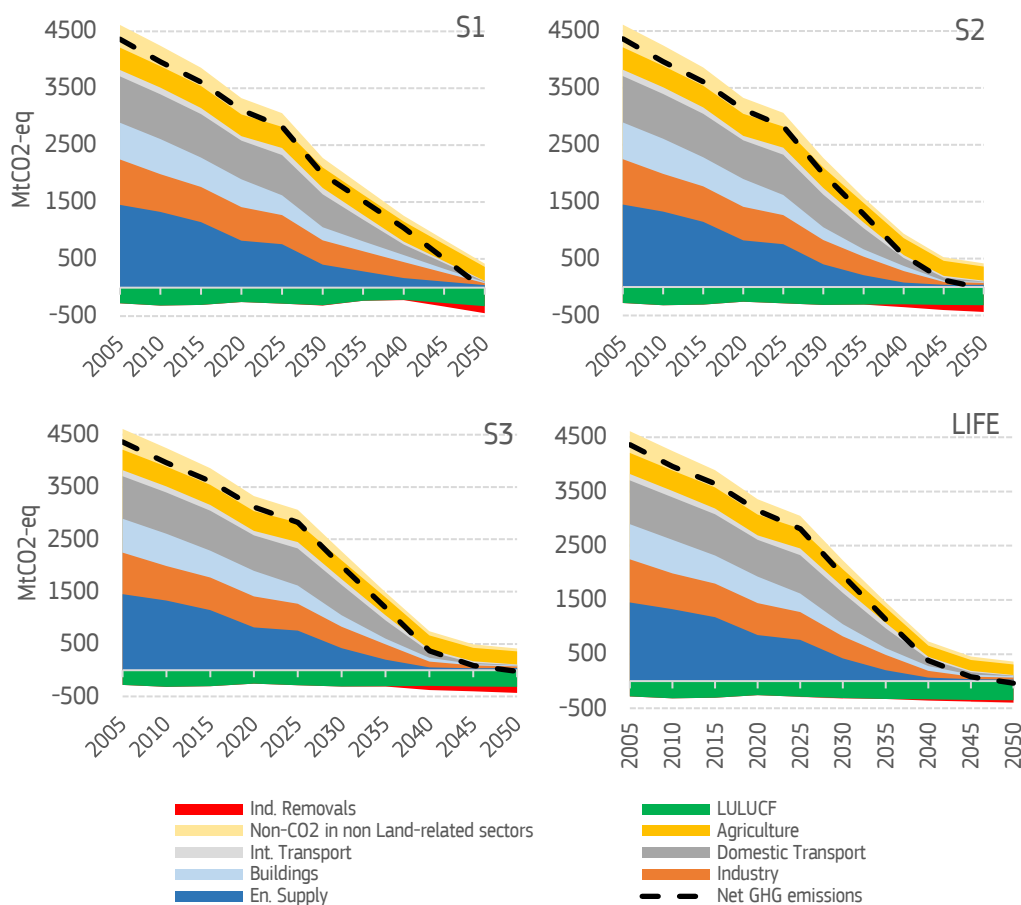
⁽³⁴⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Figure 37

⁽³⁵⁾ Ibid., Figure 35, Figure 36 and Table 16

1.1.2.5. GHG pathways

Figure 5 summarises the analysis of the previous sections and shows the net economy-wide GHG emission pathways. While all scenarios follow the same pathway until 2030, they diverge after that year, leading to distinct trajectories for the 2030-2050 decade before converging to net-zero by 2050.

Figure 5: Economy-wide GHG emission pathways



Source: PRIMES, GAINS, GLOBIOM.

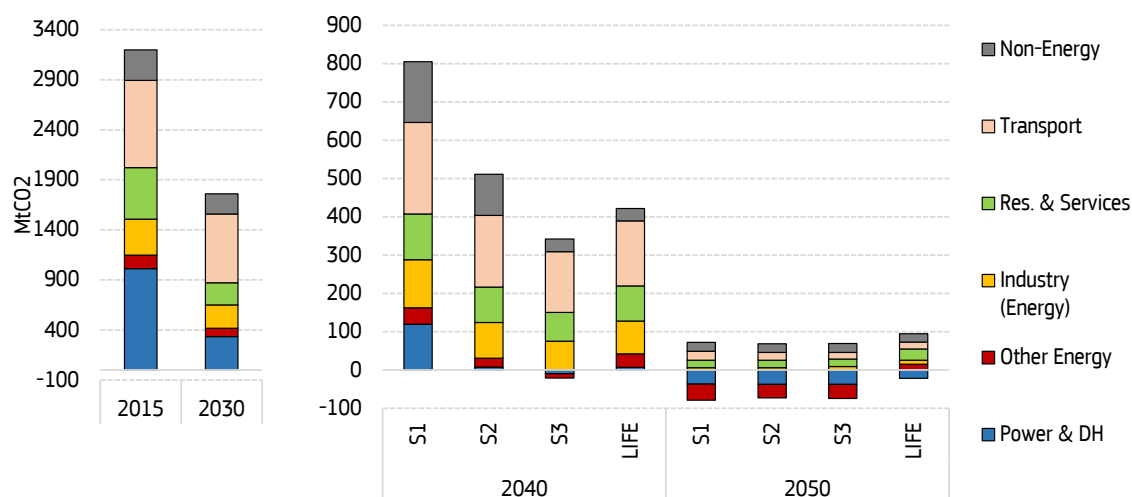
1.1.3. Energy and Industry CO₂ emissions

1.1.3.1. Net CO₂ emissions

Figure 6 shows the trajectories for the energy and industry net CO₂ emissions ⁽³⁶⁾ in the different scenarios.

⁽³⁶⁾ The emissions scope includes the net domestic energy-related CO₂, the net domestic non-energy related CO₂, the intra-EU transport and 50% of the international extra-EU maritime as per MRV.

Figure 6: Energy and Industry net CO₂ emissions



Note: Power and District Heating (DH) include BECCS. Other energy includes energy branch and DACCS. Residual and services includes fossil fuel combustion in the agriculture/fishery/forestry sector. Non-Energy includes industrial processes and fugitive emissions.

Source: PRIMES.

In line with current policies, CO₂ emissions from the energy sector are projected to more than halve already in 2030 with respect to 2015. Achieving net-zero in 2050 projects net CO₂ emissions in 2040 to be in the range of 330-800 MtCO₂ across scenarios, meaning a reduction between 80% and 92% compared to 1990. S3 reduces emissions by an additional 500 MtCO₂ with respect to S1: this amount corresponds to around 20% of 2030 total net GHG emissions, indicating the important contribution of the energy and industry sectors to decarbonise the EU economy already by 2040. In 2050, the sum of emissions coming from all sectors analysed achieves slightly negative levels in all scenarios, with industrial carbon removals compensating for the residual hard-to-abate emissions. LIFE shows a level of energy and industry CO₂ emissions intermediate between S2 and S3 in 2040, and slightly higher emissions of around 70 MtCO₂ in 2050. These additional emissions are compensated by lower emissions in agriculture (see 1.7) and enhanced land-based removals (see 1.8), highlighting a redistribution of emission reductions across sectors: total net GHG emissions levels comparable to S3 are achieved in LIFE mostly with a reduced need for industrial carbon capture.

The domestic CO₂ emissions (Table 6) decrease significantly already in the decade 2031-2040 and reach slight negative levels in the main scenarios in 2050. Energy related emissions⁽³⁷⁾ in 2040 are between 40% and 20% the level of 2030, with the power generation, district heating and transport sectors reducing the most, driven by the decarbonisation of the power system, the energy efficiency measures and the implementation of renewables in final energy sectors. Residual energy emissions are then reduced gradually in the decade 2041-2050 and reach cumulative negative values of around -40 MtCO₂ in 2050, as result of the contribution of industrial removals. Non-energy related CO₂ emissions decrease only by around 35% in 2030 vs 2015, and

⁽³⁷⁾ Essentially, the emissions from fuel combustion.

additional reductions between 20% and 80% (compared to 2030) are achieved in 2031-2040, driven by the decrease of industrial processes emissions: the large variation across scenarios is justified by the late (in S1) and early (in S3) entry into market of low-carbon innovative manufacturing technologies, including carbon capture, utilisation and storage. In 2050, emissions from industrial processes reduce to negligible values and the non-energy emissions stagnate. International emissions within the scope decrease by around half in the period 2031-2040 and range around 10-15 MtCO₂ in 2050. Further details on sectoral CO₂ emissions, including transport, are discussed in sections 1.2-1.5.

Table 6: Energy and Industry net CO₂ emissions

	2005	2015	2030	2040				2050	
	-	-	-	S1	S2	S3	LIFE	S3	LIFE
Total Energy and Industry CO₂ emissions	3837	3197	1759	805	511	321	422	-5	73
Net Domestic CO₂ Emissions: Energy Related	3381	2787	1448	594	357	247	351	-40	41
<i>Power and district heating*</i>	1300	1012	334	119	8	-10	7	-38	-22
<i>Other Energy sectors**</i>	152	136	84	43	23	-11	35	-37	15
<i>Industry (Energy)</i>	469	360	232	126	94	75	86	9	11
<i>Transport</i>	812	764	577	187	141	117	132	6	8
<i>Residential and Services***</i>	648	514	221	119	92	75	92	19	29
Net Domestic CO₂ Emissions: Non-Energy Related	325	260	176	156	109	34	33	23	22
<i>Industry (Non-Energy)</i>	288	226	150	133	86	12	11	4	2
<i>Other non-energy****</i>	37	35	26	23	23	22	22	20	19
International intra-EU and 50% extra-EU	116	107	112	52	46	41	39	11	10
<i>international intra-EU aviation</i>	35	38	43	31	29	28	26	11	10
<i>international intra-EU navigation</i>	31	27	25	7	6	4	4	0	0
<i>50% extra-EU MRV maritime MRV</i>	50	42	44	14	11	9	8	0	0
Residual CO ₂ for calibration	15	43	24	3	-1	-1	-1	0	0

Note: *Includes BECCS. **Includes emissions from energy branch and DACCS; ***Includes fossil fuel combustion in the agriculture/fishery/forestry sector; ****Includes fugitive emissions. S1 and S2 values in 2050 are similar to S3 and described in more details in sectoral sections 1.2, 1.3, 1.4 and 1.5 of this Annex.

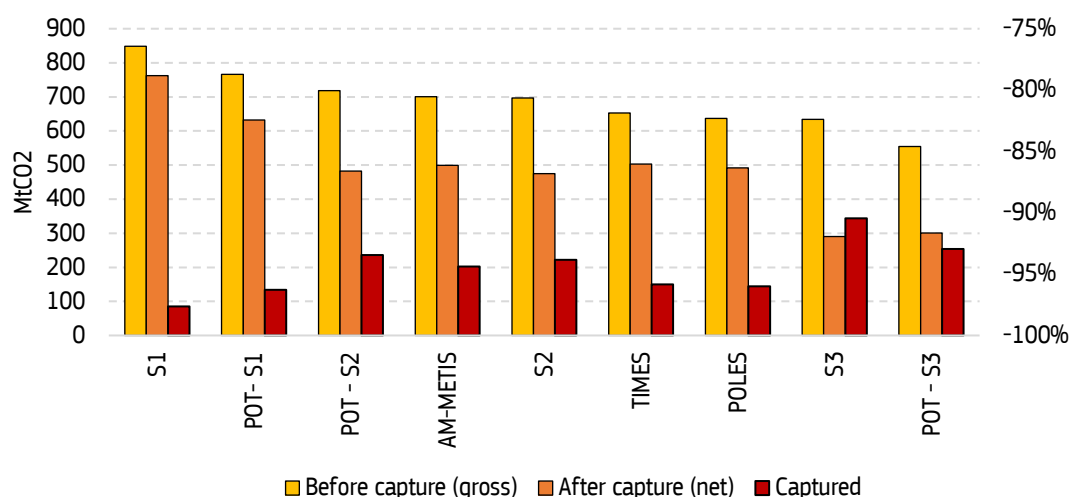
Source: PRIMES.

1.1.3.2.Role of carbon capture

To investigate the role of carbon capture and understand better the uncertainties associated to the deployment of this technology, a cross-model analysis comparing PRIMES projections with the ones provided by POTEnCIA, AMADEUS-METIS, POLES and EU-TIMES (see Annex 6) is performed (Figure 7). Results show how the level of climate ambition achievable in 2040 in the energy and industry sectors strongly depends on the amount of carbon captured and, as discussed in section 1.1.2.3, of carbon removals. The level of domestic energy and industry CO₂ emissions before capture (i.e., gross emissions) spans from 580 to 850 MtCO₂, with most of the models projecting in the 650-750 MtCO₂ range. Limited differences exist across modelling runs (reductions between -78% and -85% compared to 1990) and even in scenarios with the highest uptake of novel technologies (excluding carbon capture) the energy and industry CO₂ can reduce at most by around 85%, meaning that the 2040 potential for the implementation of mitigation solutions other than carbon capture modelled in the scenarios is mostly attained. The picture of emissions after capture (i.e., net emissions) is different. Limited carbon capture allows for a marginal further decrease in emissions (see S1 and POTEnCIA-S1 (POT-S1) on the left of Figure 7), while a more substantial

deployment of the technology achieves emission levels of around 470-520 MtCO₂ in S2, POTEnCIA-S2 (POT-S2), AMADEUS-METIS (AM-METIS), POLES and EU-TIMES, and down to around 250-350 MtCO₂ in S3 and POTEnCIA-S3 (POT-S3). Carbon capture allows to reach additional reductions of between 2-3% (corresponding to around 80-130 MtCO₂ captured in S1) and 4-6% (corresponding to around 150-240 MtCO₂ captured in S3) of 1990 levels and represents a key mitigation solution to reach deeper net GHG emission reductions. The models show that above 150 MtCO₂ (including removals) need to be captured in 2040 to achieve a total reduction of energy and industry CO₂ emissions of at least 88% and above 250 MtCO₂ to reach above 90%.

Figure 7: Energy and Industry CO₂ emissions in 2040



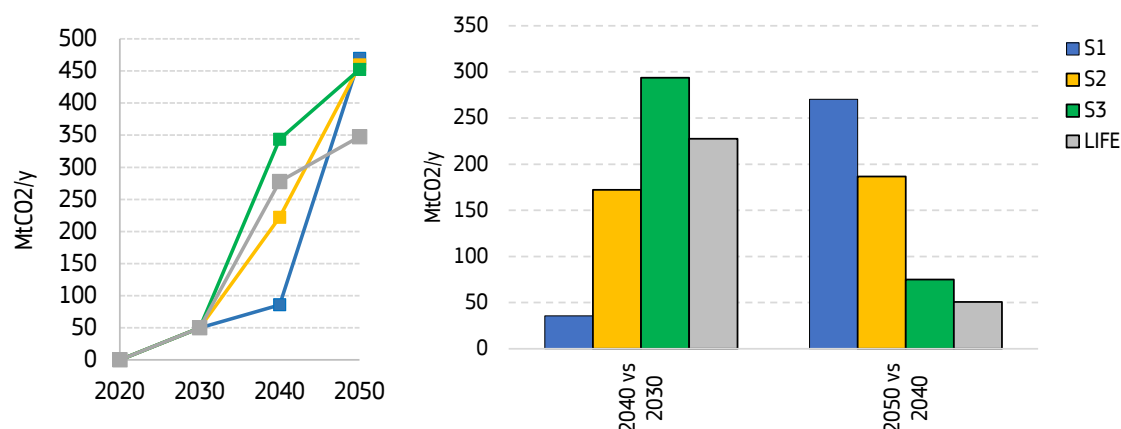
Note: Emissions (left) and relative reductions vs 1990 (right).

Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

Figure 8 shows the evolution of the carbon captured yearly (left), and corresponding additional carbon captured at the end of each decade until 2050 (right) projected by PRIMES. A yearly capture level of around 50 MtCO₂ is projected in 2030 across all scenarios, in line with the Net Zero Industry Act⁽³⁸⁾, which then increases in 2040 to around 90 MtCO₂ in S1, above 200 MtCO₂ in S2 and to 350 MtCO₂ in S3 and converges in 2050 to around 450 MtCO₂ in S1, S2 and S3. LIFE projects a level of carbon capture intermediate between S2 and S3 in 2040, and more moderate in 2050., showing that sustainable lifestyle and circular economy actions leads to a more extensive use of nature-based removals and lower the need for carbon capture in industry (see 1.4 and 1.8).

⁽³⁸⁾ COM(2023) 161

Figure 8: Total (left) and additional (right) carbon captured yearly in selected years



Source: PRIMES.

The projections for carbon capture are in line with ranges found in the literature: in 2040, the ENGAGE project depicts a yearly amount of carbon captured around 300 MtCO₂ ⁽³⁹⁾, the ECEMF ⁽⁴⁰⁾ provides a range of 215-376 MtCO₂, Rodrigues et al. ⁽⁴¹⁾ describe a range of 120-330 MtCO₂ and Ecologic indicates a range between 46 and 160 MtCO₂ (with a stronger reliance on land-based removals) ⁽⁴²⁾. For 2050, ESABCC ⁽⁴³⁾ and other literature ⁽⁴⁴⁾ show the maximum threshold for feasibility of this technology at around 500 MtCO₂.

As a result of different amount of carbon captured in 2031-2040 and 2041-2050 in the main scenarios, the additional minimum capacity ⁽⁴⁵⁾ per decade necessary to capture carbon varies significantly: in S1, delayed climate action results in additional installations capable of capturing up to 35 million tonnes of CO₂ extra in 2040, but this number multiplies by around 7.5 times by 2050. S2 shows a minimum additional capacity able to capture around 180-190 MtCO₂/y extra at the end of each decade. S3 suggests a large deployment of extra 300 MtCO₂/y captured by 2040, and only additional 75 MtCO₂/y by 2050. LIFE shows an intermediate level of additional capacity needed in

⁽³⁹⁾ ENGAGE Scenario Explorer, *Engage: Feasibility of Climate Pathways Project*, <https://www.engage-climate.org/> Accessed 15-09-23

⁽⁴⁰⁾ ECEMF (2023), ECEMF Policy Brief: Insights on EU2040 targets based on a model intercomparison exercise of EU Climate Neutrality Pathways. DOI 10.5281/zenodo.8337667. <https://zenodo.org/record/8337668> Full model range, including international bunkers.

⁽⁴¹⁾ Rodrigues et al., (2023). 2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal, *Nature Communication*, Under Review.

⁽⁴²⁾ Ecologic and Oeko-Institut, *Designing the EU 2040 climate target*, 2023.

⁽⁴³⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Table 5.

⁽⁴⁴⁾ ENGAGE Scenario Explorer, *Engage: Feasibility of Climate Pathways Project*, Accessed 15-09-23

⁽⁴⁵⁾ These values only represent indicative capacities and will have to take account of normal operational downtimes and be supported by a total geological storage capacity of several giga-tonnes of CO₂.

2040 between S2 and S3 and a minimal increase in the 2041-2050 related to the overall lower need of industrial capture in these settings.

Achievement of the required level of carbon capture capacity by 2040 is not trivial, especially in the S3 scenario. Several barriers to a large deployment of the technology exist today: the transition from R&I stage to the full-scale, replicable, commercial deployment for certain steps of the technology, the need to establish a new (cross-border) carbon value chain, including storage sites ⁽⁴⁶⁾ ⁽⁴⁷⁾, and a lack of market coordination for fast deployment of the technology. A large development of carbon capture means foreseeing the build up of commercially ready carbon capture infrastructure on existing or new-build industrial capacity, often in sectors characterized by long investment cycles. Hence, sound regulatory predisposition and long-term financial planning taking into account the impact on industrial competitiveness become necessary to provide certainty to industrial investors. Downstream of the carbon capture value chain, storage operators face high upfront costs to identify, develop and appraise storage sites before they can apply for a regulatory permit that is necessary to operate, while their future customers are willing to invest in carbon capture only if access to operating storage site is secured. Subsequently, market players have little templates for commercial contracting or risk sharing and depend on each other's plans and project progress to de-risk their own investment decisions. Regulatory uncertainty and inexperience also represent a challenge, for instance in terms of supplementing the CCS directive ⁽⁴⁸⁾ and clarifying future link between industrial removals and ETS or cross-border transport of captured CO₂. To overcome these challenges, several Member States have CO₂ value chain strategies in place or are developing them (NL, DK, FR, DE) ⁽⁴⁹⁾ and consolidated effort is needed to stimulate and guide a market development that can deliver the scale needed, as described in the Communication on Industrial Carbon Management ⁽⁵⁰⁾.

When looking at the different sources of carbon captured in 2040, and only considering this specific pathway modelled by PRIMES, a veritable “merit order” emerges (Figure 9). S1 shows that carbon is first captured in industrial processes and power generation (emitting from fossil fuels) in order to reduce emissions in those sectors, with very little coming from BECCS, the upgrade of biogas to biomethane (biogenic carbon) and DAC. A larger uptake of the technology in S2 leads first to the increase of the level of fossil carbon coming from industrial processes and power generation, and then taps into industrial removals, mostly BECCS. Being the potential for BECCS limited by sustainability constraints on biomass availability, and possible negative impact on the LULUCF net removals, an increase in demand for the production of e-fuels opens the doors to deployment of DAC in 2040: this happens already in S2 and becomes even

⁽⁴⁶⁾ Lane, J., Greig, C., & Garnett, A. (2021). Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nature Climate Change*, 11(11), 925-936. <https://doi.org/10.1038/s41558-021-01175-7>

⁽⁴⁷⁾ Koelbl, B. S., et al. (2014). Uncertainty in the deployment of Carbon Capture and Storage (CCS): A sensitivity analysis to techno-economic parameter uncertainty. *International Journal of Greenhouse Gas Control*, 27, 81-102.

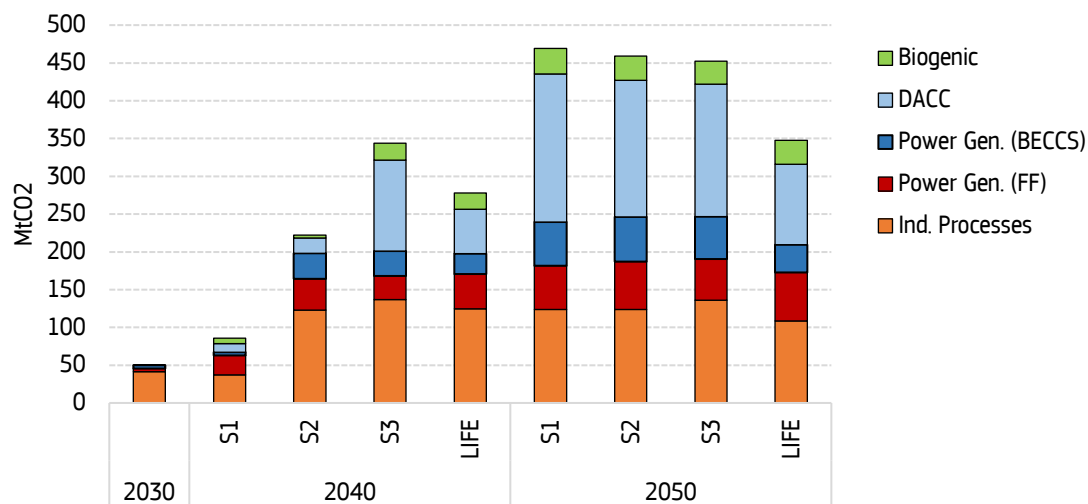
⁽⁴⁸⁾ Directive 2009/31/EC

⁽⁴⁹⁾ This list is to be published by JRC mid-october 2023.

⁽⁵⁰⁾ Industrial Carbon management Communication (upcoming).

more evident when moving from S2 to S3, where the additional carbon is captured almost exclusively through DACC. In 2050, the share of the different technologies is similar across S1-S2-S3. Proportionally, LIFE also shows a similar distribution, with less DACC than S3 in 2040 and an overall capture level in 2050 lower than the other scenarios.

Figure 9: Carbon captured by source



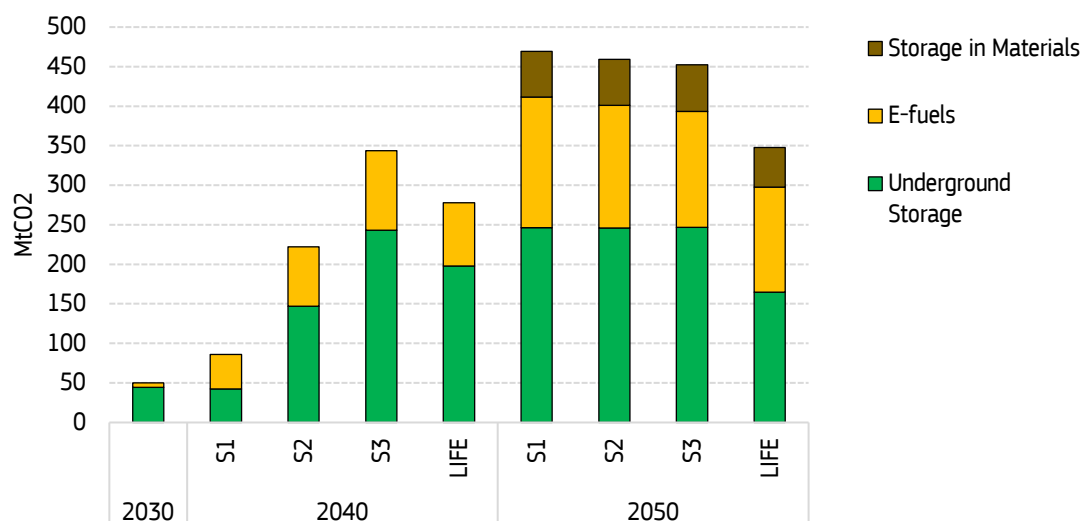
Note: Biogenic carbon indicates the carbon resulting from the upgrade of biogas to biomethane.

Source: PRIMES

The order in which carbon capture technologies are deployed to satisfy increasing demand reflects the results of the public consultation questionnaire for the 2040 target, where respondents would prioritise deployment of carbon capture from industrial process (highest priority given by 36% of respondents), followed by combustion of biomass (23%) and fossil fuel (20%). The strong preference for carbon capture from industrial process is also confirmed when looking at different stakeholders' group, indicating a general agreement on the development of this technology. The picture is less technology-specific when analysing positions papers collected during the consultation: about half of them, published by business associations, public authorities and academia, encourages the uptake of carbon capture and storage technologies, without assigning priority to one specific technology type.

The modelling shows that capture of carbon in 2040 is mainly driven by the demand for e-fuels required in other sectors and by the need to reduce net emissions within the sector through underground storage (Figure 10). In the 2041-2050 decade, where e-fuels are to be produced using fossil-free carbon and all residual emissions needs to be compensated, the action of these drivers continue, increasing the amount of carbon captured for these two applications. The increasing demand for industrial feedstock also creates a new market for storage in materials, where CO₂ is chemically bound in products, balancing industrial CO₂ needs, making local CO₂ networks an attractive option.

Figure 10: Carbon Captured by end application

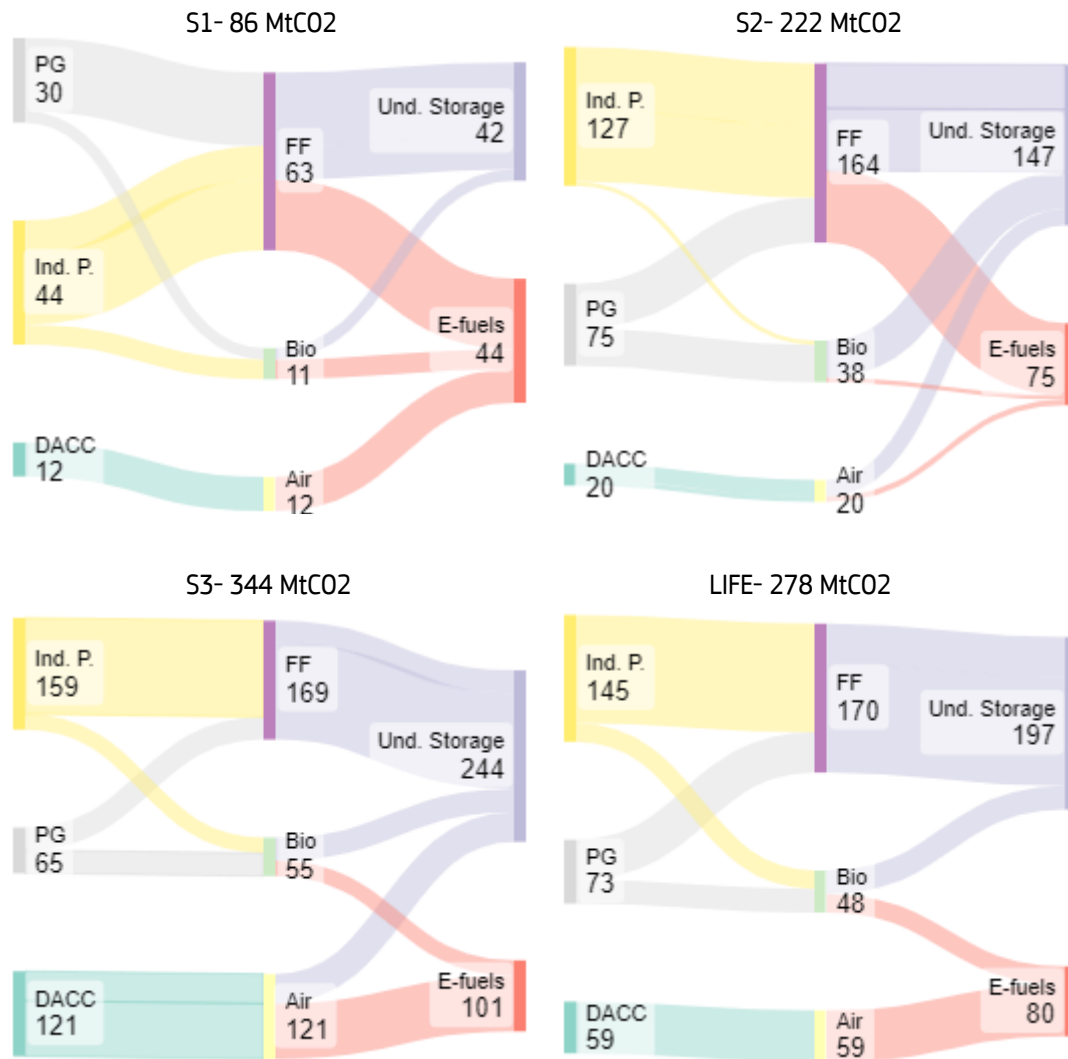


Source: PRIMES.

In the 2030-2050 period, the model shows that carbon capture does not only reduce emissions in hard-to-abate sectors, but above all generates carbon feedstock for e-fuels or fossil-free products as well as industrial removals (in terms of BECCS and DACCS). A real carbon management industry is to be created, connecting different carbon technologies and sources to final end-user applications through industrial feedstocks, balancing carbon flows in the EU economy. Figure 11 shows the carbon flows between sources and uses in 2040 in the different scenarios. These carbon flows can be also affected by the projected levels of emission reduction. For instance, while e-fuels can be produced by carbon captured from fossil fuels in power generation and industrial processes in scenarios with higher 2040 emissions (S1 and S2), the higher ambition of S3 makes necessary the permanent storage of these fossil fuel emissions. In S3, the production of e-fuels in 2040 relies mostly on fossil-free sources of carbon derived from biomass (either captured from bioenergy combusting application or of biogenic origin from the upgrade of biogas to biomethane) and, given the limited sustainable biomass resources, from DACC. Beyond 2040, when fossil fuels are excluded⁽⁵¹⁾ from possible source of carbon for production of RFNBOs across all scenarios, and e-fuels demand increases even further, they are produced mostly using carbon derived from DACC and in part from biomass. All remaining fossil carbon is then permanently stored (either underground or in products).

⁽⁵¹⁾ Commission Delegated Regulation (EU) 2023/1184

Figure 11: Flow of captured carbon in 2040



Note: “Ind. P.” stands for Industrial processes and include fossil carbon from industrial processes as well as carbon of biogenic origin coming from the upgrade of biogas to biomethane. “FF” stands for “fossil fuels”. “PG” stands for “power generation”. “Bio” refers to CO₂ produced by the combustion of biomass in power generation and produced during the upgrade of biogas into biomethane. “DACC” stands for “Direct Air Capture of CO₂”, for underground storage (DACCS) or use in e-fuels.

Source: PRIMES.

1.1.4. Non-CO₂ GHG emissions

Non-CO₂ GHG emissions declined considerably over the past decades in the EU. Currently, however, significant amounts of non-CO₂ greenhouse gases are still being emitted every year, representing around 20% of total GHG emissions. In 2015, the EU’s total non-CO₂ GHG emissions added up to more than 700 MtCO₂-eq. As shown in Figure 13, most of these were CH₄ emissions (61%), whereas the rest were N₂O and F-gas emissions (25% and 14%, respectively). Agriculture was the largest emitting sector, representing roughly 53% of the EU’s total non-CO₂ GHG emissions (mostly CH₄ and N₂O emissions associated to enteric fermentation, manure management and fertiliser application), followed by waste treatment (17%, mostly CH₄ emissions stemming from uncaptured emissions caused by anaerobic digestion of solid waste and wastewater streams), energy and transport (16%, mostly methane leakage and emissions related to

fuel combustion), and heating/cooling installations (11%, mostly F-gas emissions), as shown in Figure 12.

In the S1 scenario, which considers mitigation due to current policies (but no more), non-CO₂ GHG emissions drop to around 457 MtCO₂-eq in 2040 (i.e., 35% less than in 2015). Note that the degree of reduction by 2040 varies considerably across sectors (see Figure 12). Agriculture is the sector showing the smallest decrease in relative terms (9% reduction between 2015 and 2040). Non-CO₂ GHG emissions from the waste management sector decline by 42% over the same period (driven by the implementation of existing legislation on landfilling and additional legislative proposals, such as the proposal on a revised Urban Wastewater Treatment Directive, see Section 1.6.1 and Annex 6), while the energy and transport sector shows a deep reduction (-71%) driven by the phase down of fossil fuel use in the energy system. The heating and cooling sector shows the largest decrease in relative terms (97% relative to 2015), driven mostly by the assumed implementation of the F-gas regulation proposal (see Annex 6). Looking at the disaggregation per gas, total N₂O emissions across all sectors decrease by 14% between 2015 and 2040, CH₄ emissions decline by 32% over the same period, and F-gas emissions decrease by more than 90%, as shown in Figure 13.

The S2 and S3 scenarios show a more ambitious reduction of net GHG emissions by 2040 than the S1 scenario, and this requires stronger non-CO₂ emission reductions than those delivered by current policies. In the S2 scenario, total non-CO₂ GHG emissions go down to 376 MtCO₂-eq in 2040 (i.e., 81 MtCO₂-eq less than in the S1 scenario), that is to say, they decrease by 47% compared to 2015. In the S3 scenario, total non-CO₂ GHG emissions drop to 345 MtCO₂-eq in 2040 (i.e., 112 MtCO₂-eq less than in the S1 scenario), which translates into a 51% reduction compared to 2015 (i.e., more than three-quarters of the emissions reduction trajectory between 2030 and 2050). As shown in Figure 12, the main difference compared to the S1 scenario are additional reductions in emissions in the agriculture sector (22% reduction between 2015 and 2040 in S2, 13 percentage points more than in S1, and 30% reduction between 2015 and 2040 in S3, 21 pp more than in S1). Most of this additional reduction corresponds to N₂O emissions from agricultural soils and CH₄ emissions from enteric fermentation and manure management (see Figure 13 and Section 1.7.5). In the S3 scenario, all sectors (including agriculture) are close to reaching their maximum mitigation potential both in 2040 and in 2050.

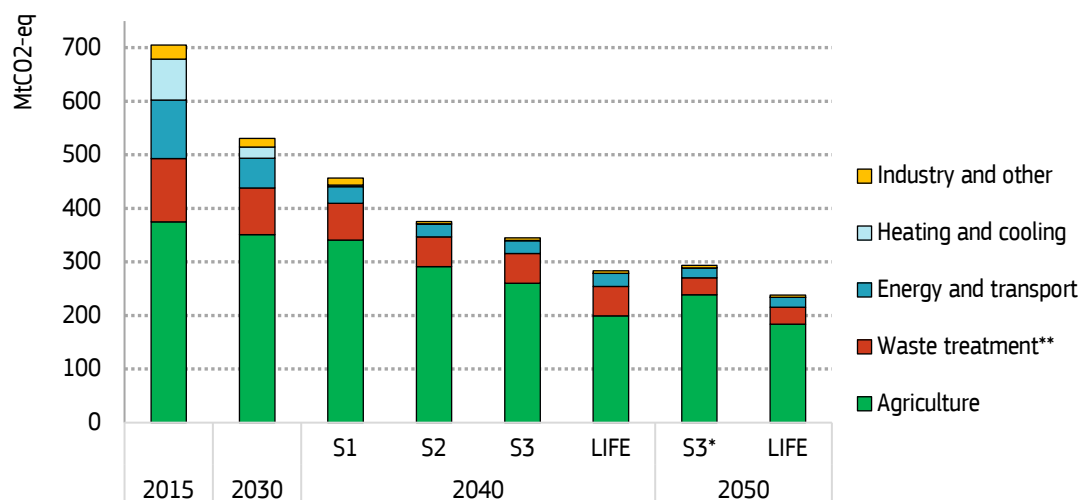
In LIFE, total non-CO₂ GHG emissions go down to 284 MtCO₂-eq in 2040 (which means a 60% reduction relative to 2015, and 61 MtCO₂-eq less than in S3) and 238 MtCO₂-eq in 2050 (i.e., 55 MtCO₂-eq less than in S3). As shown in Figure 12, the only significant difference compared to the S3 scenario is an additional decrease in emissions in the agriculture sector (47% reduction between 2015 and 2040, 17 percentage points more than in the S3 scenario), which is mainly due to the smaller amount of livestock and lower use of mineral fertilisers assumed in LIFE. All sectors (including agriculture) are close to reaching their maximum mitigation potential both in 2040 and in 2050.

A more detailed analysis of the non-CO₂ GHG emission trajectories in all scenarios can be found in Sections 1.6 and 1.7.

Table 7 shows the emission residuals related to the calibration of the GAINS and PRIMES models to the UNFCCC inventory, which have not been considered in the discussion above. These residuals are small and not assigned to any particular sector. The

table also shows the CO₂ emissions produced by the agriculture sector (including only “category 3” emissions).

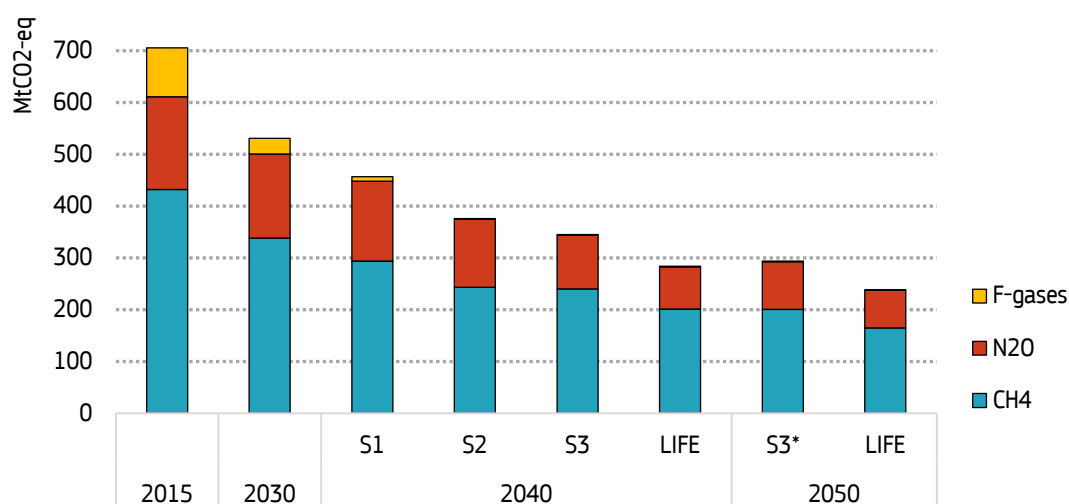
Figure 12: Evolution of non-CO₂ greenhouse gas emissions by sector



Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **The waste treatment sector includes solid waste and wastewater treatment. ***Emission residuals related to the calibration of the GAINS and PRIMES models to the UNFCCC inventory (which are small and not assigned to any sector) are not included in this figure.

Source: GAINS.

Figure 13: Evolution of non-CO₂ greenhouse gas emissions by gas



Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **Emission residuals related to the calibration of the GAINS and PRIMES models to the UNFCCC inventory (which are small) are not included in this figure.

Source: GAINS.

Table 7: Total non-CO2 GHG emissions in all sectors and CO2 emissions from agriculture

	Greenhouse gas emissions (MtCO2-eq)							
	2015	2030	2040				2050	
			S1	S2	S3	LIFE	S3*	LIFE
Non-CO2 emissions	705	531	457	376	345	284	294	238
Non-CO2 calibration	2	-3	-3	-3	-3	-3	-3	-3
CO2 emissions from agriculture (category 3)	10	10	10	10	10	10	10	10

Source: GAINS.

1.2. Energy sector transformation

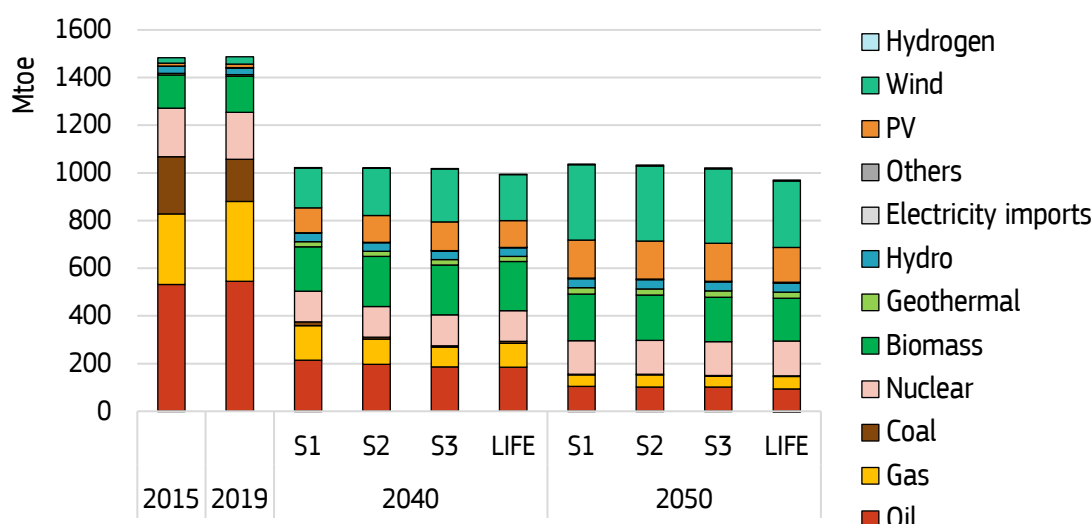
1.2.1. Energy supply

Gross Available Energy ⁽⁵²⁾ ⁽⁵³⁾ (GAE) reduces to between 1 018-1 022 Mtoe across the S1-S2-S3 scenarios in 2040, corresponding to approximately a 30% reduction compared to 2019 (see Figure 14). Thanks to the circular economy measures and consumption patterns, LIFE further reduces GAE. After 2040, GAE stabilises around 1020–1040 Mtoe, except for LIFE where, in 2050, it is further reduced by more than 50 Mtoe compared to other scenarios.

⁽⁵²⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

⁽⁵³⁾ Gross Available Energy refers to the overall supply of energy for all activities of a country. It includes energy needs for energy transformation, for the energy sector itself, transmission and distribution losses, final energy consumption and the use of fuels for non-energy purposes. It also includes fuel purchased within the country that is used elsewhere (e.g., international aviation and shipping). These figures exclude ambient heat (from heat pumps).

Figure 14: Gross Available Energy by energy vector, 2015-2050



Note: Biomass and waste include non-renewable waste. Natural gas includes also manufactured gas.

Source: PRIMES.

Profound changes in the energy mix underpin the overall reduction of GAE over time. Fossil fuels are gradually reduced, from approximately 1060 Mtoe in 2019 to between 275 and 375 Mtoe in the S1-S2-S3 scenarios (a 65 to 74% reduction compared to 2019). In 2050, approximately 155 Mtoe of residual fossil fuels remain with little differences between the S1, S2 and S3 scenarios (-85% compared to 2019), largely consumed for non-energy uses and from long distance transport. In 2040, fossil fuels account for 27 to 37% of GAE in the S1-S2-S3 scenarios, down from more than 70% in 2019. Fossil fuels reach a share of total GAE of approximately 15% in 2050 across all scenarios.

Renewables undergo a pronounced growth in their share of total GAE as they gradually replace fossil fuels as the backbone of the EU energy system. The share of renewables in total GAE grows from just 17% in 2019 to 50-60% in the S1-S2-S3 scenarios (around 520-610 Mtoe) in 2040. Then, in 2050 the share of renewables reaches more than 70% in 2050 (around 690-735 under the S1-S2-S3 scenarios). LIFE decreases the overall use of renewables in GAE by more than 40 Mtoe in 2040 and more than 50 Mtoe in 2050.

Based on nuclear capacity assumptions in line with the Member State policies as described in the 2019 National Energy and Climate Plans⁽⁵⁴⁾, cf. sub-section 2.5.2.2, nuclear power is projected to experience a reduction in output over this decade from around 200 Mtoe in 2019 to 130 Mtoe in 2030 after which it broadly stabilizes, accounting for 13-14% of total GAE from 2040 onwards without major differences across scenarios.

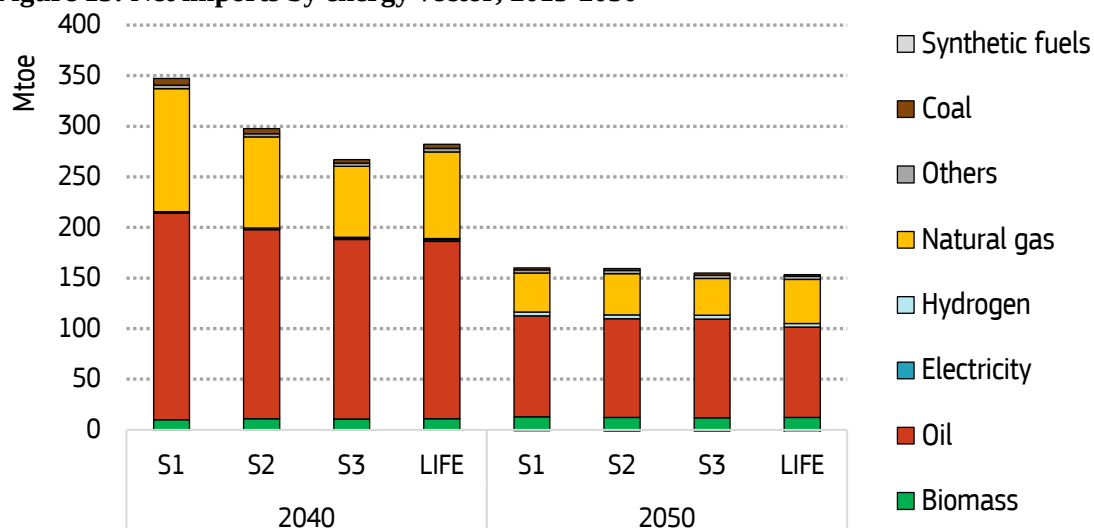
⁽⁵⁴⁾ These assumptions reflect the situation until March 2023. In June 2023, France has adopted a law which removes the objective of reducing the share of nuclear power in the electricity mix. Additional 3.3 GWe nuclear capacity was officially announced for deployment by mid-2030s. See the box in 6.2.1 of the main Impact Assessment and the assumptions in Annex 6. Future EU policies and analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted.

Overall, total GAE is quite stable across the S1, S2 and S3 scenarios, varying by less than 1% in 2040 and less than 2% in 2050, but measures in the LIFE scenario further decrease GAE. However, the trajectories (in terms of GAE) of the various energy vectors are characterised by considerable variations across scenarios: the S3 scenario shows a faster uptake of renewables at the expense of fossil fuels, while S1 scenario shows a slower uptake.

The gradual substitution of fossil fuels (largely imported from outside the EU) with renewables deployed domestically implies a steep reduction of net imports of energy commodities (Figure 15).

Total net imports of energy commodities are projected to reduce by 62%-71% in the S1-S2-S3 and LIFE scenarios (for a total of 270-350 Mtoe) compared to 2019. In 2050, net imports further decrease to 150 and 160 Mtoe in the S1-S2-S3 scenarios, 83% lower than in 2019. Net imports of coal virtually end by 2040 in all scenarios and those of natural gas and oil products drastically reduce with a very similar pace as the one of overall net imports. All scenarios meet the goal of the REPowerEU plan to phase out import of Russian gas ⁽⁵⁵⁾. The amounts of imports of hydrogen and e-fuels remain relatively small in 2040, due to still relatively high costs.

Figure 15: Net imports by energy vector, 2015-2050



Note: Biomass and waste include non-renewable waste. Natural gas includes also manufactured gas. When the scenario name is not indicated for future years, the reasons is that trends are almost identical across scenarios.

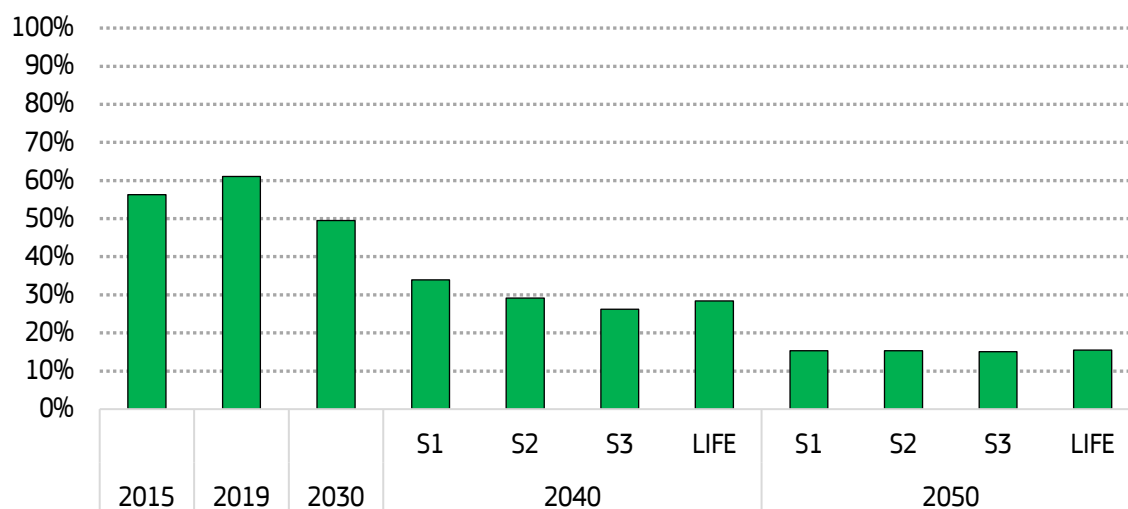
Source: PRIMES.

As shown in Figure 15, the main difference in the fuel-specific pattern across scenarios is associated to natural gas: total net import in 2040 under the S3 achieves three-quarters of the level of the S2 scenario (around 70 Mtoe and 90 Mtoe respectively). Oil and natural gas are the last fossil fuels to be phased out and significant imports still occur in 2050. However, by mid-century almost half of oil consumed in the EU is used to make products in the non-energy sector. In 2050, more than half of the liquid fuels used for energy purposes in end-use sectors are RFNBOs.

⁽⁵⁵⁾ COM/2022/230 final

The decline in imports has profound consequences for the EU's security of energy supplies. Import dependency (defined as the ratio of net imports to GAE excluding ambient heat) decreases from 61% in 2019 to 50% in 2030 and to 34% – 26% in 2040 (depending on the scenario). By 2050, only approximately 15% of the fuels used in Europe will be imported. The energy transition will greatly reduce the EU's dependency on energy imports. However – due to the decline of indigenous production and the fact that oil is the last fossil fuel to be abandoned – a large decrease in imports will occur only with deep decarbonisation (see Figure 16). As shown in Figure 15, import reduction is similar across scenarios depending mainly on the decarbonisation target.

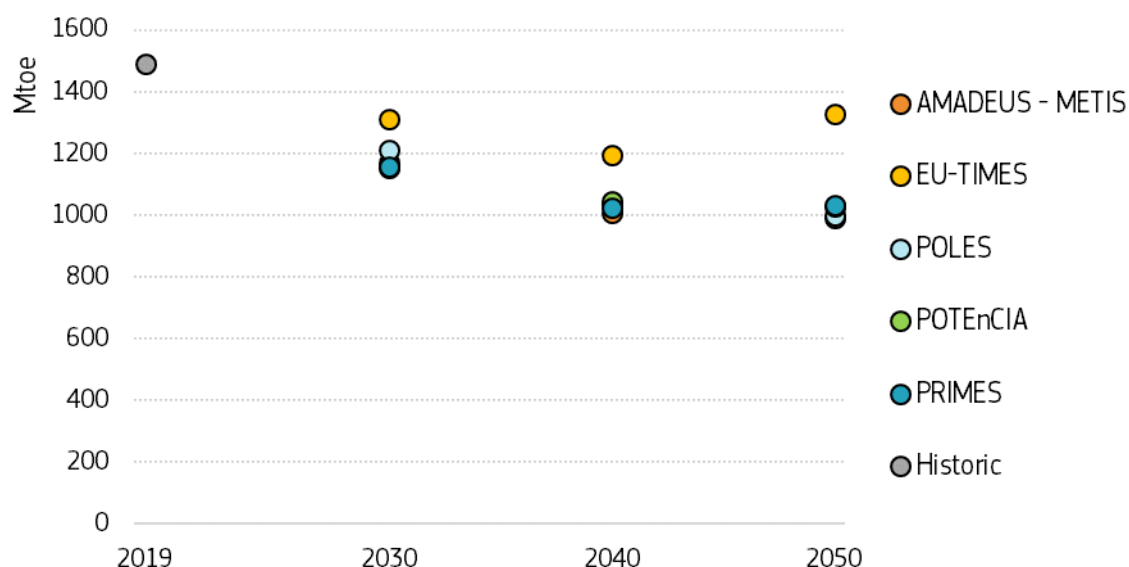
Figure 16: Import dependence



Source: PRIMES.

As introduced in Annex 6, complementary modelling tools have been used in addition to PRIMES to model the decarbonisation scenarios. Figure 17 compares the projections for total Gross Available Energy obtained from the POTEnCIA, AMADEUS-METIS, EU-TIMES and POLES models for the S2 scenario. Values and patterns are comparable across all models, with EU-TIMES showing the highest GAE throughout the time horizon and a trajectory that reduces up to 2040 and then increases again afterwards. The highest GAE in EU-TIMES is explained mainly by the lowest reduction in FEC (see Figure 17) linked to an extensive use of RFNBOs in comparison with electricity (see Figure 33 later in the text), and a high reliance on industrial carbon removals to compensate for emissions in hard-to-abate sectors, which has associated significant consumption of electricity and heat.

Figure 17: Total Gross Available Energy from different energy models, 2019-2050



Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

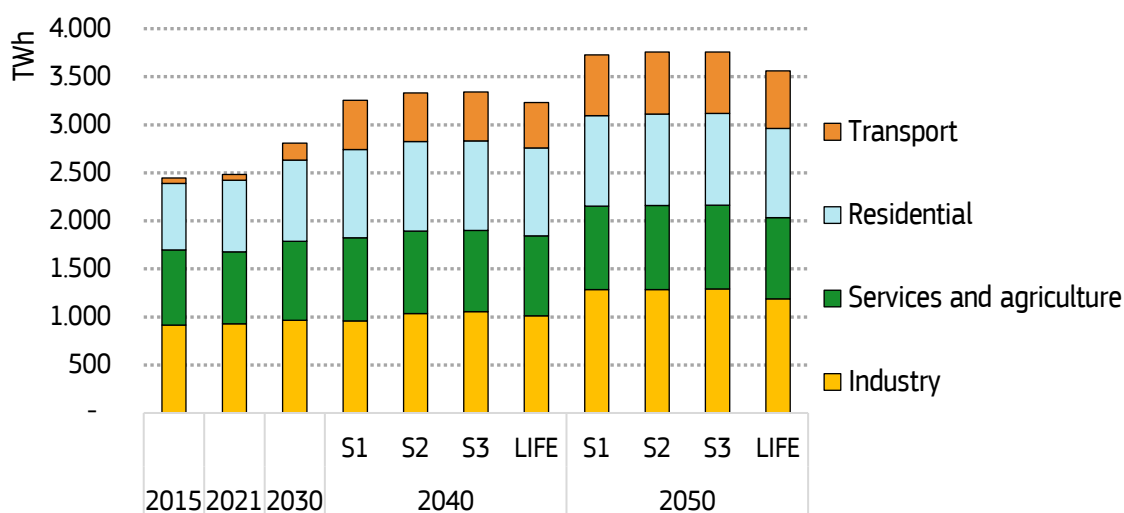
1.2.2. Power generation sector

The coming decades require an increase in electricity supply due to the increasing electrification of the economy and the production of RFNBOs. Fossil fuel-fired electricity generation decreases substantially and is replaced by variable renewable electricity generation. To match variable supply and demand, more smart solutions are needed. The variability of wind and solar can be addressed through real time pricing signals and flexibility solutions on the demand side. Sector coupling technologies like storage, interconnection and carbon free dispatchable power generation are expected to play an increasingly important role ⁽⁵⁶⁾.

In the context of reducing fossil fuels use in favour of direct electrification of end-use sectors, for instance via the deployment of heat pumps, electric vehicles and electrified low and mid-temperature industrial processes, demand for electricity increases by 31-34% between 2021 and 2040 in S1-S2-S3 (Figure 18).

⁽⁵⁶⁾ Koolen, D. et al., Flexibility requirements and the role of storage in future European power systems, EUR 31239 EN, Publications Office of the European Union, Luxembourg, 2023, ISBN 978-92-76-57363-0, doi:10.2760/384443, JRC130519.

Figure 18: Final electricity consumption by end-use sector



Note: Total electricity consumption consists of final electricity consumption from end-use sectors (hereby shown), own consumption of the energy sector, RFNBOs production and transmission/distribution losses.

Source: PRIMES.

As shown in Figure 18, electrification of the economy drives final electricity demand in the transport, services & agriculture, industry and residential sectors. Total final demand increases from 2 485 TWh in 2021 to 2 810 TWh in 2030 and to 3 255-3 340 TWh in S1-S2-S3 in 2040. Measures following LIFE are projected to reduce electricity demand by 110 TWh.

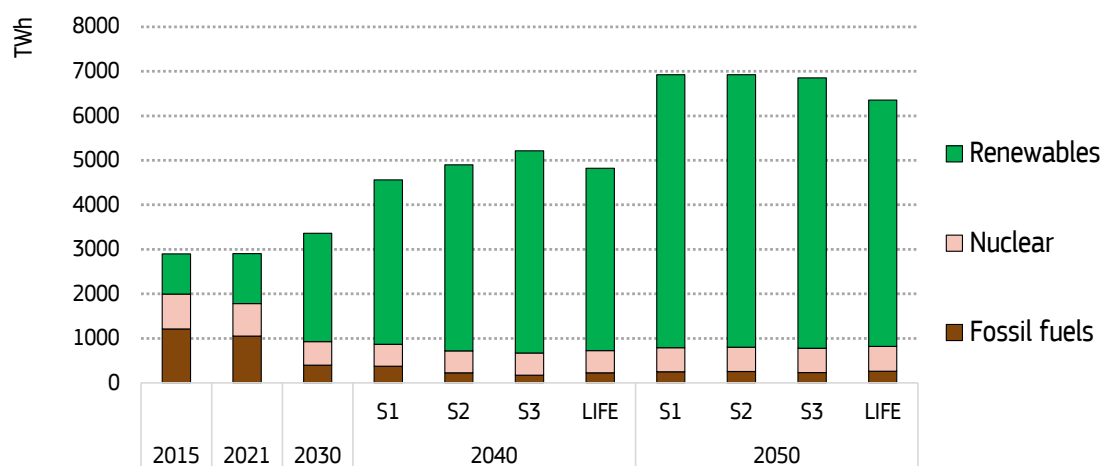
In the residential sector, overall electricity demand will increase by 23-25% between 2021 and 2040 due to an increased uptake of heat pumps replacing oil and gas-based heating systems (see Section 1.3.3). Due to the high efficiency of heat pumps, the overall increase of electricity demand is lower than the energy savings resulting from phasing out gas and oil boilers. There are only minor differences between the scenarios, with S1 reaching 920 TWh and S3 reaching 935 TWh.

Industry, agriculture and services show a similar picture. In those sectors, the share of electricity in the final energy demand is rising sharply due to the slight increase in electricity demand and the overall drop of final energy consumption. As a result of the interplay of electrification and energy efficiency, electricity demand in these sectors increases by 12% (industry) and 15% (services and agriculture) between 2021 and 2040 (S2). See sections 1.3.3 and 1.3.4 for more details.

The transport sector undergoes the strongest growth in final electricity consumption between 2021 and 2040, attributed to the large development of electric transport (see Section 1.5.3). Overall, final electricity demand in the transport sector will increase over the period 2021 to 2040 by a factor of 8 with no major differences between scenarios. In absolute terms, final electricity demand increases from 60 TWh in 2021 to 180 TWh in 2030 and 505-510 TWh in 2040, respectively. The LIFE measures would reduce final electricity consumption in the industry by 35 TWh.

Between 2040 and 2050, total final electricity demand increases again by 13% to 3 760 TWh. Transport (+26%) and industry (+22%) increase further sharply while the residential, services and agriculture sectors face a slowdown (both + 2%).

Figure 19: Electricity generation by energy carrier, 2015-2050



Source: PRIMES.

As a result of increased electricity demand, electricity generation increases from 2 905 TWh in 2021 to 3 360 TWh in 2030. The increase continues even more strongly until 2040 resulting in total electricity generation to reach 4 565-5 210 TWh in S1-S2-S3 in 2040 (+57 to 80% since 2021) (see Figure 19). The measures from LIFE are projected to reduce need for electricity generation by 390 TWh. The difference in electricity generation between scenarios is only to a small extent due to the final demand for electricity. Rather, it is driven by differences in the electricity required for the production of RFNBOs from 2030 onwards (which does not fall under final electricity demand). In 2040, electrolyzers, RFNBO synthesis processes and DAC combined consumes approximately 490 TWh more electricity in the S3 scenario than in S1 (a 51% increase). The S2 scenarios consumes approximately 225 TWh more than S1 for the same purposes (23% increase).

The share of fossil-fired generation is projected to steadily decrease from 36% in 2021 to 12% in 2030 and further down to 3% – 8% in S1-S2-S3 in 2040. The residual fossil-fired generation in the last decade before 2050 is projected to consist almost solely of gas-fired power plants, with and without CCS. The plants equipped with CCS will generate the majority of the gas-fired electricity, while the ones without CCS equipment will only be used as peakers. Renewables in the electricity system generated around 40% of total electricity supply in 2021 and are expected to cover 81% – 87% by 2040. Nuclear power generation decreases over the decades from 730 TWh in 2021 to around 495 TWh in 2040 (-30%). Due to the high increase in overall electricity supply, the share of nuclear generation is projected to decrease from 25% in 2021 to 10 – 11% in 2040. The results in nuclear generation are based on nuclear capacity assumptions in line with the Member State policies as described in the 2019 National Energy and Climate Plans ⁽⁵⁷⁾, cf. sub-section 2.5.2.2.

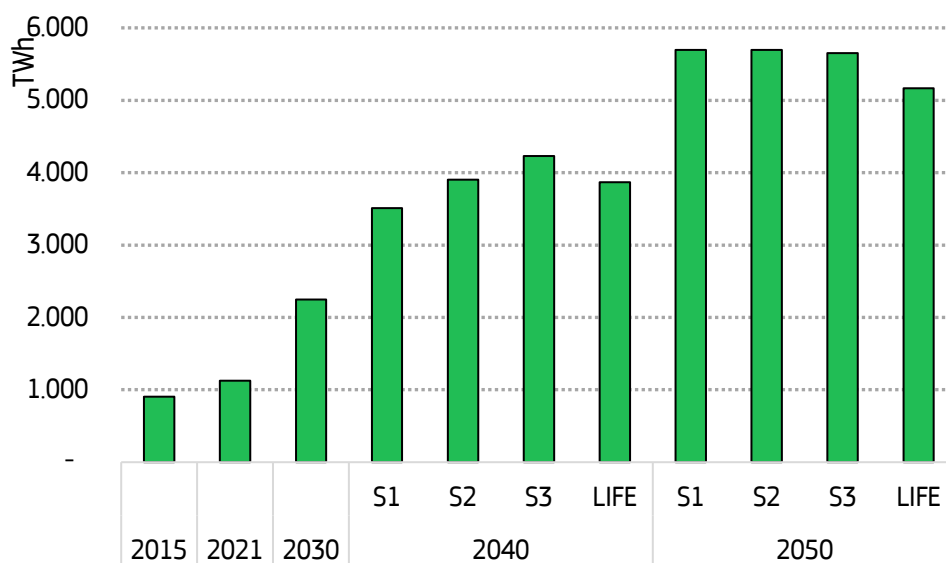
The three scenarios follow the same trend in the electricity mix with minor deviations. The higher production of RFNBOs in S3 requires more renewable electricity generation

⁽⁵⁷⁾ Future EU policies and analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted.

(around 850 TWh more in 2040 compared to S1). At the same time, S1 shows a higher use of fossil-fired generation by 2040 (around +200 TWh in comparison to S3) and result in overall lower emission reductions.

The electricity system will increasingly face the need to integrate variable wind and solar generation. Renewable generation will increase from 1 125 TWh in 2021 to 3 700 to 4 540 TWh in 2040 in the S1-S2-S3 (see Figure 20). As the total demand for electricity generation increases significantly but less than renewable generation, the share of renewables in the electricity mix increases continuously, from 39% in 2021 to 85% in 2040 and almost 90% in 2050.

Figure 20: Electricity generation from renewables, 2015-2050

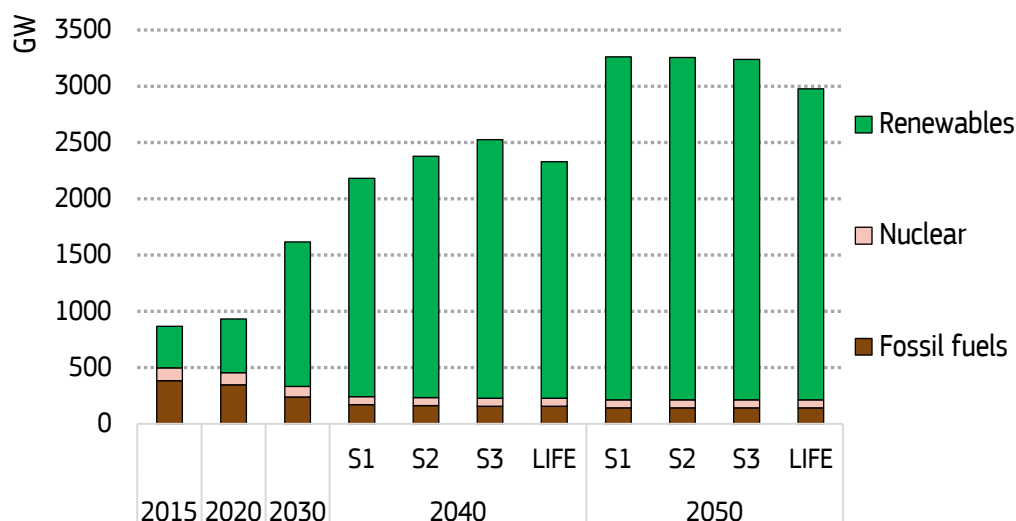


Source: PRIMES.

Due to the relatively low full load hours of wind and solar PV generation, total installed capacity is projected to grow more than two times faster than the amount of electricity generated between 2015 and 2040. The net capacity increases from 870 GW in 2015 to 2 180-2 525 GW in S1-S2-S3 in 2040, led by an increase of renewable capacity (see Figure 21). The implementation of LIFE measures reduces the need for installed power capacity by around 195 GW in 2040.

During the same time, the installed fossil-fuel capacity will decrease from 385 GW in 2015 to only 155-170 GW in 2040. While today the share of gas-fired power capacity is about half of total fossil-fired capacity, the share is projected to increase to around 90% in 2040 due to the overall decrease of fossil-based generation. A small amount of coal- and oil-fired capacity remains during this period.

Figure 21: Net installed capacity by energy carrier, 2015-2050



Source: PRIMES.

By 2030, the EU's nuclear power capacity is projected to decline from around 110 GW in 2015 to 95 GW in 2030 and 70 GW in 2040, under the current modelling assumptions, cf. sub-section 2.5.2.2. The decline in capacity can be attributed to the policy decisions of the respective EU Member States ⁽⁵⁸⁾.

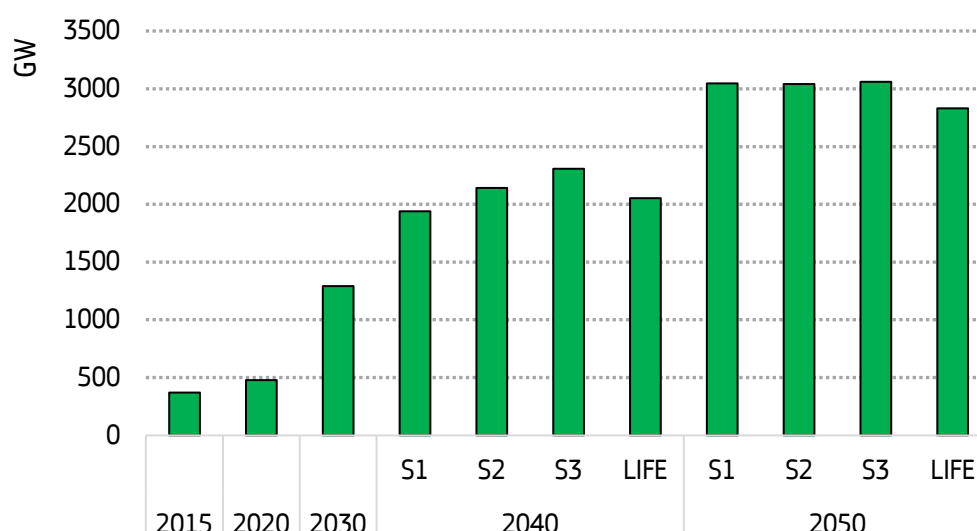
Only a limited use of CCS for power generation is projected in the considered scenarios. In 2030, there is only a small amount of CCS-equipped installed capacity which increases to 10-20 GW in 2040 in S1-S2-S3 and 30 GW in 2050 in the S2 scenario.

The difference in the scenarios for total installed capacity results from the higher electricity consumption in the S3 scenario. The difference to S1 in total installed capacity is 345 GW, which is covered by higher renewable capacity deployment.

Net installed renewable capacity increases dramatically by a factor of 4 to 5 between 2020 and 2040 (see Figure 22).

⁽⁵⁸⁾ The installed nuclear capacity is mostly exogenous based on the NECPs submitted in 2019 and modifications based on discussions with Member States, which however reflect the status only until March 2023. In June 2023, France has adopted a law which removes the objective of reducing the share of nuclear power in the electricity mix. Additional 3.3 GWe capacity was officially announced for deployment by mid-2030s. . See the box in 6.2.1 of the main Impact Assessment and the assumptions in Annex 6. Forthcoming analysis will take the revised policies into account, as reflected in the updated National Energy and Climate Plans which are currently being drafted. See Annex 8 for more details.

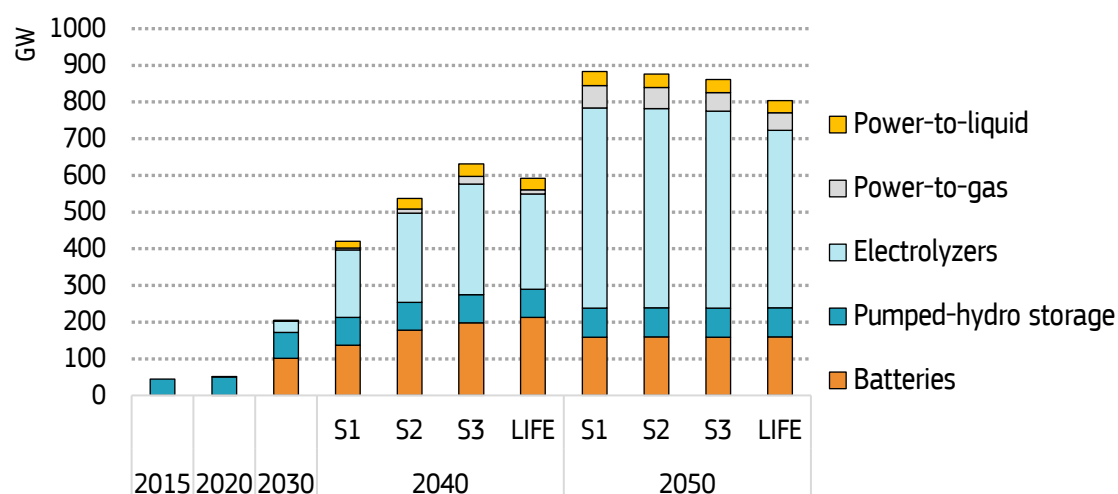
Figure 22: Net installed renewable capacity, 2015-2050



Source: PRIMES.

The increasingly high share of variable renewable electricity generation will increase flexibility requirements. These flexibility needs will increasingly be addressed by new flexibility technologies and storage solutions. Regarding the latter, pumped hydro storage and increasingly batteries will allow to store electricity when demand does not match supply. Albeit not the main driver, electrolyzers may also provide some form of storage in the form of power-to-power. Total capacity from technologies that may provide such storage solutions is multiplied by 10 (from 50 to 350-530 GW) between 2020 and 2040 in the S1-S2-S3 (see Figure 23). Pumped-hydro storage capacity is projected to grow from 50 GW in 2020 to 75 GW in 2040. Deployment of battery storage is projected to accelerate after 2030, from 100 GW to 135-200 GW in S1-S2-S3 in 2040 enabling mostly the daily and weekly storage of electricity. Electrolyser capacity increases from 30 GW in 2030 to 185-300 GW in 2040. The measures accompanying LIFE reduce the need for flexibility, in particular of electrolyser capacity. Comparing the 2040 scenarios, the increased deployment of renewables in S3 results in an additional 180 GW of installed storage technologies in comparison to S1. Between 2040 and 2050, batteries and pumped storage are projected to remain relatively stable, while electrolyzers show additional growth (from 300 to 535 GW).

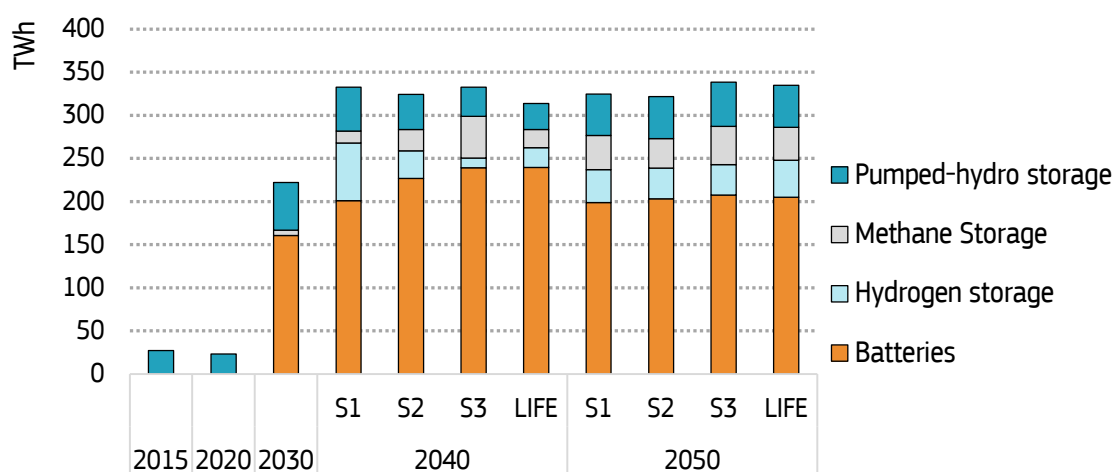
Figure 23: Net installed storage and new fuels production capacity, 2015-2050



Power-to-X technologies provide additional flexibility in the future by adjusting production levels to match the pattern of intermittent electricity generation. Installed power-to-gas and power-to-liquid capacities remain relatively low amounting to 5-20 GW and 20-35 GW, respectively, by 2040. Power-to-X capacity further increases from 55 GW in 2040 to 85 GW in 2050.

Electricity is stored in the form of direct electricity storage (via pumped-hydro storage or batteries) and chemical storage (via hydrogen or clean gas). Figure 24 shows the stored energy across scenarios. Storage needs are currently met by pumped hydro storage and increasingly batteries. The electricity stored in pumped hydro is projected to grow from 25 TWh in 2020 to 35-50 TWh in 2040. Batteries are expected to surpass pumped hydro storage as the main source of providing storage between 2025 and 2030, reaching 160 TWh in 2030. By 2040, electricity stored in electrolyzers (10-70 TWh) plays a minor role in providing storage to the electricity system than that stored in batteries (200-240 TWh), as the available electrolyser capacity to produce hydrogen (see Figure 23) will be used in sectors other than the power sector. In 2040, methane storage, i.e., clean gas, will play a minor role covering 4-15% of stored electricity in S1-S2-S3. The measures of LIFE are projected to result in a slight reduction in stored electricity in 2040. The four scenarios result in different compositions of stored electricity by technology. Methane storage displays a crucial uptake in S3 where it reaches 50 TWh or 15% of all stored electricity in 2040. The lower use of methane storage in S1 is compensated by hydrogen, which covers 20% of the total stored electricity, in contrast to S3, where it only accounts for 4%. Until 2050, batteries remain the dominant electricity storage covering 63% of all stored electricity. The amount of total stored electricity remains stable between 2040 and 2050 despite the uptake of renewables in the electricity mix.

Figure 24: Stored energy by technology, 2015-2050

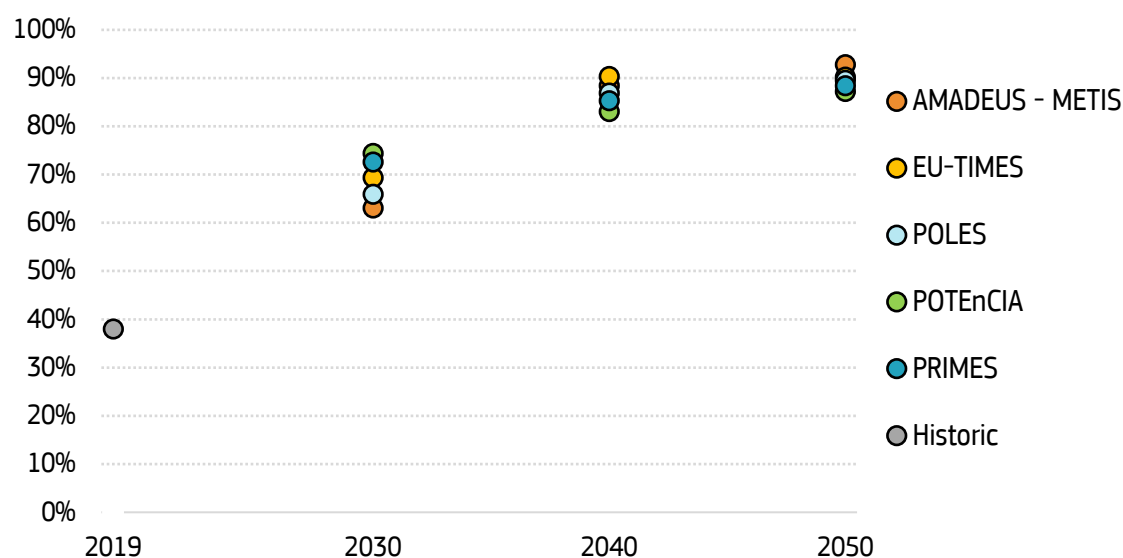


Source: PRIMES.

The five models used for this impact assessment show a high degree of similarity in the trajectory of the share of renewables in gross electricity generation, which increases quite steeply over the course of this decade to fulfil the Renewable Energy Directive and then at slower pace over the rest of the time horizon. Figure 25 shows the share of renewables in gross electricity generation across models. Four out of five models reach a renewable share in gross electricity generation around 85% in 2040, while one already achieves

90% by then. Then, in 2050 all five models identify that the share of renewables reaches around 90% (87-93%) to achieve the 2050 climate neutrality objective.

Figure 25: Share of renewables in gross electricity generation, 2019-2050



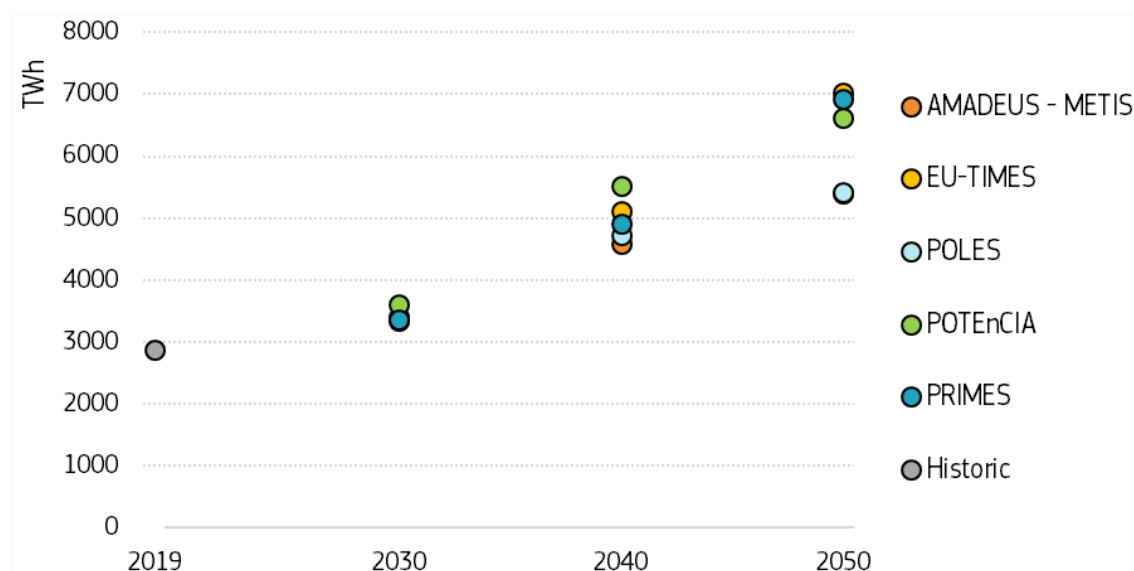
Note: renewables include solar PV, wind, hydro, concentration solar power, biomass, geothermal, tidal and marine.

Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

It is worth noting that while the share of renewables is very similar across the five models, the renewable electricity generation in absolute terms shows a large variation. While all models feature an increase in renewable electricity generation over time, that is more pronounced in PRIMES, POTEnCIA and EU-TIMES – which feature a very similar trajectory – than in POLES and AMADEUS-METIS.

Projections for electricity generation across models show more variability as shown in Figure 26. This happens because energy models have more degrees of freedom in computing indicators such as electricity generation (compared to indicators such as GAE that is constrained by assumptions on economic activity and by emissions reduction targets). For example, in 2040 the POTEnCIA model projects 13% more electricity generation than PRIMES, which is largely due to a higher number of heat pumps deployed by the former model. On the other hand, PRIMES deploys significantly more RFNBOs than POTEnCIA in 2040 and 2050, which results in higher electricity generation in 2050 in PRIMES. POLES and AMADEUS-METIS show the lowest level of electricity production throughout the time horizon and particularly in 2050. This is mainly due to the fact that these models feature the smallest deployment of DAC and the smallest production of e-fuels. Overall, these results highlight the fact that different technology pathways are possible to reach the 2050 carbon neutrality target, which entail different levels of gross electricity generation.

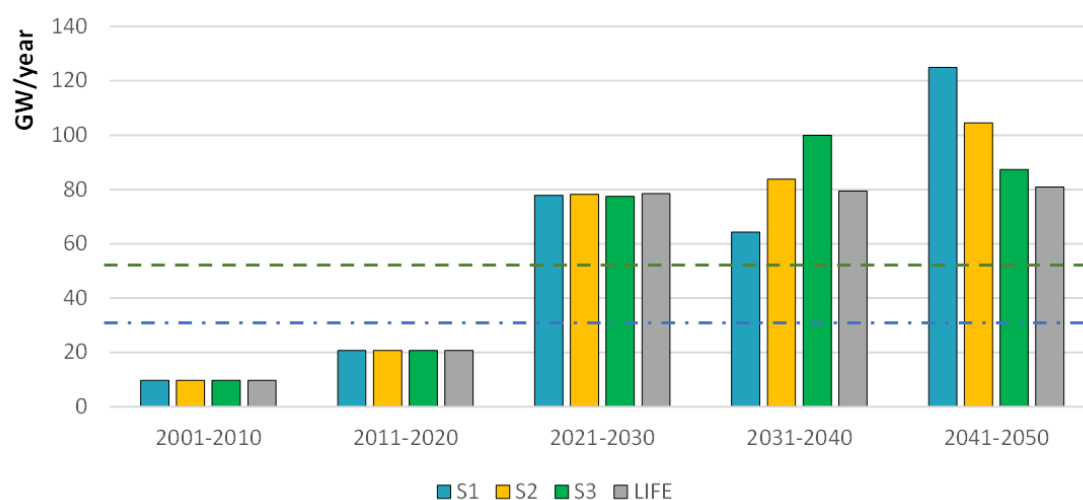
Figure 26: Gross electricity generation in different energy models, 2019-2050



Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

Figure 27 compares annual deployment of wind and PV in different scenarios to the average of recent years (2016-2050, blue line) and to the maximum value reached in 2022 (green line).

Figure 27: Average annual deployment of wind and PV



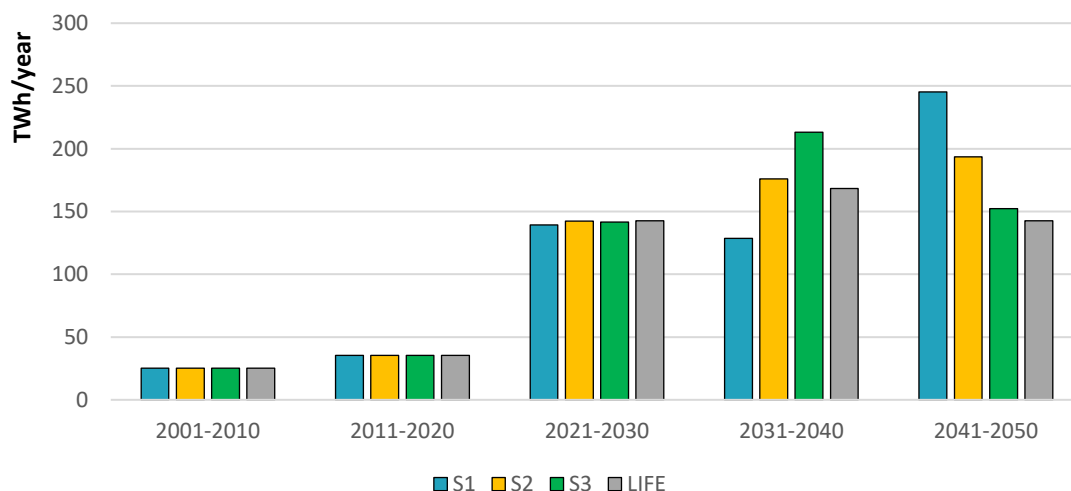
Note: Blue line: average 2016-2020; Green line: max historical deployment (occurred in 2022).

Source: PRIMES

The pace of the energy transition will increase in the 2031- 2040 decade, both compared to recent year and (especially in some scenarios) to the projections for 2030. Some patterns emerge across scenarios. The effort in the S1 scenario in the decade between 2030 and 2040 is comparable or slightly lower to that required to reach the 2030 target. However, in the 2041 – 2050 decade, the effort in S1 is significantly higher than in the other scenario (see Figure 28).

On the contrary the S3 scenario anticipates decarbonisation in the years 2031-2040 with lower effort required up to 2050. The S2 scenario lies in between S1 and S3. These trends are repeated for several other key indicators and is particularly noticeable when considering the annual increase in renewable power generation required to electrify the energy system (see Figure 28).

Figure 28: Average change in renewable power generation



Source: PRIMES

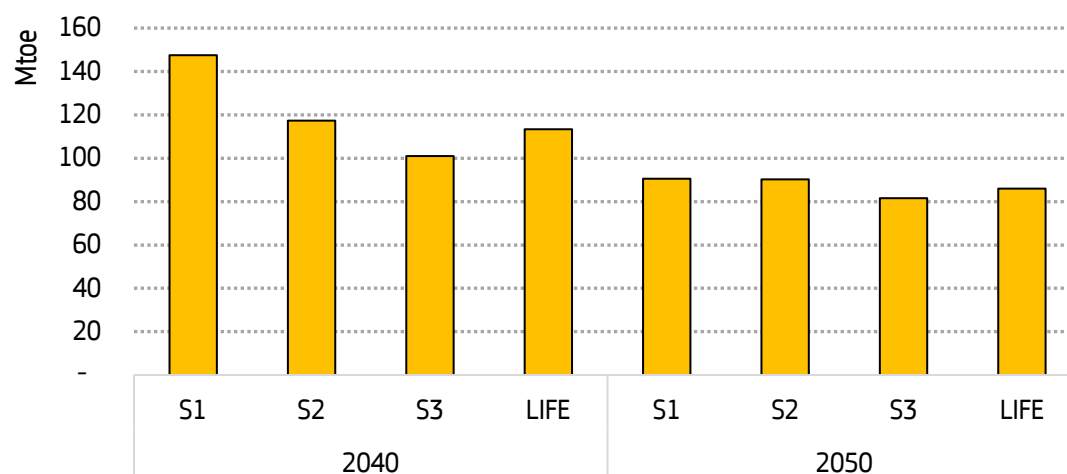
The combined needs of carbon capture, RFNBOs and electrification of final demand will require a very rapid increase in power generation. The rate of change up to 2040 is extreme in the S3 scenario. On the contrary, S1 requires the largest increase by far up to 2050. In this respect the S2 scenario shows a safer trajectory with an effort better balanced between the decades 2031 – 2040 and 2041 – 2050. Notably, LIFE allows to contain the needs for decarbonised power compared to the other scenarios.

1.2.3. Gaseous fuels

The RepowerEU Plan aims at rapidly reducing Europe's dependence on Russian fossil fuels by fast-forwarding the clean transition and achieve a more resilient energy system. REPowerEU builds on the full implementation of the Fit-for-55 package, but the fast phasing-out of fossil fuel imports from Russia affects the transition trajectory – and how we reach the EU climate neutrality target – compared to previous assumptions. The EU's consumption of natural gas is expected to reduce at a faster pace than expected before the crisis (*e.g.*, in the Climate Target Plan 2030).

Consumption of gaseous fuels is expected to decrease by between 54% and 68% between 2020 and 2040, reducing from 319 Mtoe in 2020 to 100 to 150 Mtoe in 2040 in S1-S2-S3 (Figure 29). The impact of the LIFE measures is projected to slightly increase the overall consumption of gas. The consumption of gaseous fuels amounts to 100 Mtoe in the S3 scenario. By 2050, gas consumption in the EU is further declines to around 80 Mtoe.

Figure 29: Consumption of gaseous fuels in the gas network, 2040-2050

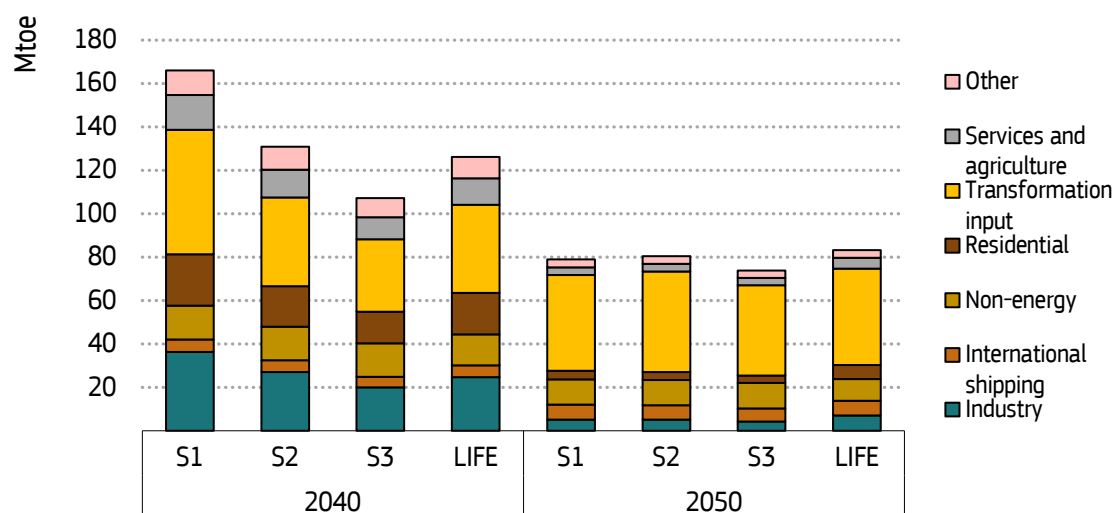


Note: the consumption of gaseous fuels hereby represented refers to gas consumed as transformation input in thermal power stations and district heating plants, consumption of the energy branch, and gas available for final consumption (including final non-energy consumption). It includes natural gas, clean gas and biomethane. Biogas is not covered in this figure and related analysis as it is not injected in the gas network.

Source: PRIMES.

In the gas network, this decrease in the consumption of natural gas is partly compensated by an increase in the consumption of biomethane. The sector with the largest absolute decrease in consumption of gas in the gas networks by 2040 is the residential sector, with -55 Mtoe (-70%) to -64 Mtoe (-82%) between 2020 and 2040. European energy policies encourage building renovation and energy efficiency improvements in the residential and commercial sector reducing the need for heating fuel.

Figure 30: Consumption of gaseous fuels by sector, 2040-2050



Note: Gaseous fuels include natural gas, biogas and biomethane.

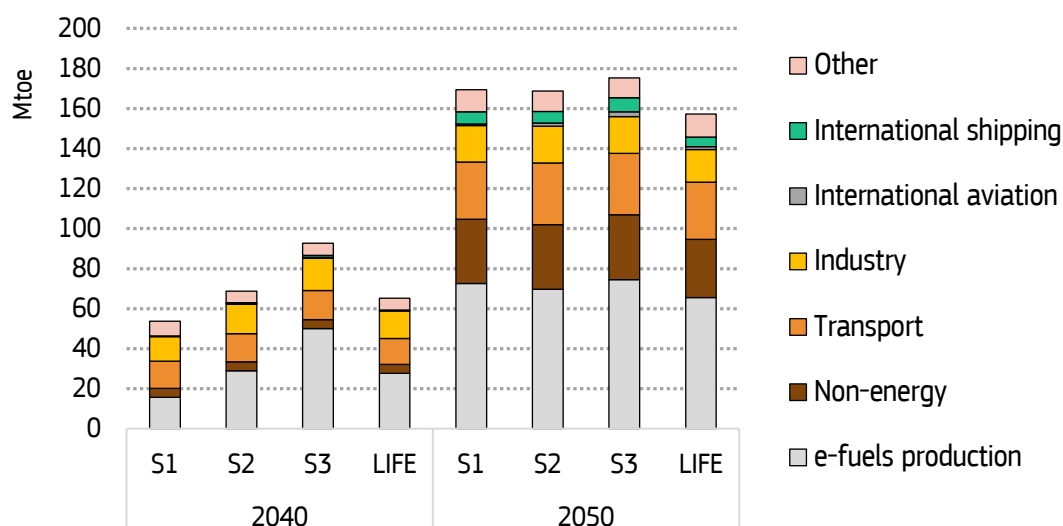
Source: PRIMES.

Consumption of gaseous fuels per sector differs across scenarios in 2040, with notable differences for some sectors. At this time horizon, gas consumption in the industrial sector is higher in S1 compared to S3 (35 Mtoe versus 20 Mtoe). In the residential sector,

consumption is also significantly higher in S1 compared to S3 (25 Mtoe versus 15 Mtoe) as well as in agriculture and services (15 Mtoe versus 10 Mtoe).

Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 reflect the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024. The consumption of hydrogen as energy vector beyond traditional applications (like the chemical sector and refineries) appears in the EU energy system and contributes to decarbonise the hard-to-abate sectors and to support the operation of the power sector with high shares of variable renewable energies providing seasonal storage. In this decade, the consumption of hydrogen remains limited (see Figure 31), both because hydrogen-based technologies are generally characterised by relatively low maturity level and because the models prioritise the decarbonisation of sectors characterised by lower marginal abatement costs. Hydrogen consumption rapidly scales up, achieving in 2040 55-95 Mtoe in the S1-S2-S3 scenarios. The production of e-fuels (both gaseous and liquid) accounts for the lion's share of total hydrogen consumption in 2040, followed by industry and – very closely – transport (in the S1, in 2040 the consumption of hydrogen in transport is higher than in industry). These three sectors alone account for more than three-fourths of total hydrogen consumption in 2040 in all scenarios. As a large deployment of e-fuels occurs in S3, this scenario experiences the highest level of hydrogen consumption in 2040 (*i.e.*, about 95 Mtoe) and is characterised by a tremendous growth in hydrogen use in the next decade. The main driver of the higher hydrogen consumption in the S3 scenario is the production of e-fuels, which consumes by itself around 50 Mtoe of hydrogen. In 2050, the consumption of hydrogen doubles with respect to 2040, attaining about 170-175 Mtoe in the S1-S2-S3 scenarios. LIFE measures would reduce the production of hydrogen by around 15 Mtoe. In 2050, the production of e-fuels continues being the main driver of hydrogen use in the EU energy system (70-75 Mtoe across scenarios), followed by non-energy uses (about 30 Mtoe across scenarios), then very closely followed by transport (about 30 Mtoe across scenarios) and finally by industry (20 Mtoe across scenarios).

Figure 31: Consumption of hydrogen by sector, 2040-2050

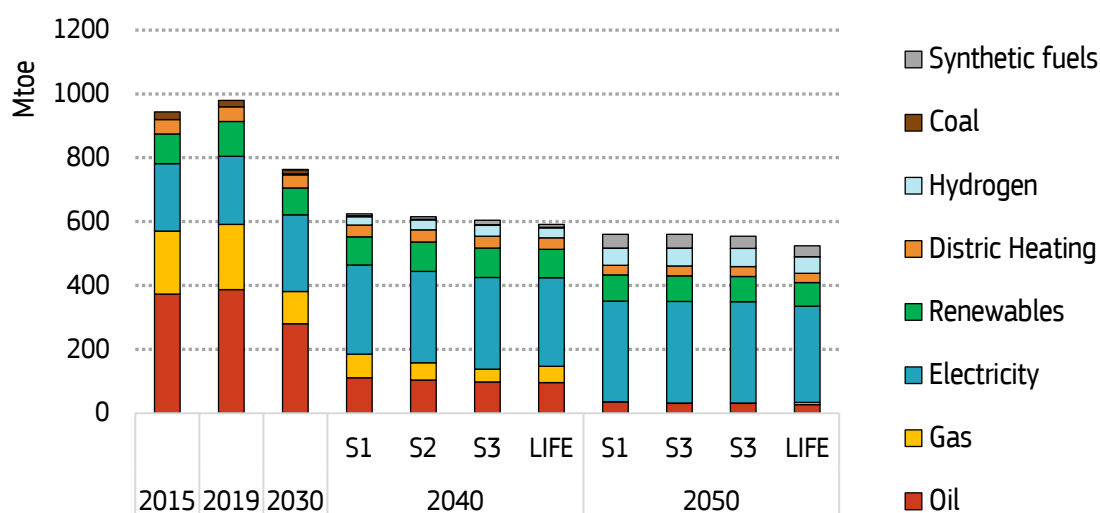


Source: PRIMES.

1.2.4. Final Energy Consumption

Final Energy Consumption (FEC) declines steadily, attaining in 2030 the 763 Mtoe targeted by the Energy Efficiency Directive (Figure 32). Then, FEC further reduces to 606-624 Mtoe in the S1-S2-S3 and scenarios. LIFE measures are projected to reduce FEC by additional 12 Mtoe. In 2050, FEC reaches approximately 560 Mtoe. The fuel and sector split of total FEC also changes progressively and the sector-specific drivers and dynamics are described in the relevant sections (Sections 1.3, 1.4 and 1.5).

Figure 32: Final Energy Consumption by fuel, 2015-2050



Source: PRIMES.

The share of fossil fuels in total FEC decreases from above 60% in 2019 to 52% in 2030, between 23% and 30% in 2040 under the various scenarios and 6% in 2050. Coal FEC becomes very small in 2030 and disappears shortly after 2040, driven by phase out in buildings after 2030 (pushed by the policies of several Member States) and by significant reductions in industry after 2030. Encouraged by the gradually more stringent CO₂

emission standards, oil FEC in 2030 reduces by 28% (108 Mtoe) compared to 2019 levels. After 2035, the reduction in oil FEC accelerates in light of the CO₂ emissions standards mandating sales of zero-emission vehicles only: in 2040, oil FEC attains approximately 100-110 Mtoe in the S1-S2-S3 scenarios. Natural gas FEC gradually reduces to only small quantities by 2040⁽⁵⁹⁾. That is mainly due to improved energy performances of the building stock and to fuel switching towards mainly electricity in the building sector and hydrogen and electricity in the industrial sector. Natural gas FEC differs significantly in the S1 and S3 scenarios compared to the S2 scenario (-27% in S1 compared to S3 and -46% for S3), as the three scenarios are underpinned by different renovation rates (see section 1.3.2) and fuel switching to hydrogen and e-fuels. The share of renewable energy in gross FEC increases from 42.5% in 2030 (in line with the Renewable Energy Directive target) to between 65% and 75% in 2040 (with the S3 scenario requiring 10% more renewable energy than S1).

The contribution of electricity in FEC increases across all scenarios, and electricity becomes the dominating energy vector in final energy sectors. From 23% in 2015, the share of electricity in final demand increases to more than 30% in 2030 (240 Mtoe), to above 45% in 2040 across scenarios (280-290 Mtoe). The measures in LIFE reduce the need for electricity in FEC by 9 Mtoe. In 2050, it reaches 57% (320 Mtoe). Such increase is mainly driven by the uptake of electric vehicles in the transport sector, the penetration of heat pumps in buildings and electrification of low and medium temperature industrial processes.

Fossil fuels are also partially replaced by hydrogen and other RFNBOs, whose uptake only scales up at the end of this decade. Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 reflect the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024.

Combined, RFNBOs account for 1% of total FEC in 2030 (5 Mtoe), 5-12% in 2040 (about 30-65 Mtoe) and 20% in 2050 (105 Mtoe). Measures from LIFE in 2040 have only a limited impact on the FEC of RFNBOs. Hydrogen is mostly consumed by heavy-duty trucks and in energy intensive industrial processes that can be hardly electrified. Gaseous e-fuels are consumed in almost equal proportions by the industrial sector and by the residential sector, and in lower amounts in the services sector as well. Liquid e-fuels are consumed entirely in the transport sector. Under the S3 scenario, the decline of FEC of oil and natural gas accelerates and in 2040 fossil fuels only account for approximately 23% of total FEC. This acceleration is driven by the need to rapidly reduce emissions in industry, buildings and transport sectors, which should get to almost net zero in early 2040s.

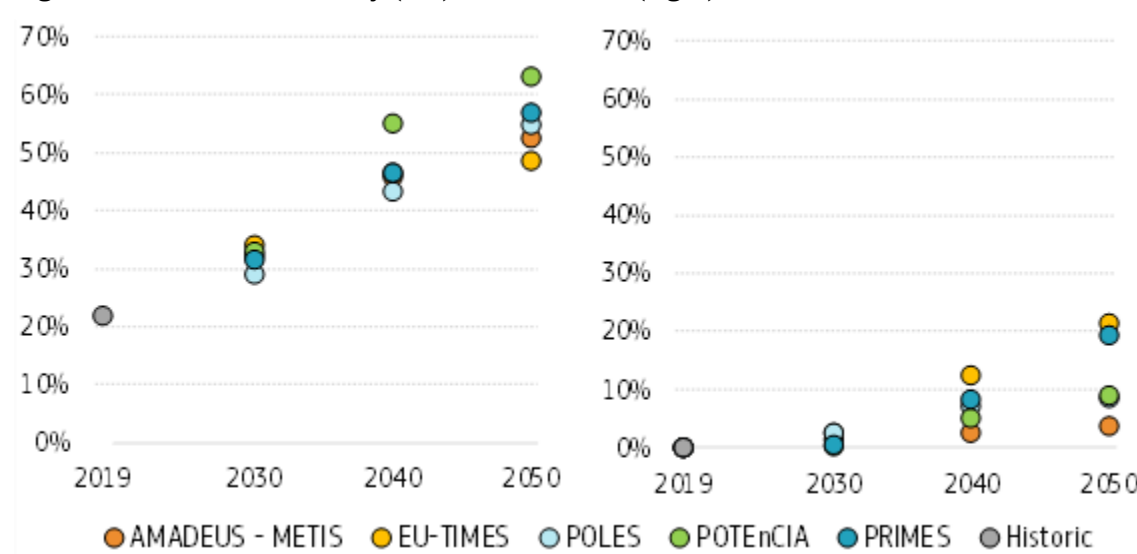
All five energy system models used in this impact assessment project a major increase in the contribution of electricity in total FEC, with high similarity in the overall trend in four of the five models (see Figure 33). In particular, POTEnCIA features a higher level of electrification than the other models from 2035 onwards: in 2040, it reaches 55% share

⁽⁵⁹⁾ Natural gas is still used as feedstock for the industry after 2040.

of electricity in FEC compared to 43-46% in the other models and in 2050 it reaches 63% compared to 49-57%. The higher electrification rate in POTEnCIA is mainly explained by POTEnCIA's technology choices in the transport and residential sectors, i.e., POTEnCIA features a larger adoption of heat pumps in buildings and higher roll-out of electric vehicles.

Regarding the share of RFNBOs in total FEC, the different models show a larger variability in the results, especially after 2035. In 2030, all five models see the contribution of RFNBOs to total FEC at below 3%. Afterwards, a larger degree of variability emerges in the results, with EU-TIMES showing the largest uptake – at 912 in 2040 and 21% in 2050 - and AMADEUS-METIS the smallest one – 3% in 2040 and 4% in 2050. This suggests that while electrification of end-use sectors is broadly considered a robust pathway for the decarbonisation of the EU energy system, there is more uncertainty on the actual role that RFNBOs are going to play.

Figure 33: Share of electricity (left) and RFNBOs (right) in FEC, 2019-2050



Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

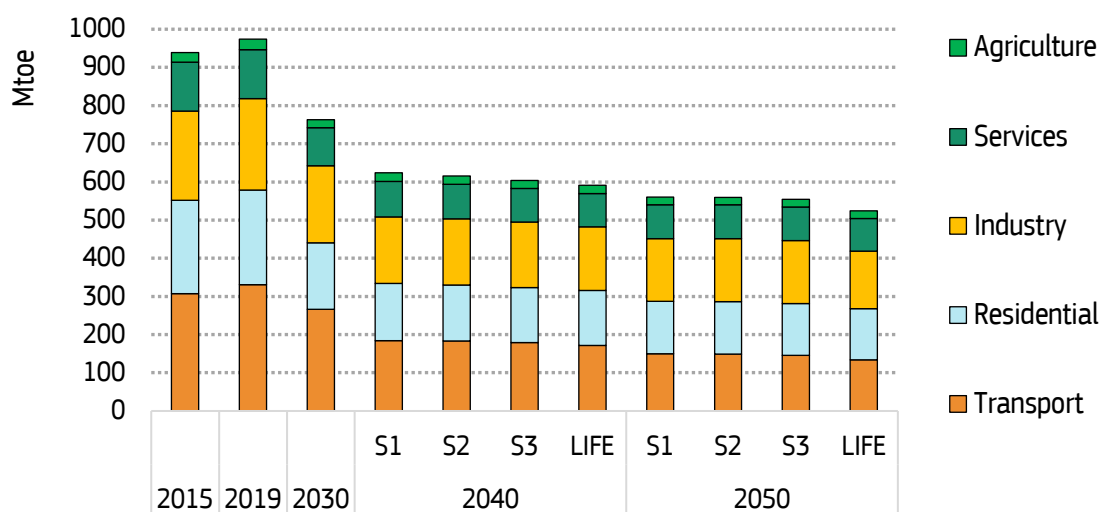
FEC of district heating and renewable heating (solar thermal, biomass and geothermal) in PRIMES slightly reduces over the time horizon, mainly due to better energy performances of the building stock, without particular variations across scenarios. The reduction of renewables FEC is lower than that of total FEC. As a result, the share of renewable heating in total FEC grows from 10% in 2015 to about 15% in 2040 and 2050.

Among the end-use sectors, the residential sector is expected to experience the largest reduction in energy consumption in this decade with almost -30% in 2030 (175 Mtoe) with respect to 2015, triggered by dedicated policies and measures (Figure 34). The residential sector is projected to further reduce its energy consumption by 39-41% under the S1-S2-S3 scenarios (around 140-150 Mtoe), up to reducing by 44% in 2050 (140 Mtoe). The measures of LIFE only have a minor impact.

Transport FEC undergoes a markedly different trajectory: the reduction with respect to 2015 is limited to -13% by 2030 (about 270 Mtoe), but afterwards it experiences a steep reduction to reach -42% in 2040 (about 180 Mtoe) across all scenarios and -53% in 2050 (about 150 Mtoe) – the largest reductions across end-use sectors. Such dynamics is largely explained by the CO2 emission standards, which are gradually tightening until

2030 and then from 2035 mandate sales of zero-emission vehicles only (See Section 1.5.3 for more details). The impact of LIFE further reduces FEC in transport by 9 Mtoe in 2040. FEC in services and agriculture combined reduces at slower pace than in the residential sector, attaining -21% in 2030 (about 120 Mtoe) with respect to 2015; -25, -29% under the S1-S2-S3 scenarios, and -29% in 2050 (about 110 Mtoe). Finally, industry undergoes the smallest reduction in FEC of all end-use sectors throughout the time horizon, with -13% in 2030 with respect to 2015 (about 200 Mtoe), -27% in 2030 (about 170 Mtoe) and -39% in 2050 (about 165 Mtoe). Such dynamics are mainly due to the fact activity grows significantly in many energy-intensive sectors. Nevertheless, circular economy measures, as well as material, resource and energy efficiency are able to partially offset the economic growth and still lead to a FEC reduction in the sector (see Section 1.4.2 and 1.4.3 for more details).

Figure 34: FEC by sector, 2015-2050



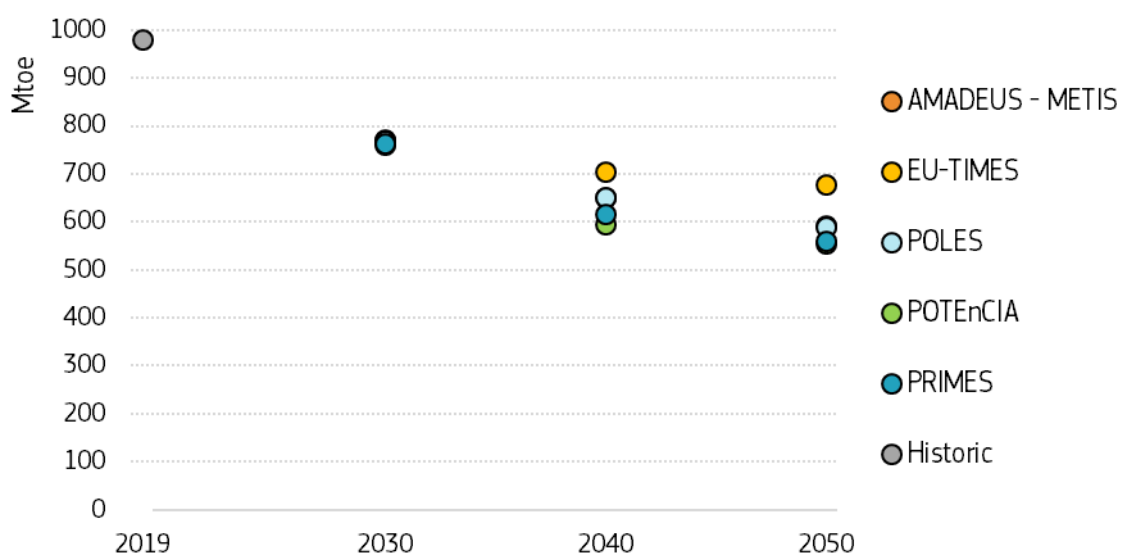
Source: PRIMES.

The above-mentioned sectoral dynamics lead to a different sectoral composition of FEC, with industry and agriculture and services becoming relatively more important over time, while residential and transport are declining.

The different scenario assumptions in the S1-S2-S3 scenarios have a somehow limited effect on energy consumption by sector. For each sector considered, the differences between scenarios are limited to approximately 5%.

Figure 35 compares projections for Final Energy Consumption from different energy system models and finds good alignment between them. In 2030, all models fulfil the target of the Energy Efficiency Directive, but different trends can be appreciated afterwards. EU-TIMES in particular features the slowest pace of reduction in total FEC: its total FEC is 14% and 21% higher than PRIMES's total FEC in 2040 and 2050 respectively. EU-TIMES' higher FEC than other models is largely explained by the fact that it features the lowest degree of electrification of end-use sectors and the highest reliance on RFNBOs (see also Figure 33). Results from the PRIMES and POTEnCIA models are very close throughout the time horizon (with a maximum difference below 4% over the 2035 – 2050 period).

Figure 35: Total FEC from different energy models, 2019-2050



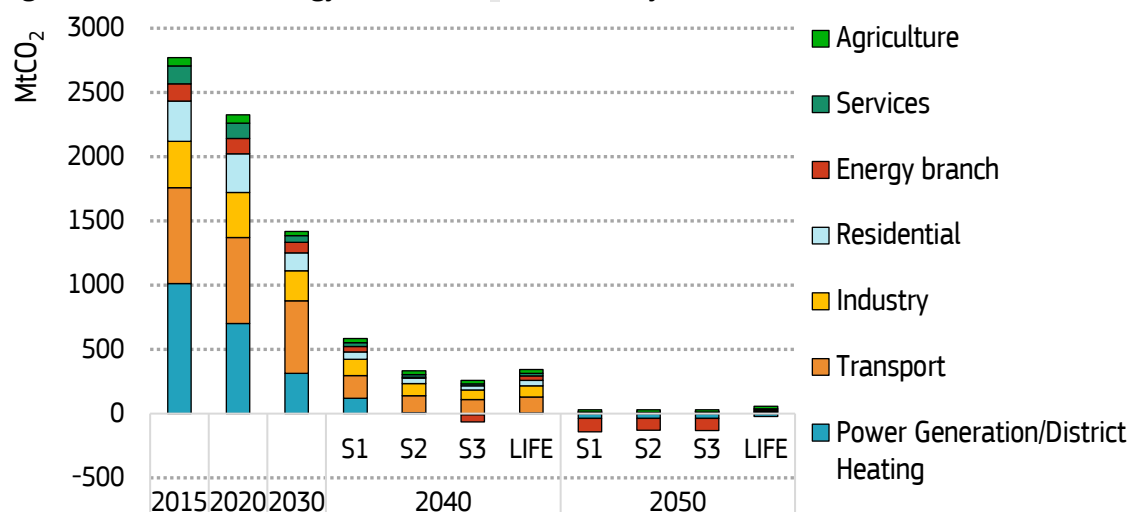
Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES

1.2.5. Energy related CO₂ emissions

Figure 36 illustrates the energy-related CO₂ emissions profile over the modelling time horizon for the main energy sectors and for all the scenarios assessed. Achieving the climate neutrality objective in 2050 requires energy-related CO₂ emissions in 2040 to be in the range of 200-590 MtCO₂ across scenarios. This is equivalent to a reduction in CO₂ emissions with respect to 1990 in the range of 83-94%.

Historically, the power generation and district heating sectors were the largest emitter of CO₂ from combustion processes. With about 1 010 MtCO₂ emitted in 2015, it accounted for 37% of all energy-related CO₂ emissions. However, the power generation and district heating sectors reduce CO₂ emissions at the fastest pace across the energy system and are the first achieving net-zero emissions. This result is in line with the findings of the public consultation on the EU climate targets for 2040, where respondents have most frequently identified “power generation and district heating” as the first sector to achieve climate neutrality. In 2040, less than 10 MtCO₂ are emitted from these sectors in the S2 scenario (99% reduction with respect to 1990) and under the S3 scenario negative emissions are achieved (thanks to BECCS) shortly before 2040. In 2050, these sectors become a negative emitter in all the scenarios analysed, with 30-40 MtCO₂ of negative emissions, thus partially offsetting residual emissions from the other sectors. The relatively fast pace in CO₂ emission reductions from the power generation and district heating sectors is explained by the stringency of the emission reduction target and the availability of a broad set of technologies to generate carbon-free electricity backed by proven storage technologies. The reductions in energy-related emissions for the other energy sectors is discussed in dedicated sectoral sections.

Figure 36: Domestic energy-related CO₂ emissions by sector, 2015-2050

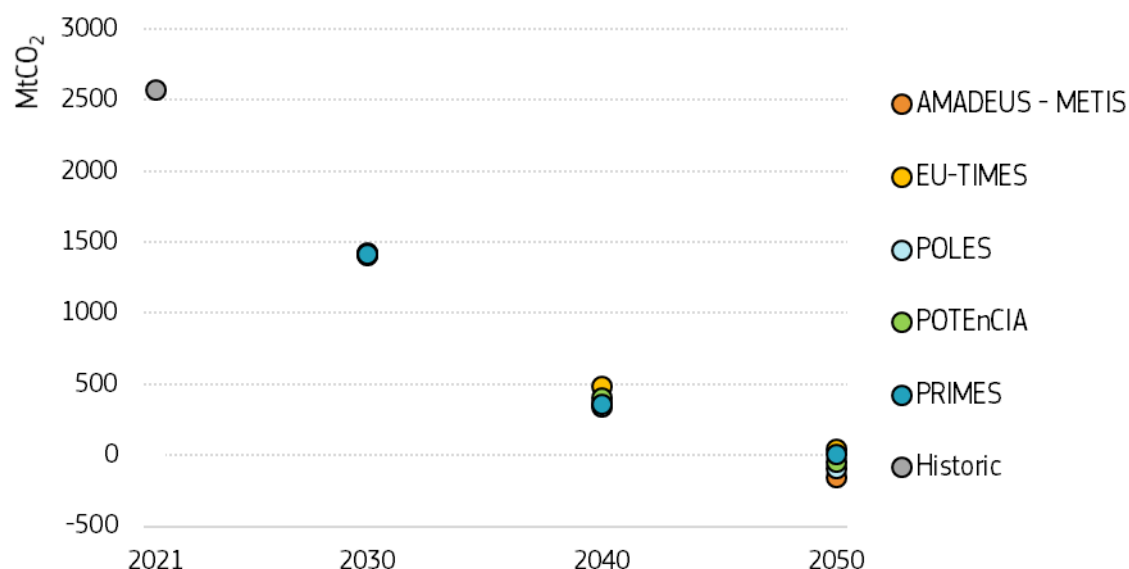


Note: the transport sector covers road, rail, inland navigation, domestic aviation and other transport.

Source: PRIMES.

The energy-related CO₂ emission reduction trajectory is very similar in the S2 scenario across the energy models used in this impact assessment. Overall, there is good agreement among the five energy models in identifying that energy-related CO₂ emissions in 2040 should reduce between 86% and 90% compared to 1990 (Figure 37). The AMADEUS-METIS model attains the largest CO₂ emission reductions in 2050 and EU-TIMES is the least ambitious model. In 2050, three models (i.e., AMADEUS-METIS, POLES and POTEnCIA) attain negative energy-related CO₂ emissions, while the other two models achieve almost net-zero emissions.

Figure 37: Comparison of domestic energy-related CO₂ emissions, 2021-2050



Note: the figures for the five energy models refer to the S2 scenario.

Sources: AMADEUS-METIS, EU-TIMES, POLES, POTEnCIA, PRIMES.

1.2.6. Raw materials' needs

The manufacturing and deployment of net-zero technologies will increase the needs for Critical Raw Materials (CRMs). With the scenario S3, the deployment of five net-zero technologies (wind turbines, solar PV, batteries, electrolyzers and heat pumps) in the decade 2031-2040 would imply the need of up to 500 000 tonnes of copper each year. This compares with a global copper demand of 26 million tonnes in 2022 according to the IEA, including 370 000 tonnes for electric vehicles and 1.2 million tonnes for wind and solar. In 2030, global demand for copper could achieve 261 million tonnes in the Net Zero Emissions by 2050 scenario of the IEA ⁽⁶⁰⁾.

Wind power on its own would create needs of up to 50 000 tonnes of manganese and 125 000 tonnes of copper per year. Batteries would create needs of up to 900 000 tonnes of aluminium, 80 000 tonnes of lithium and 60 000 tonnes of cobalt per year. Solar PV would also create needs of gallium (50 tonnes per year) and germanium (3 000 tonnes per year). Raw materials' needs would be lower in scenarios S1 and S2, as in 2040, net installed renewable power capacity is lower by 7% in S2 and by 16% in S1 compared with S3. As regards batteries though, deployment is relatively comparable in S1, S2 and S3, as battery capacity in 2040 is lower by only 1% in S2, and by 2.6% in S1 compared with S3. As a comparison, global lithium demand in 2022 was 130 000 tonnes, including 69 000 tonnes for electric vehicles according to the IEA. In 2030, global demand for lithium could be as high as 721 000 tonnes in the Net Zero Emissions by 2050 scenario of the IEA ⁽⁶¹⁾.

1.3. Buildings

The building sector ⁽⁶²⁾ (including the residential and services sectors) accounted for 42% of final energy consumption in the EU in 2021 ⁽⁶³⁾. The projections discussed below show that in this decade energy efficiency measures – i.e., renovating the building envelope and adopting minimum energy performance standards – is the main lever for buildings to contribute to the Fit for 55 targets in 2030. By reducing the useful energy needs, energy renovation enables to diminish the size of the heating and cooling equipment, thus reducing related capital and running costs and shielding vulnerable consumers from the impact of increasing energy prices. Fuel switching from fossils to renewable electricity for space heating is a key decarbonisation lever throughout the time horizon and is also essential to contribute to security of supply. In order to achieve climate neutrality by 2050 and to achieve significant emission reductions already in 2040, electrification in buildings needs to be intensified and – to a lower extent - accompanied by fuel switch to low-carbon gases. Besides, the push for high standard renovation must be kept beyond 2030 at higher rates than historically.

⁽⁶⁰⁾ IEA (2023), Critical Minerals Data Explorer, IEA, Paris <https://www.iea.org/data-and-statistics/data-tools/critical-minerals-data-explorer>. Accessed on 05 December 2023.

⁽⁶¹⁾ Ibid

⁽⁶²⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

⁽⁶³⁾ Eurostat, *Complete Energy Balances European Union (27 countries) – 2021*, 2023.

1.3.1. Buildings activity

In the residential sector, the total floor area of households is projected to grow by 21% and 26% respectively in 2040 and 2050 with respect to 2015. Although the European population is projected to remain quite stable in the first half of the century (less than 1% reduction in 2050 compared to 2015), the total floor area of households grows due to two concurring dynamics:

- The average number of inhabitants per household is projected to reduce over time, which tends to increase the number of dwellings.
- The average size of the houses is projected to grow, as new houses have significantly larger surfaces than the existing ones.

In the commercial and services sector, the overall floor area of the buildings is projected to slightly reduce reaching in 2040 and beyond a floor area around 5% higher than 2015. These socio-economic dynamics push up the energy consumption in building, which makes the effort to mitigate energy demand and CO₂ emissions of buildings harder.

Heating degree days (HDD) and cooling degree days (CDD) are climate-based indicators commonly used to represent buildings' space heating and cooling needs in energy system models. HDDs and CDDs in historic years are based on EUROSTAT, and projections depart from statistics considering the effect of climate change on these indicators based on the findings of climate models⁽⁶⁴⁾. Projections of HDDs and CDDs are the same across the S1-S2-S3 scenarios, where - due to rising global average temperature - in the future HDDs are assumed to reduce in all member states with respect to today. In particular, in most member states the reduction in 2050 is in the range of -3/-11% compared to 2022. Consistently, CDDs are assumed to increase in all Member States compared to today. In particular, Member States characterised by colder climates, which today do not use air conditioning or make very limited use of it, are expected to increase CDDs the most in the future in relative terms, in some cases more than tripling compared to today⁽⁶⁵⁾. LIFE assumes a decrease/increase of the thermostat setpoint for heating and cooling respectively to mimic behavioural change related to thermal comfort. The thermostat setpoint is changed gradually, reaching +/-1.5 degrees in 2040 and remaining at that level until 2050.

1.3.2. Energy efficiency in buildings

Energy efficiency in buildings consists in two main types of action. For existing buildings, it implies renovating the building envelope - in order to reduce the demand for space heating and cooling while ensuring high comfort levels – and deploying renewables and energy efficient equipment for heating, cooling, cooking and appliances.

⁽⁶⁴⁾ Dosio, A, Fischer, E.M. (2018): Will half a degree make a difference? Robust projection of indices of mean and extreme climate in Europe under 1.5°C, 2°C and 3°C global warming, *Geophysical Research Letter*, 45(2), 935-944, DOI:10.1002/2017GL076222

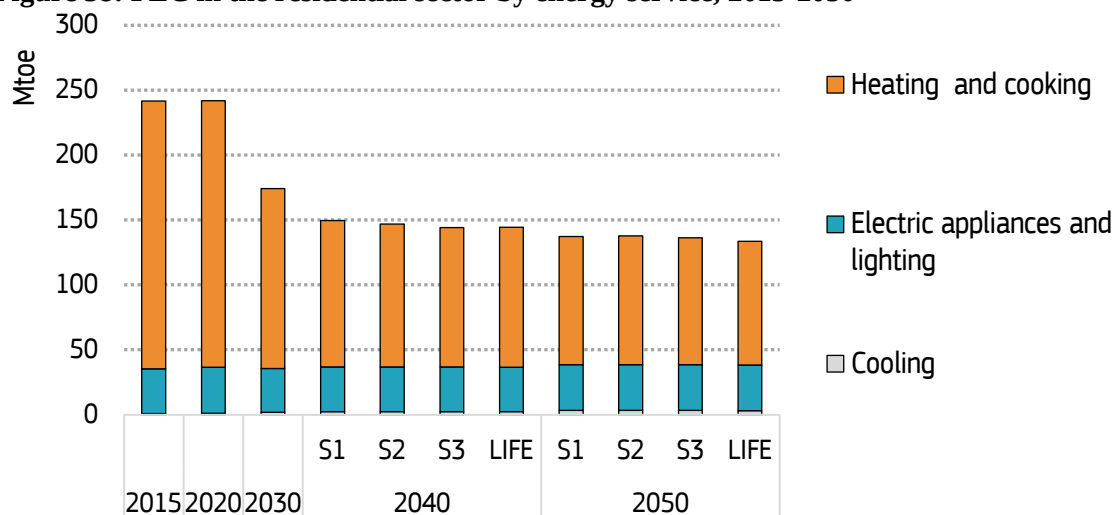
⁽⁶⁵⁾ Energy consumption associated to cooling buildings is much lower than the one associated to heating and thus a large growth in CDDs provides a limited contribution to the overall change in building energy (see Figure and Figure).

For new buildings, it implies sticking to the minimum energy performance standards, as outlined in the Energy Performance of Buildings Directive (EPBD).

The current policy context is expected to significantly reduce energy consumption in buildings already in the course of this decade. Climate neutrality by 2050 requires reductions in buildings' energy demand beyond the levels reached in 2030. Encouraged by several policy initiatives that extend their impact after 2030, as well as by possible long-term effects of current energy crisis and pressure on gas imports, energy savings in buildings reach 35-38% across scenarios in 2040 and 40% in 2050. The residential sector would contribute more than the services sector to the overall energy savings in buildings, with 29% savings in 2030 with respect to 2015 (vs 23% savings in services), 39-41% across scenarios in 2040 (27-32% savings in services) and 44% in 2050 (31% savings in services).

The most important energy use in buildings is for space heating, which in 2015 accounted for more than three-quarters of final energy consumption in buildings.

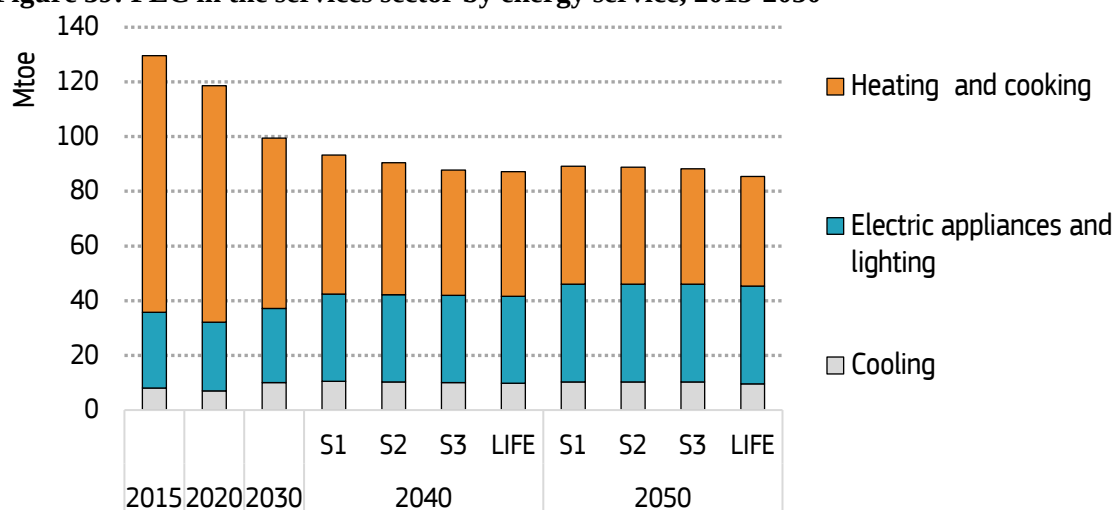
Figure 38: FEC in the residential sector by energy service, 2015-2050



Note: heating refers to both space heating and water heating.

Source: PRIMES.

Figure 39: FEC in the services sector by energy service, 2015-2050



Note: "Heating" refers to both space heating and water heating.

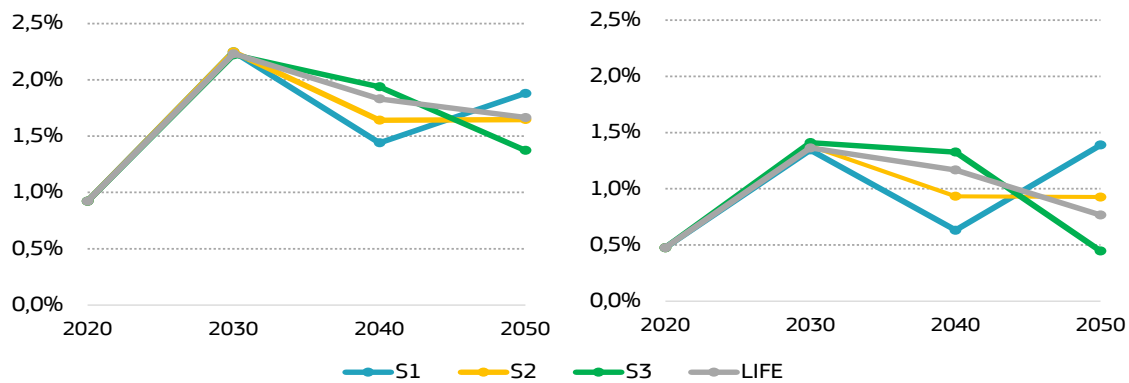
Source: PRIMES.

Final energy consumption related to heating in buildings is projected to reduce by one third in 2030 compared to 2015, by 46-47% across the S1-S2-S3 scenarios and by 51% in 2050, with almost identical dynamics in the residential and services sector ⁽⁶⁶⁾. Final energy consumption related to cooling buildings accounted for only 2% of the total in 2015, but its share is projected to double by 2040 mainly due to higher comfort needs. The final energy consumption of appliances and lighting accounted for less than 20% of total energy consumption in buildings and the dynamics of this end-use sector are outlined in detail in Section 8.1.3.4 below.

The reduction of energy demand for space heating & cooling is largely achieved via the improvement of the thermal integrity of the building envelopes via increased renovation rates of existing buildings and high energy performance standards for renovated and new buildings. Renovation rates of the building envelope increase significantly in the future compared to historically observed rates. Higher renovation rates are encouraged by existing policies (e.g., the EPBD, ETS2, Energy Efficiency Directive) and increasing material circularity, and assuming that market failures - such as access to finance and split-incentives - that currently limit renovations are addressed.

⁽⁶⁶⁾ The figures on heating include energy used for space heating, water heating and cooking, although the two latter have minor contributions.

Figure 40: Renovation rates in the residential and services sectors, 2020-2050



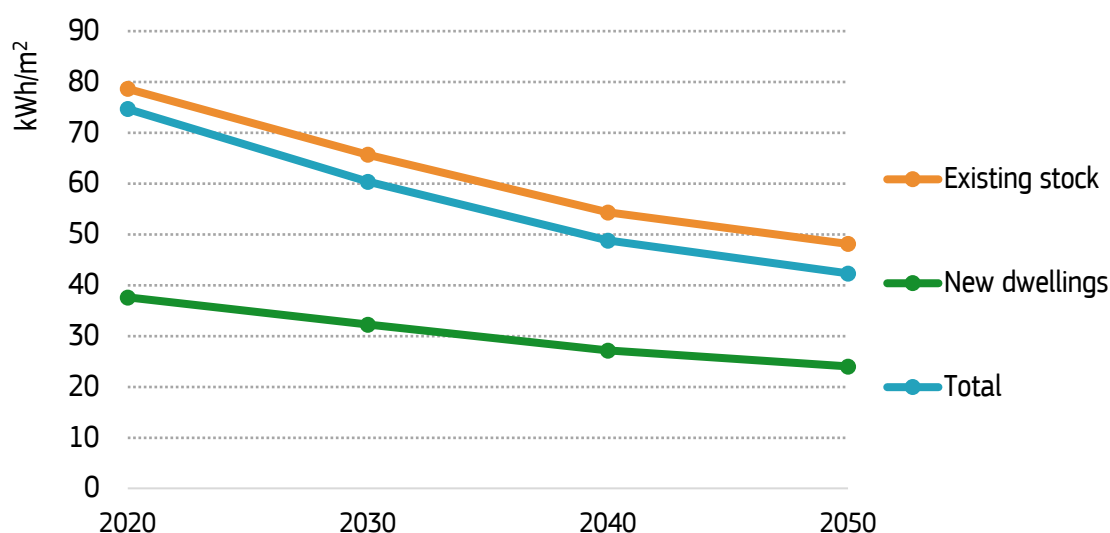
Source: PRIMES

Over the course of this decade, the residential sector doubles the building shell renovation rate, from 0.9% in 2020 to 2.2% in 2030 and 1.4% to 1.9% in 2040. The faster renovation rate of buildings than historically is in line with the findings of the public consultation on the climate target for 2040: 80% of individuals and 64% of organisations claim that the transition to climate neutrality should accelerate up to 2040. In the S3 scenario, the renovation rate in the residential sector changes to 1.6% in 2040 and then stabilises at that level. The S3 and S1 are characterised by opposite dynamics after 2030. The S3 scenario anticipates the renovation effort in the next decade (attaining 1.9% in 2040, the maximum across scenarios) and then limits the renovation in 2050 to a rate of 1.4% (the minimum level across scenarios). On the other hand, the S1 scenario after 2030 reduces substantially the renovation rate (attaining 1.4% in 2040) to then accelerate it in the 2040-2050 decade until 1.9% in 2050 (the highest level across scenarios) to compensate for missed climate action in the earlier decade. Similarly, in the services sector the renovation rate increases from 0.5% in 2020 to 0.6 to 1.3% in 2040. In the S2 scenario it gradually reduces (although at higher levels than historical) to 0.9% in 2040 and finally stabilizes at that level. The S1 and S3 scenarios show similar dynamics as in the residential sector, with the S3 anticipating the renovation effort and the S1 delaying it to the last decade of this analysis.

The renovation rates discussed above lead to 29% of the EU residential buildings fleet having been renovated in 2030, up to 40%-43% in the S1-S2-S3 scenarios) and finally to 55% in 2050. Regarding the services building fleet, 15% get renovated by 2030, 20% in the S2 scenario in 2040 (between 18% and 22% in the S1-S2-S3 scenarios) up to 32% in 2050.

The improvement of the energy performance standards and the renovation of the building fleet contribute to a gradual reduction in the average useful energy consumption for space heating (Figure 41). For new dwellings, the average useful energy for space heating at EU level will be pushed down from 36 kWh/m²/year in 2015 to 32 in 2030 (-11%), to 27 in 2040 across scenarios (-25% compared to 2015) and 24 kWh/m²/year in 2050. Existing dwellings will reduce useful energy for space heating from almost 80 kWh/m²/year in 2015 to 66 in 2030 (-14% compared to 2015), 54-57 in 2040 across scenarios (-25/29% compared to 2015) and approximately 48 kWh/m²/year in 2050 (-36% compared to 2015).

Figure 41: Average useful energy for space heating (S3)



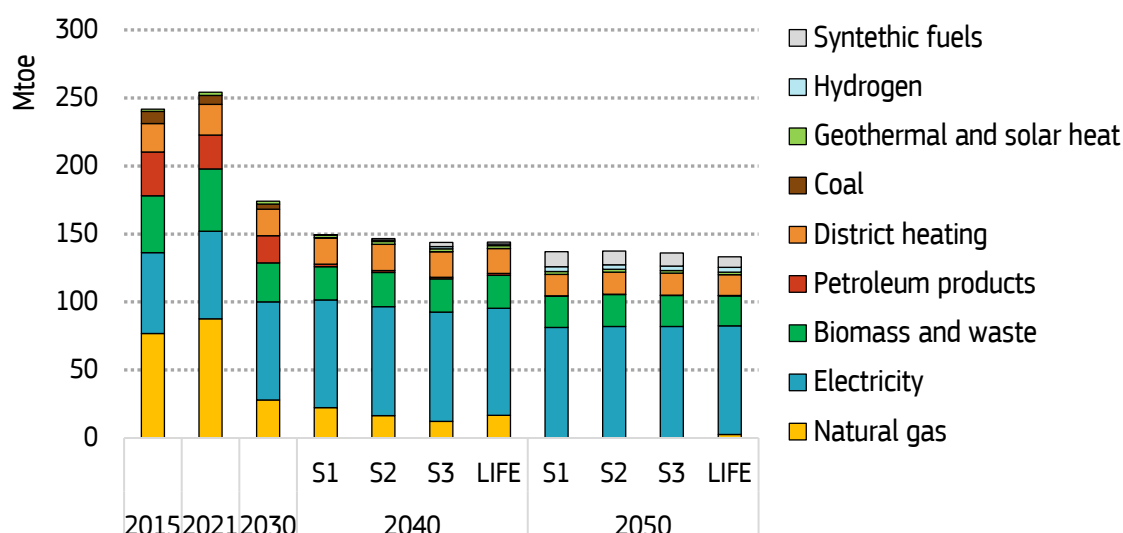
Source: PRIMES.

1.3.3. Fuel mix in buildings

The main trend related to the fuel mix that can be observed in buildings is the rapid growth of electricity consumption and the decrease of fossil fuels (notably natural gas) (see Figure 42 and Figure 43). In 2015, fossil fuels accounted for almost half of the final energy consumption in the buildings sector (about 170 Mtoe), with natural gas giving the largest contribution (about 110 Mtoe). By 2040, fossil fuels account for 9-15% under the S1-S2-S3 scenarios (20-37 Mtoe). In 2040 the consumption of oil and coal in buildings is almost entirely phased-out in all scenarios. By 2050, natural gas is phased-out from buildings as well.

Electricity becomes the backbone of the buildings sector. It increases from one-third of buildings energy demand in 2015 (about 120 Mtoe), to more than half in 2030 (140 Mtoe), up to 61-64% under the S1-S2-S3 scenarios (about 150 Mtoe) in 2040 and 67% in 2050. The electrification pattern is quite different between the residential and services sectors. In the residential sector, the share of electricity is projected to grow from one-fourth today to just above 40% in 2030, 53-56% across the S1, S2 and S3 scenarios in 2040 and up to 60% in 2050. In services, the electricity share today is already much higher: almost 50% and would increase to around two-thirds in 2030, more than 75% in all scenarios in 2040, until achieving almost 80% in 2050.

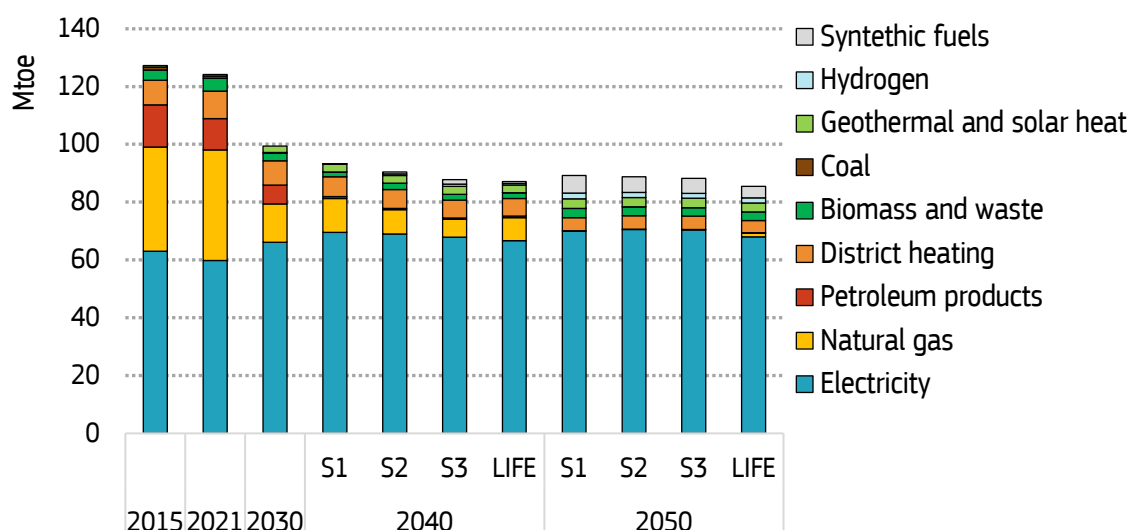
Figure 42: FEC in the residential sector, 2015-2050



Note: Biomass and waste include non-renewable waste. Ambient heat is not shown.

Source: PRIMES.

Figure 43: FEC in the services sector, 2015-2050



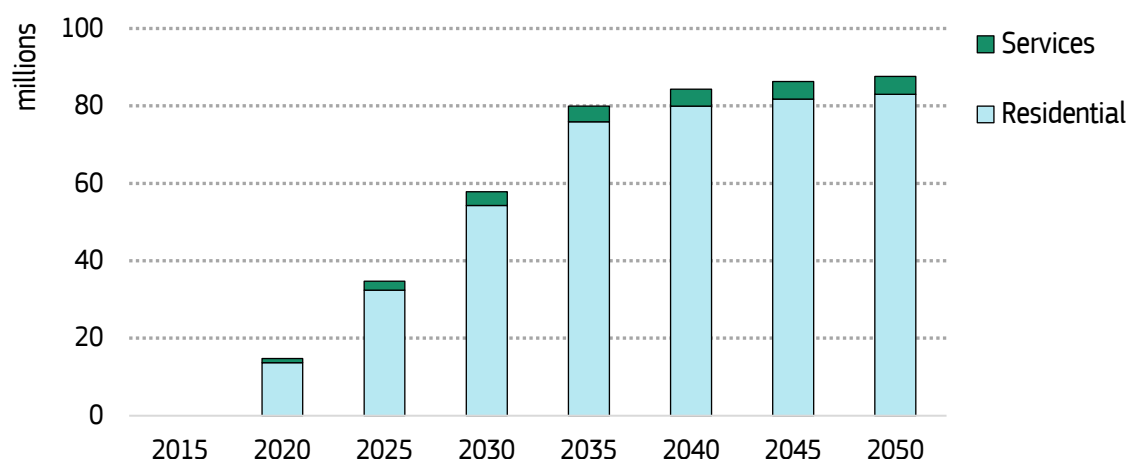
Note: Biomass and waste include non-renewable waste. Ambient heat is not shown.

Source: PRIMES.

Electrification of the buildings sector is characterised by the deployment of efficient electric heating and cooling technologies (notably heat pumps), energy efficient appliances and LED lighting. Efficiency of the electricity use in the buildings sector is well illustrated by the fact that the growing use of equipment consuming electricity is accompanied by limited growth in absolute electricity consumption: from 123 Mtoe in 2015 to almost 140 in 2030 (+12% compared to 2015), almost 150 Mtoe in 2040 across scenarios (+21% compared to 2015) and almost 155 Mtoe (+24%) in 2050.

Since space heating accounts for the lion's share of energy consumption in buildings, fuel switch in buildings' heating services is the key avenue for buildings to contribute to the carbon neutrality objective in 2050 and to curb emissions in 2040. Electrification of space heating and cooling is driven by the uptake of heat pumps (triggered partly by RepowerEU Plan), which experience a tremendous growth especially in the next two decades (see Figure 44).

Figure 44: Stock of heat pumps in the residential and services sector, 2015-2050



Source: PRIMES.

Hydrogen and gaseous e-fuels ⁽⁶⁷⁾ start featuring an uptake in the buildings sector from 2035 and partially substitute the use of natural gas, thus supporting the phase out of such fossil fuel (see Section 1.2.4). However, the consumption of RFNBOs in the buildings sector remains extremely limited, at 1-3% in the S1-S2-S3 scenarios and below 10% in all scenarios in 2050.

Renewable energy sources (such as geothermal and solar heat) have marginal shares in buildings energy consumption and only experiences a moderate growth during the time horizon. Rather, the use of heat pumps with electricity provided by solar PV is expected be a more competitive technology option underpinned by faster cost reductions. Biomass (used in modern stoves) broadly maintains constant its share of energy consumption in buildings throughout the projections' time horizon. In the residential sector, where biomass accounted for 17% of residential energy consumption in 2015, the consumption of biomass almost halves between 2015 and 2050, at the same pace as total energy consumption in the residential sector. ⁽⁶⁸⁾ In the services sector, the share of biomass remains stable as well, although at much lower level than in the residential sector - around 3%. District heating increases slightly its share of total energy demand in buildings reaching approximately 11% in 2040 in all scenarios.

It is worth noting that the role of RFNBOs in the decarbonisation of the building sector is highly uncertain. A literature review has found out that hydrogen's role in global energy scenarios is extremely inconsistent: only two out of ten studies reviewed feature a contribution of hydrogen to space heating, which is less than 15% of total space heating

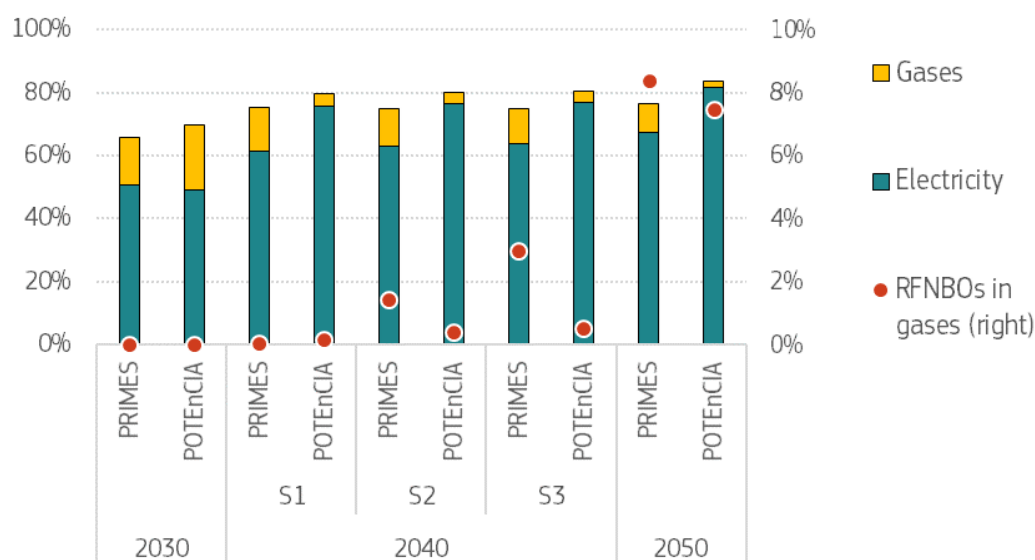
⁽⁶⁷⁾ Renewable hydrogen is a rapidly evolving technology and sector. The modelling results for 2030 reflect the EU RFNBO targets, and associated hydrogen production, as per the revision of the Renewable Energy Directive under the Fit-for-55 package. However, the modelling for the future design of the post-2030 policy framework will take into account the updates of the National Climate and Energy Plans due in June 2024.

⁽⁶⁸⁾ Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

demand even in the most hydrogen ambitious scenarios in 2050. ⁽⁶⁹⁾. Another recent literature review has found out that few EU energy system models see RFNBOs used in buildings in 2030 (and with a share below 1% of total energy consumption in buildings). In 2040, more models feature hydrogen demand in buildings, which remains below 6% of final demand. In 2050, EU models are characterised by very different levels of RFNBOs consumption in buildings, ranging from nothing or extremely low levels up to 16% of final demand in buildings.

Both PRIMES and POTEnCIA project a similar growing trajectory in terms of combined share of gaseous fuels (natural gas, hydrogen and synthetic gas) and electricity in total buildings' FEC (Figure 45). However, the two models differ in that PRIMES features a higher and longer reliance on the gas network to fulfil buildings' energy needs, while POTEnCIA features a deeper and faster electrification. Such difference is partially explained by the fact that PRIMES reduces the carbon intensity of the gas mix provided to buildings by producing RFNBOs to be injected in the gas network earlier and in larger amounts.

Figure 45: Contribution of electricity and gaseous fuels to buildings' FEC, 2030-2050



Sources: POTEnCIA, PRIMES

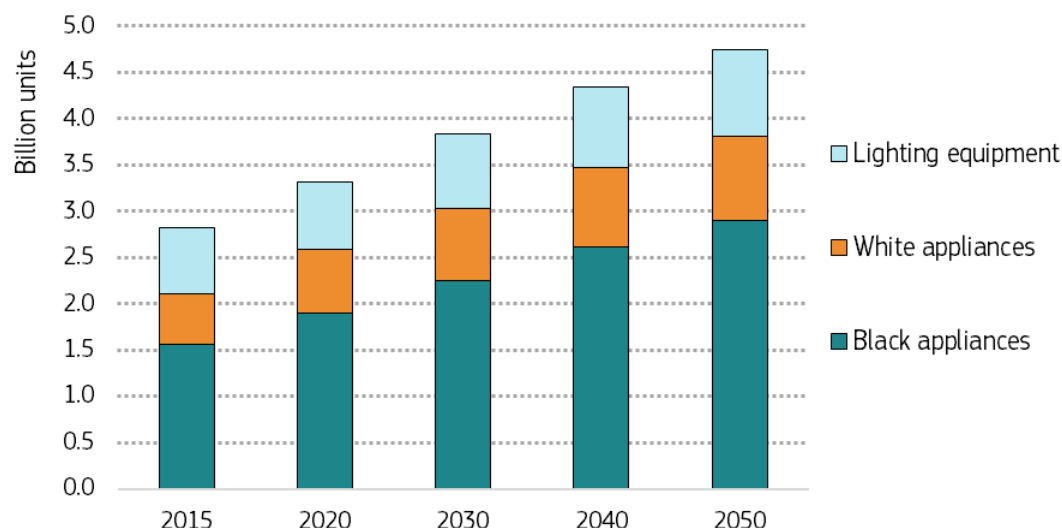
This analysis underlines that a very similar level of decarbonisation of the building sector – as other sectors - can be achieved via different pathways, with the largest differences around 2040. The balance between the use of heat pumps rather than RFNBOs to heat households has important implications on the economics of the gas network and on the sizing of the electricity distribution network.

⁽⁶⁹⁾ Quarton C.J, Tlili O., Welder L., Mansilla C., Blanco H., Heinrichs H., Leaver J., Samsatli N.J., Lucchese P., Robinius M., Samsatli S. (2020), The curious case of the conflicting roles of hydrogen in global energy scenarios, Sustainable Energy Fuels, 4, 80, DOI: 10.1039/c9se00833k

1.3.4. Appliances

The growing number of dwellings (Section 1.3.1), higher GDP and living standards drive up the number of appliances (Figure 46). Compared to 2015, the stock of black appliances grows by 44%, 68% and 86% respectively in 2030, 2040 and 2050 respectively⁽⁷⁰⁾. Information and communication appliances experience the largest growth, more than doubling their stock already in 2030. The stock of white appliances grows at slightly lower pace, by 41%, 55% and 65% respectively in 2030, 2040 and 2050 with respect to 2015 ⁽⁷¹⁾. The growth of the stock of lighting equipment is more limited compared to that of appliances.

Figure 46: Stock of black and white appliances and of lighting equipment, 2015-2050



Note: the stock of appliances and of lighting equipment does not vary across scenarios.

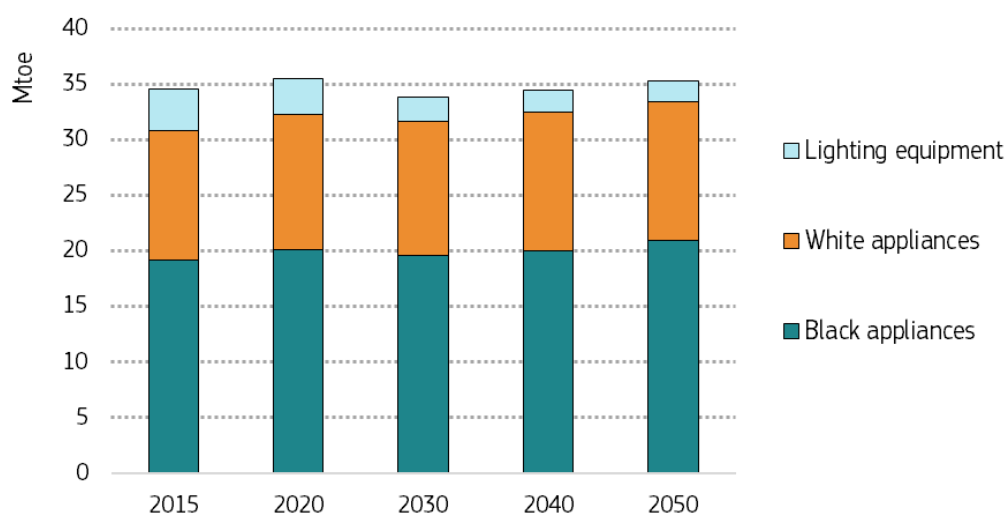
Source: PRIMES.

Such ever increasing number and use of appliances is moderated by energy efficiency measures (such as eco-design and energy labelling legislation targeting the energy efficiency of appliances) resulting in almost constant electricity demand from appliances and lighting, at around 35 Mtoe throughout the projections' time horizon (see Figure 47). Since energy demand for space heating is projected to reduce significantly, the share of energy demand for appliances out of total energy demand in buildings grows from 14% in 2015 to 19% in 2030, 23% in 2040 and 26% in 2050 across scenarios.

⁽⁷⁰⁾ Black appliances refer to vacuum cleaners, small appliances, information and entertainment appliances.

⁽⁷¹⁾ White appliances refer to dishwasher, dryers, freezers, refrigerators and washing machines.

Figure 47: Electricity demand associated to appliances and lighting, 2015-2050

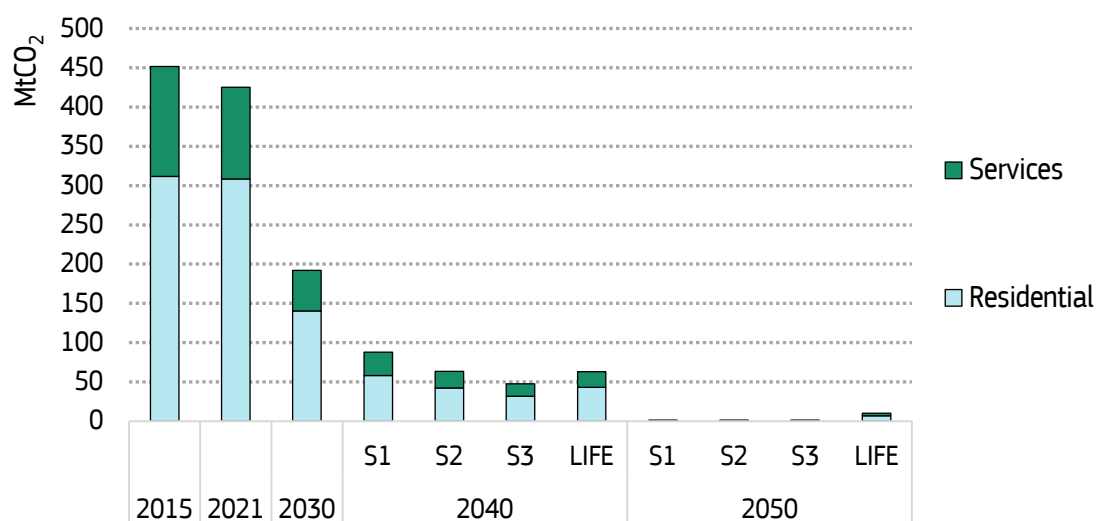


Source: PRIMES.

1.3.5. CO₂ emissions from buildings

Direct CO₂ emissions from buildings experience a rapid decrease already in this decade, from about 450 MtCO₂ in 2015 to 190 MtCO₂ in 2030, i.e., -57% (Figure 48). Then, CO₂ emissions further reduce to about 50-90 MtCO₂ under the S1-S2-S3 scenarios in 2040 and reach almost zero emissions in 2050 for all scenarios. The residential and services sectors face a similar pace of CO₂ emission reductions throughout the projection time horizon. This is largely explained by the fact both sectors rely on essentially the same mitigation options, which have very similar costs, and are triggered by the same policy measures.

Figure 48: Buildings CO₂ emissions trajectory by sector, 2015-2050



Note: CO₂ emissions shown in the figure are only direct emissions, i.e., related to the combustion of fuels consumed in the building sector. Emissions related to the production of the electricity and RFNBOs consumed in the buildings sector are accounted in the upstream sectors.

Source: PRIMES.

The CO₂ emissions discussed above only account for direct CO₂ emissions, i.e., those directly related to the combustion of fuels consumed in the building sector. Instead,

emissions associated to the production of electricity and RFNBOs consumed by buildings are accounted in the upstream sectors. Given that the buildings sector is expected to experience a significant electrification (see Figure 42 and Figure 43) and to consume – to a lower extent – RFNBOs, the building sector is responsible for significant amounts of indirect CO₂ emissions as well. However, the power generation sector is set to decarbonise rapidly and become completely carbon neutral by around 2040.

The reduction in CO₂ emissions from buildings is achieved mainly via the faster rate of renovation of the buildings' envelopes, which reduces the overall energy consumption, and by the replacement of fossil fuels space heating equipment with heat pumps. The deployment of renewables and the blending of low-carbon gases in the gas network also contributes to lower emissions. As discussed in detail in Sections 1.3.2 and 1.3.3, these transformations are largely driven by climate policies extending their impact beyond 2030, such as the ETS2. Finally, CO₂ emission reductions are also achieved by reducing energy consumption from heating, cooling and cooking equipment and appliances – driven by the eco-labelling policy.

1.4. Industry

1.4.1. Introduction

According to IEA, global industry ⁽⁷²⁾ accounts for one-third of total final energy consumption, and the CO₂ emitted (9 GtCO₂) represents one-quarter of all energy and process CO₂ emissions ⁽⁷³⁾. In the EU, industrial emissions have been decreasing steadily since 1990, overcoming also the rebound due to the restart of economic activity after the COVID-19 pandemic ⁽⁷⁴⁾, and in 2020, they represented 26% of total net GHG emissions ⁽⁷⁵⁾.

No silver bullet exists to decarbonise industry, and different solutions are to be implemented to the various subsectors to achieve climate neutrality. Reduction of raw materials demand, for instance by implementation of circular economy and demand-side actions, can reduce emissions by 20% in 2040 ⁽⁷⁶⁾. Energy efficiency, together with indirect and direct electrification can reduce emissions by 25% ⁽⁷⁷⁾, acting on the industry energy needs. Replacement of fossil fuels by bio- and e-fuels can contribute to decarbonisation where electrification is not technically possible and carbon capture can be implemented where low carbon alternative processes have limited potential. Literature

⁽⁷²⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

⁽⁷³⁾ IEA, (2022). Achieving Net Zero Heavy Industry Sectors in G7 Members.

⁽⁷⁴⁾ COM/2022/514 final

⁽⁷⁵⁾ McKinsey, (2020). Net-Zero Europe Decarbonization pathways and socioeconomic implications.

⁽⁷⁶⁾ Kalcher, L. et al., (2023). The post-2030 climate target debate starts now, *Strategic Perspectives and Climact*. <https://strategicperspectives.eu/the-post-2030-climate-target-debate-starts-now/>

⁽⁷⁷⁾ Madeddu, S., et al. (2020). The CO₂ reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters*, 15(12), 124004.

shows that combining all approaches can reduce industrial emissions by 86% in 2050 compared to 2019 ⁽⁷⁸⁾.

1.4.2. Activity

The activity in the three main scenarios build on a continuation of trends of sector-specific material demand and associated production. LIFE illustrates how a more efficient use of materials resources, through technological innovations and a higher circularity of the EU's economy, can impact positively sectoral CO₂ emissions.

Future production of steel in EU is likely to maintain current levels ⁽⁷⁹⁾, and this trend is reflected in the main scenarios, where sector decarbonisation happens mainly through the increase of electric arc furnace share and a larger use of hydrogen in the reduction of iron ore ⁽⁸⁰⁾. A more efficient use of steel and an increasing recycling rate could lead to a decrease in primary production and an increased share of secondary steel, reducing overall demand by up to 15-17% in the period 2040-2050 compared to the most recent years ⁽⁷⁷⁾⁽⁷⁸⁾. LIFE follows this approach and projects a decrease in demand of around 15% in 2050 (25% of primary) compared to the main scenarios.

According to BNEF ⁽⁷⁹⁾, global production for aluminium is projected to increase by around 40% by 2050, intensifying especially secondary aluminum. Studies also show that a more efficient use of this material, especially in terms of scrap recycled and lifetime extension of products, can instead maintain production level to similar values as today ⁽⁷⁷⁾. In S1, S2 and S3, an increase of aluminum production of around 35% until 2050 is assumed, while LIFE models an optimisation of material use resulting in a reduction of 20% of production when compared to the main scenarios.

The paper sector is expected to moderately increase production, as the decline in printing-related paper production is outweighed by growth in packaging and sanitary paper products ⁽⁸¹⁾. The high recycling rates of today are projected to increase further ⁽⁸²⁾, expanding the secondary share of production and unlocking the possibility to reduced paper demand of up to 14% in 2050 (vs 2015) ⁽⁷⁸⁾. The modelling captures these trends, projecting a 5% increase of production by 2050 in S1, S2 and S3 and a decrease in LIFE of around 20% in 2050 (40% for primary), thanks to higher recycling rates and material efficiency, and implementation of reusable packaging.

Production of cement (including clinker) in EU is assumed to increase by around 20% in the main scenarios by 2050 ⁽⁷⁹⁾. However, low-carbon cement alternatives, high share of recycled cement in concrete, and changes in lifetime and utilisation rate of buildings could decrease demand, with estimates showing lower demand by 25% in 2040

⁽⁷⁸⁾ CLEVER, (2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables, *Final Report*. https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf

⁽⁷⁹⁾ BNEF, (2023). New Energy Outlook: Industry.

⁽⁸⁰⁾ Agora Industry and Wuppertal Institute, (2023). 15 insights on the global steel transformation.

⁽⁸¹⁾ IEA, (2023). Tracking Clean Energy Process, Tracking Pulp and Paper.

⁽⁸²⁾ Directive 94/62/EC (Amended by Directive(EU) 2018/852).

compared to 2019 ⁽⁷⁷⁾ or by 38% in 2050 compared to 2015 ⁽⁷⁸⁾. LIFE assumes a demand-driven production around 25% lower in 2050.

The global demand for petrochemicals, including a larger share of chemically recycled feedstock, is projected to double by 2050 compared to 2021, with the EU representing around 4% of market share by mid-century ⁽⁷⁹⁾. In the main scenarios, an increase of demand for organic chemical and petrochemicals in end-user products of around 23% with respect to the average production in 2015-2020 is assumed, taking also into account a steep increase in recycling rate. According to literature, additional demand-side actions could lead to an optimisation of production of chemicals, with savings of up to around 28% of olefins and ammonia in 2040 (vs 2019) ⁽⁷⁷⁾ and up to 23% in 2050 (vs 2015) when encompassing all chemicals ⁽⁷⁸⁾. Introduction of additional measures in LIFE such as a ban of single use water bottles and strong reduction of plastic-packaging are projected to save approximately 15% of primary input material in 2050.

Table 8 summarises the variation of industrial production assumed in the analysis.

Table 8: Assumptions on evolution of industrial domestic production for selected materials

	S1, S2, S3	LIFE
	2050 vs 2015	vs S1, S2, S3 in 2050
Steel	0%	-15% (-25% primary)
Aluminum	35%	-20%
Paper	5%	-20% (-40% primary)
Cement (including clinker)	20%	-25%
Petrochemicals and organic materials	25%*	-15%

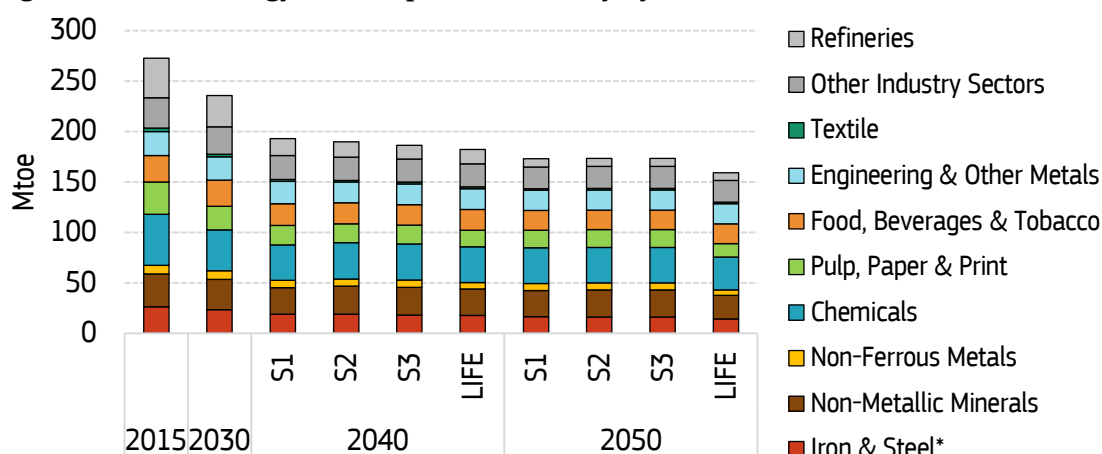
*Note: *Value calculated with respect to the 2015-2020 average production.*

1.4.3. Final Energy Consumption

As result of improved energy efficiency and changes in activity, energy consumption ⁽⁸³⁾ in the industrial sector decreases by around 20% in the 2031-2040 decade and by 7 additional percentage point in 2041-2050 (vs 2030) in the main scenarios, showing that a significant part of the mitigation potential allocated to efficiency improvement is attained already by 2040. LIFE shows for 2040 a nearly identical value as the other scenarios and for 2050 an additional reduction of few percentage points (Figure 49).

⁽⁸³⁾ Final energy consumption (FEC) and consumption in refineries

Figure 49: Final Energy Consumption in industry by sector



Note: *The iron and steel sector includes blast furnaces.

Source: PRIMES.

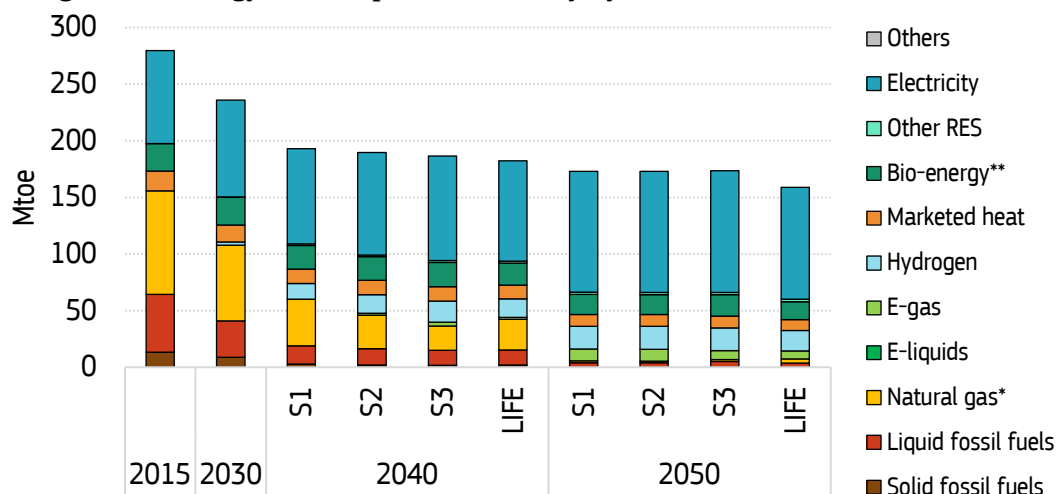
When looking at the share of the different fuels in industry consumption (Figure 50), the model shows an increasing electrification trend in all scenarios. Electrification share reaches around 48% in 2040 and 62% in 2050 from around 21% in 2021⁽⁸⁴⁾, in line with figures of around 50% in 2040 and 60% in 2050 projected by Eurelectric⁽⁸⁵⁾. The model also shows a progressively higher contribution of RFNBOs, representing around 1%, 10% and 18% of FEC in 2030, 2040 and 2050. Electrification share in Final Energy Consumption (FEC-E) varies little across scenarios, indicating that it is based on a number of commercial technologies and consolidated trends already available in S1 and deployed similarly across S1, S2 and S3. Fossil fuels, in particular natural gas, are replaced partially by biofuels and mostly by an increasing amount of RFNBOs, in particular hydrogen, whose share in FEC-E increases from 7% to 9% and 12% when moving from S1 to S2 and S3 (Eurelectric shows hydrogen shares of around 10-15%⁽⁸⁶⁾). LIFE shows a use of RFNBOs in line with S2 and more moderate compared to S3: additional emission reductions in sectors outside energy and industry slightly delays the need for extensive deployment of e-fuels. In 2050, almost all fossil fuels disappear, as result of complete fuel switch in furnaces and introduction of alternative heating processes.

⁽⁸⁴⁾ Eurostat, (2023). Complete Energy Balances European Union (27 countries) – 2021.

⁽⁸⁵⁾ Eurelectric (2023). Decarbonisation speedways: Accelerating Europe's journey to net zero with realistic 2040 targets. Slide 19. <https://www.eurelectric.org/publications/decarbonisation-speedways-full-report>

⁽⁸⁶⁾ Ibid

Figure 50: Energy Consumption in industry by fuel



Note: The energy consumption includes the final energy consumption plus the consumption in refineries.

**Natural gas including manufactured gas (coke-oven gas, blast furnace gas & gasworks gas), but not e-gas.*

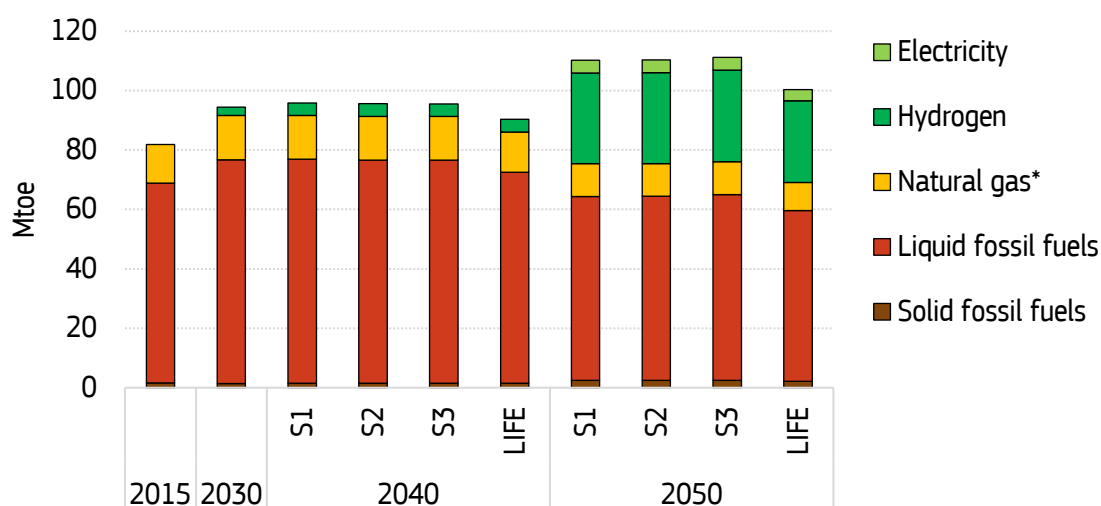
***Bioenergy including bio-solids, biofuels, biogas (including waste gas and biomethane) and solid waste.*

Source: PRIMES.

1.4.4. Final Non-Energy Consumption

Figure 51 shows the evolution non-energy consumption in industry, representing fuels that are used as raw materials (for instance oil transformed in plastics or bitumen used in road construction). In 2031-2040, total consumption is maintained around 2030 levels, while significant changes occur in 2041-2050: fossil fuels which represents around 90% of the industrial feedstock until 2040 decrease by 15 Mtoe and are partially replaced by hydrogen and electricity. In the same decade, hydrogen increases of around 25 Mtoe. Negligible differences can be found between S1, S2 and S3. A small decrease in non-energy consumption in LIFE is projected in around 5% in 2040 and 10% in 2050, as result of decrease in activity in the petrochemical and other industrial sectors.

Figure 51: Final Non-Energy Consumption in industry by fuel



Note: *including manufactured gas (coke-oven gas, blast furnace gas & gasworks gas), but not e-gas.

Source: PRIMES.

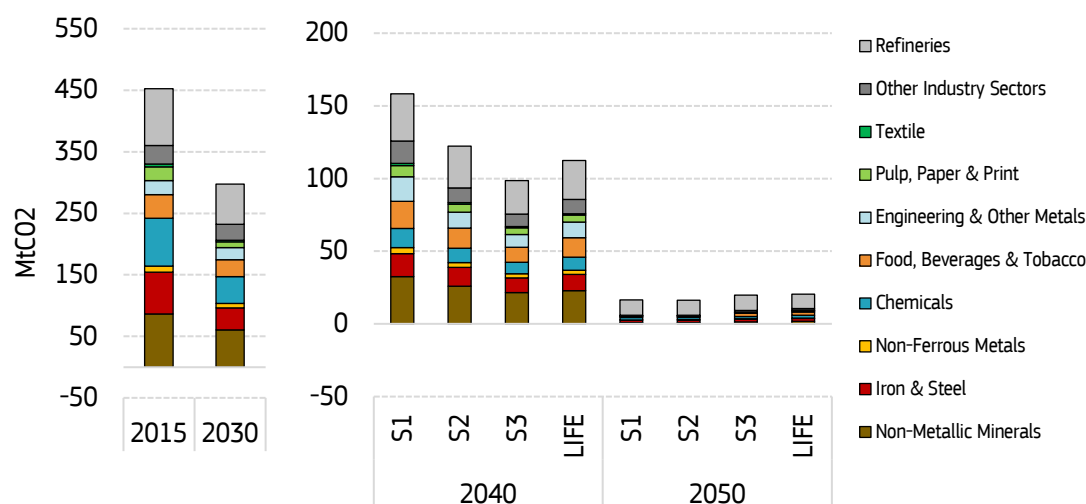
1.4.5. CO₂ emissions from industry

1.4.5.1. Energy-related CO₂ emissions

Significant reduction of the energy-related CO₂ industrial emissions appears in the decade 2031-2040: -47% in S1, -63% in S2 and -80% in S3 (Figure 52). Emissions reduce in all sectors, as result of electrification process and gradual uptake of RFNBOs and carbon capture technologies. The variation across scenarios for all main sectors ranges between 12 and 32 percentage point, with the chemical sector achieving the highest reduction in 2040 (down to 82% below 2030 level). The iron and steel emissions achieve around -55% in S1, -65% in S2 and -70% in S3 when compared to 2030 levels. These values result from an increased electrification occurring in S1, on top of which carbon capture and RFNBOs deploy progressively in S2 and S3. In 2050, an even higher share of electricity and RFNBOs in industrial consumption (see Figure 49), together with larger development of carbon capture, reduce or eliminate further residual emissions in all sectors in a similar way across the three scenarios.

LIFE shows emissions higher than S3 and in line with S2 in 2040, since the additional reductions in non-CO₂ and the LULUCF allow for less constraints in the energy and industrial emissions. This translates into a lower use of RFNBOs in 2040 (see also Figure 50) and a lower amount of carbon captured in 2050.

Figure 52 : Energy-related CO₂ emissions in industry by sector

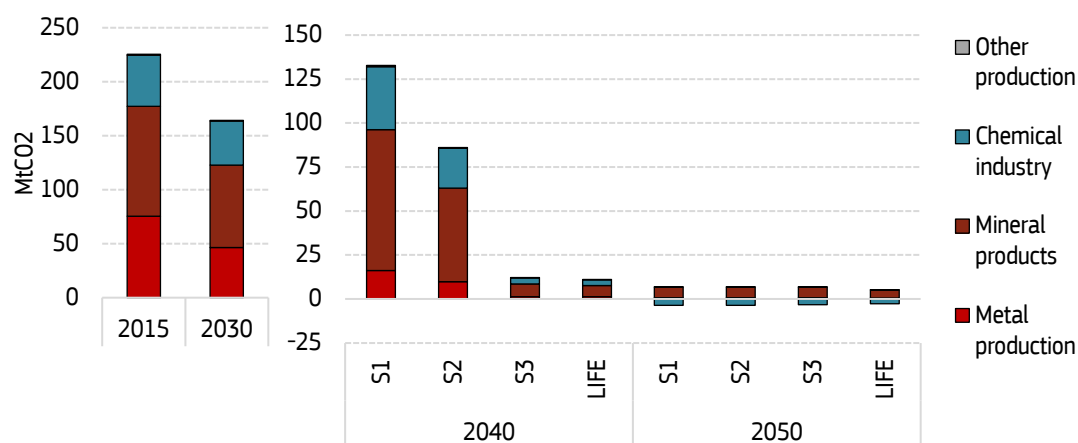


Source: PRIMES.

1.4.5.2. Process-related CO₂ emissions

Figure 53 shows that process-related CO₂ emissions, are projected to decreased by around 30% in 2030 compared to 2015. In 2040, emissions amount respectively to around 135, 85 and 10 MtCO₂ in S1, S2 and S3, i.e., reducing approximately between 20% and 95% (vs 2030). By 2050, all scenarios show negligible residual emissions.

Figure 53: Process CO₂ emissions in industry by sector



Note: Metal production includes both ferrous and non-ferrous materials. For 2050, S1 and S2 values are similar to S3 and not represented.

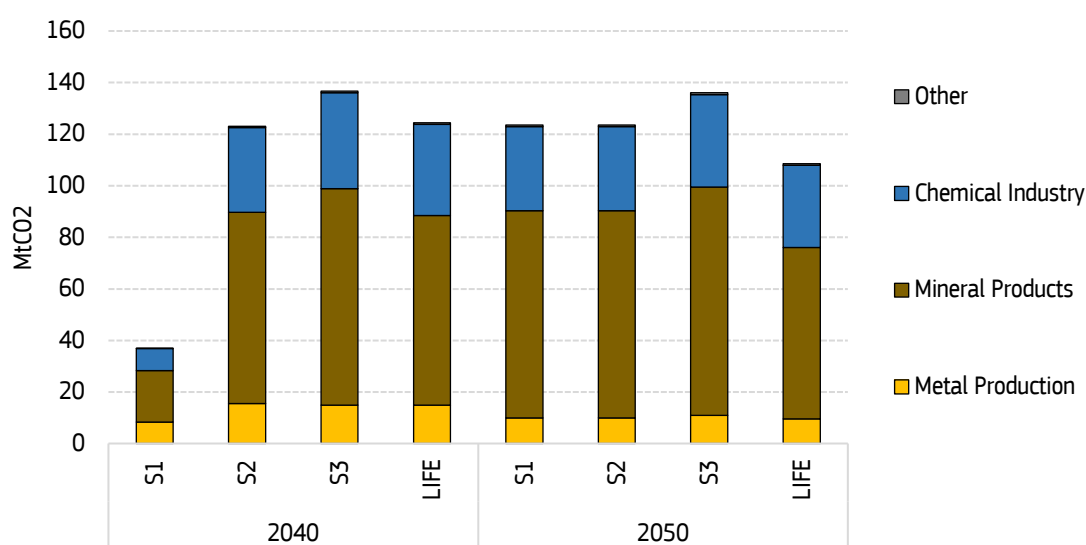
Source: PRIMES

The role of carbon capture⁽⁸⁷⁾ is pivotal to explain differences on total net process emissions across scenarios in 2040 and the negligible emissions in 2050 (Figure 54). In S1

⁽⁸⁷⁾ Industrial challenges explained in 1.1.3.2 are associated to the development of carbon capture, but these challenges are assumed to be overcome in the projections.

only around 40 MtCO₂ are projected to be captured in 2040, in line with the limited uptake of capture technologies. This value leaps to around 120 MtCO₂ in S2, of which around 65% goes to e-fuel production and 35% goes to underground storage (see Figure 11 section 1.1.3.2). The stored CO₂ is not considered as emitted, and total net industrial process emissions reduce by a corresponding amount. In S3, the carbon captured increases moderately compared to S2, but it is mostly stored underground or in materials and not dedicated to e-fuels productions, reducing further the net process emissions. By 2050, the amount of total carbon captured increases for S1, and it is similar to 2040 values for S2, but in both scenario it is fully stored either underground or in materials, reducing net emission further than in 2040 and reusing CO₂ within the industry. In S3, a similar amount of carbon is captured yearly between 2040 and 2050, resulting in limited reduction in net emissions in the 2041-2050 decade. In LIFE, carbon capture falls short to S3 in 2040 and 2050, as result of more emission reductions elsewhere (see 1.4.2 in this Annex).

Figure 54: Carbon captured in industrial processes.



Note: Metal production includes both ferrous and non-ferrous materials.

Source: PRIMES

The different reduction rates and residual emissions shown by the iron and steel, the chemical and the mineral product sectors are explained by the different availabilities of decarbonisation technologies in each sector (in addition to carbon capture). In the steel sector, options exist today ⁽⁸⁸⁾: a large implementation of hydrogen-based alternative steelmaking process reduces emissions between 65% and 80% (before carbon capture and depending on the scenario) by 2040, when compared to 2015. Carbon capture completes then the decarbonisation process. The chemical sector relies almost exclusively on carbon capture by 2040 while implementation of low-carbon processes by replacement of fossil fuel feedstock and use of fossil-fuel free CO₂ as feedstock occurs only in 2041-2050. In the 2041-2050 decade, capture still plays a prominent role in chemistry, leading to even negative emissions in 2050, as result of improved flow of CO₂ within the industrial sector and storage in materials of carbon coming from non-fossil fuel feedstock ⁽⁸⁹⁾. Production

⁽⁸⁸⁾ BNEF, (2021). Decarbonizing steel – Technologies and Costs.

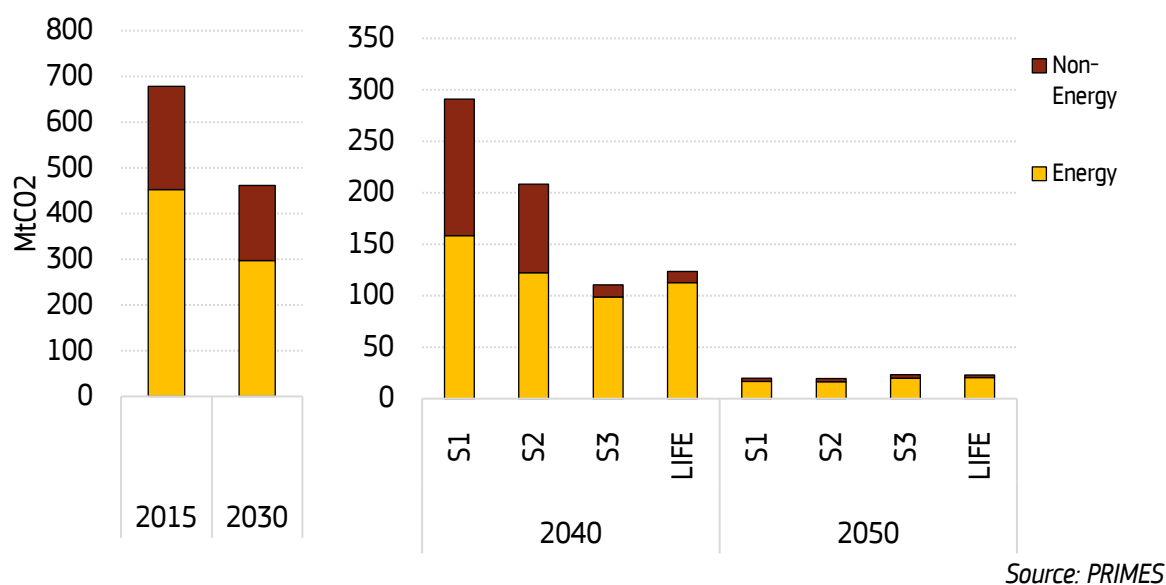
⁽⁸⁹⁾ CEFIC, (2021). Shining a light on the EU27 chemical sector's journey toward climate neutrality.

of minerals, such as cement, are the hardest to decarbonise: literature shows that residual emissions from cement in 2050 can be as high as 25% of 2017 levels ⁽⁹⁰⁾, and massive deployment of carbon capture and storage is projected to be the most common options for decarbonisation of the sector.

1.4.5.3.Total CO2 from industry

Figure 55 summarises the energy and process related CO2 emission from the industrial sector, showing that total net CO2 reduces by 37%, 55% and 76% in S1, S2 and S3, in 2040 compared to 2030 ⁽⁹¹⁾. This correspond to a decrease between 60% and 90% in comparison with 1990 levels, well aligned with literature: a report from the NAVIGATE project comparing the results of seven IAM states that industrial emissions should reduce by at least 55% in 2040 vs 2020 to be compatible with the 1.5°C case ⁽⁹²⁾, report from the CLEVER project show how industry can reduce emissions by 86% in 2050 vs 2019 ⁽⁹³⁾ and Ecologic illustrates that the industrial sector should reach emissions between -78% and -91% in 2040 vs 1990 to comply with climate neutrality ⁽⁹⁴⁾. Acceleration of the decarbonisation of the industry is also supported by the public consultation results, where almost 48% of respondents, and a number of position papers indicated “Industrial processes and waste” as one of the sectors that can do more to reduce emissions.

Figure 55: CO2 Emissions from industrial sector



⁽⁹⁰⁾ McKinsey, (2020). Laying the foundation for zero-carbon cement.

⁽⁹¹⁾ Carbon capture from DACCS not included.

⁽⁹²⁾ Kriegler, E. et al., (2023). The EU’s 2040 target Insights from the NAVIGATE project, NAVIGATE.

⁽⁹³⁾ CLEVER, (2023). Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables, *Final Report*. https://clever-energy-scenario.eu/wp-content/uploads/2023/06/clever_final_report-exec_summary.pdf

⁽⁹⁴⁾ Ecologic and Oeko-Institut, (2023). Designing the EU 2040 climate target.

1.4.6. Complementary analysis

1.4.6.1. Introduction

Circular Economy (CE) actions can contribute significantly to decarbonise industrial sectors, especially in fields where other mitigation options are under development or available but still come at a cost premium (e.g., electrification of high temperature heat or hydrogen). One of the key channels through which CE actions can support industrial decarbonisation is by reducing the demand for primary production of industrial outputs through the extension of the lifetime of products and materials as well as the substitution of primary with less carbon-intensive, secondary materials. Literature reports 20% GHG emission saving potential in the EU due to CE actions until 2050 ⁽⁹⁵⁾, that can go up to 25% in certain Member States ⁽⁹⁶⁾. More ambitious estimates, which also include sufficiency actions can go beyond that level ⁽⁹⁷⁾, ⁽⁹⁸⁾. CE can also bring several additional co-benefits e.g., reducing the environmental pressure associated with natural resource consumption and increasing strategic autonomy of the EU by derisking supply chain for critical and other raw materials (see section 1.9.4).

The following complementary analysis investigates the impact of a limited group of relevant CE actions on the decarbonisation of iron and steel, aluminum, paper and pulp, cement, ethylene, and glass sectors. It shows results on future material production, GHG emissions and energy demand. A broad circular economy approach and the overall impact of CE actions across the whole economy fall outside the scope of this study ⁽⁹⁹⁾,⁽¹⁰⁰⁾, and is taken into account in S1, S2, S3 and LIFE analysis.

1.4.6.2. Methodology

The complementary analysis focuses on a subset of materials produced by energy-intensive industries EIIs (Iron and Steel, Cement, Aluminium, Glass, Ethylene and Pulp and Paper). It projects future material production, and by mean of the FORECAST tool, (see Annex 6), it models GHG emissions and energy demand in two different decarbonisation scenarios: CIRC (after circularity) and STD (after standard). While the

⁽⁹⁵⁾ Ellen MacArthur Foundation, Completing the picture: How the circular economy tackles climate change (2019). 20% GHG emission saving potential due to CE actions until 2050.

⁽⁹⁶⁾ Agora Industrie, Systemiq (2023): Resilienter Klimaschutz durch eine zirkuläre Wirtschaft: Perspektiven und Potenziale für energieintensive Grundstoffindustrien. Agora estimates circular economy potential to be around 25% until 2050 for Germany.

⁽⁹⁷⁾ Ramboll, Fraunhofer ISI, Ecologic Institute (2020). *Quantification methodology for, and analysis of, the decarbonisation benefits of sectoral circular economy actions*. Final Report.

⁽⁹⁸⁾ IRP (2020). Resource Efficiency and Climate Change: *Material Efficiency Strategies for a Low-Carbon Future*. Hertwich, E., Lifset, R., Pauliuk, S., Heeren, N. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

⁽⁹⁹⁾ Ellen MacArthur Foundation, Completing the picture: How the circular economy tackles climate change (2019). 20% GHG emission saving potential due to CE actions until 2050.

⁽¹⁰⁰⁾ Agora Industrie, Systemiq (2023): Resilienter Klimaschutz durch eine zirkuläre Wirtschaft: Perspektiven und Potenziale für energieintensive Grundstoffindustrien. Agora estimates circular economy potential to be around 25% until 2050 for Germany.

STD assumes the partial implementation Circular Economy Action Plan (CEAP) ⁽¹⁰¹⁾, the CIRC includes additional selected CE actions that are listed in Table 9. The main common assumptions of the CIRC and STD are in line with the main scenarios S1, S2, S3 with some significant differences. For instance, in STD and CIRC, deployment of carbon capture is limited to industrial processes in sectors where residual emissions are projected in 2050 (the cement industry ⁽¹⁰²⁾ ⁽¹⁰³⁾), and removal compensation outside EII sectors (DACCS), are not considered. Moreover, the CIRC scenario only reflects selected CE action, without considering a large circular economy framework including sufficiency or shared economy measures. Finally, the analysis focuses on the decarbonisation of industrial sectors and is limited to the savings that could be achieved only during production stage. It does not take into account decarbonisation in the other sectors leading to EU economy-wide climate neutrality, thus, allowing only for comparison in relative terms with scenarios S1, S2 and S3. These limitations need to be taken into account when interpreting the magnitude of the modelled impacts. More details on the methodology can be found elsewhere ⁽¹⁰⁴⁾.

⁽¹⁰¹⁾ The STD scenarios implements actions from the CEAP (COM/2020/98) that have been legislated or agreed until March 2023.

⁽¹⁰²⁾ McKinsey, (2020). Laying the foundation for zero-carbon cement.

⁽¹⁰³⁾ Cembureau, (2023). Cementing the European Green Deal. Reaching climate neutrality along the cement.

⁽¹⁰⁴⁾ Herbst, A. et al. (2023): Role of the circular economy as a contributor to industry decarbonisation beyond 2030. Report prepared for DG CLIMA: Job number 330301101. Fraunhofer ISI & ICF.

Table 9: List of circular economy actions applied to the CIRC scenario

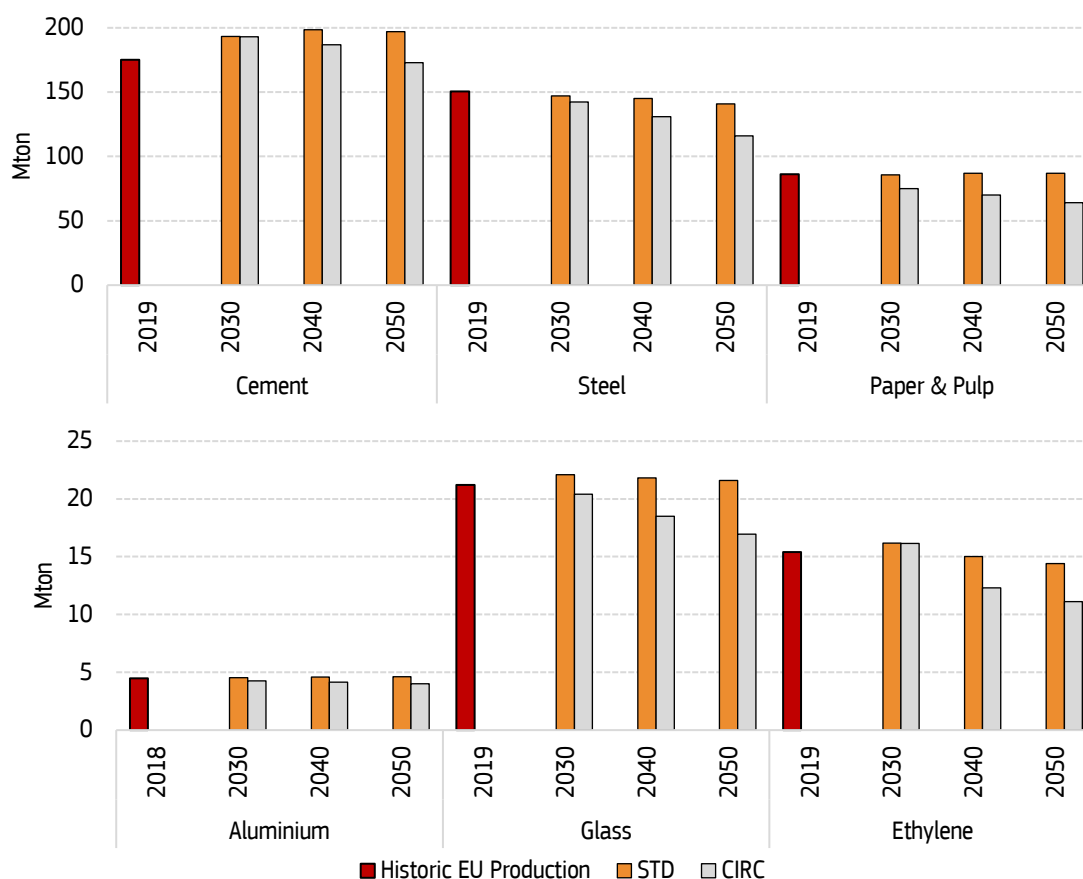
MATERIAL	CE ACTION
Aluminium	Increased aluminium recycling from buildings (increase collection rate from 96 to 100% by 2045)
	Increased recycling of aluminium cans (reduce losses and disposal to 0 by 2030)
	Reduction of scrap exports (to 0 by 2050)
	Reduction of exports of EoL cars (to 0 by 2050)
	Alloy sorting of post-consumer scraps (reduce input of primary aluminium for dilution of scrap from 20 to 5%)
	Lifetime extension of cars (increasing from 15 to 20 years on average)
	Lifetime extension of buildings (decreasing building demolition by up to 30%)
	Lifetime extension of machinery (from 25 to 30 years on average)
Cement	Using up to 20% recycled cement in buildings
	Use innovative binders as substitute for ordinary cement (market share of up to 10%)
	Lifetime extension of buildings (decreasing building demolition by up to 30%)
	Design for building disassembly, and make standardised building elements (reusing up to 38% of prefab building elements)
	Reducing use of structural concrete at design stage by up to 41%
	Using cement with lower clinker shares (reducing average from 0.73 to 0.7)
Ethylene	Redesign multi-material packaging of different layers to ensure recyclability from the year 2030
	Increasing the recycled content in plastic bottles
	Reduction in single-use plastics packaging from supermarkets by 50%
	Ban single use water bottles
Glass	Recycling of municipal waste to increase to 55%, 60% and 65% by weight by 2025, 2030 and 2035 respectively
	Increase share of reusable glass bottles and containers
Iron and Steel	Reduction of scrap exports from 28Mt in 2020 to 0 in 2050
	Reduction of exports of EoL cars from 72600 cars in 2020 to 0 in 2050
	Alloy sorting of post-consumer scraps to increase the quality of recycled steel which enables the European usage of formerly exported and downcycled steel scrap
	Lifetime extension of cars (increasing from 15 to 20 years on average)
	Lifetime extension of buildings (decreasing building demolition by up to 30%)
	Lifetime extension of machinery (increasing from 22 to 27 years on average)
	Reusing up to 6% structural steel from buildings
	Design for building disassembly, and make standardised building elements (reusing up to 38% of prefab building elements)
	Lightweighting of steel-intensive products (depending on product, reduction of 5-10% product weight by 2050)
	Reducing use of structural steel at design stage (reducing overspecification up to 41%)
Paper and Pulp	Recycling of municipal waste to increase to 55%, 60% and 65% by weight by 2025, 2030 and 2035 respectively
	Increase paper recycling
	Increase the market share of reusable packaging to 40% by 2050
	Lightweighting of paper packaging (Decreasing paper packaging weight by 20% in 2050 compared to 2020)

Note: This list only applies to the CIRC scenario. The actions listed in the Circular Economy Action Plan are assumed to be already implemented up to the cutoff date of March 2023 both in the STD and the CIRC scenarios.

1.4.6.3. Activity

Figure 56 summarises the projections of the total demand for the different materials in the STD and the CIRC scenario and includes historical data of the material production in EU as reference.

Figure 56: Historical EU production and future demand for specific materials



Note: 2019 is taken as the calibration year for the FORECAST model. In case 2019 historic values are not available, first previously available year is represented (e.g., 2018 for Aluminium).

Source: FORECAST production database, FORECAST model.

For all materials, the material demand reduces, leaving a gap between the two scenarios that increases over time in the period 2030-2050. Around 5% and 10% of total cement are saved in CIRC in 2040 and 2050 compared to STD, which in 2050 splits into around 10% of reduction of conventional cement and 10% replacement of conventional cement by low-carbon cement. Building lifetime extension and demand reduction through reuse, preparing for re-use, and modification of overspecification has the highest optimisation potential among the actions analysed, followed by the substitution of conventional cement by wood and low carbon cement produced using alternative cement constituents ⁽¹⁰⁵⁾, ⁽¹⁰⁶⁾. The use

⁽¹⁰⁵⁾ Le Den, et al., (2020). Quantification methodology for, and analysis of, the decarbonisation benefits of sectoral circular economy actions. Final report.

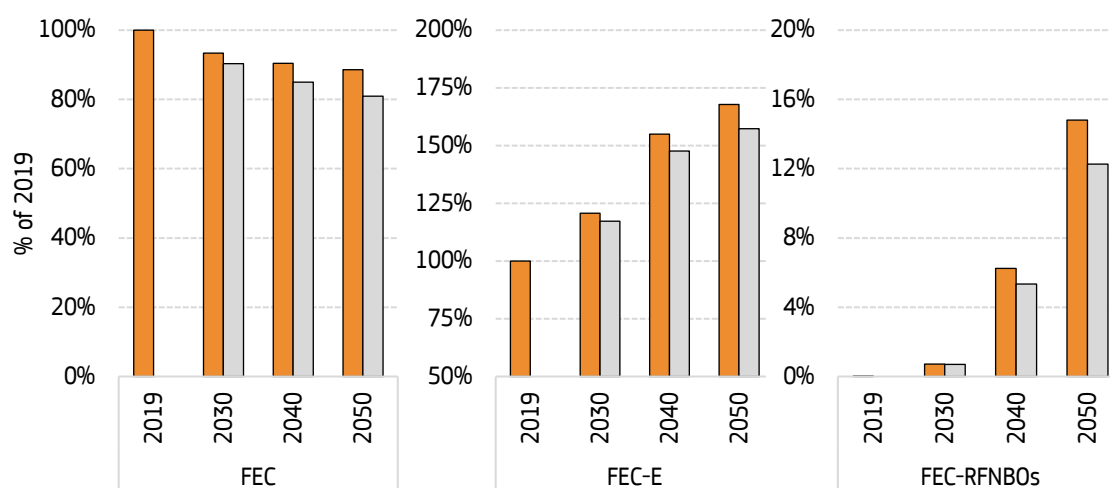
⁽¹⁰⁶⁾ Rehfeldt, M. et al., (2020). Modelling circular economy action impacts in the building sector on the EU cement industry. *ECEEE Industrial Summer Study Proceedings*, 133–143.

of wood has been restricted only to certain construction elements and in single family houses⁽¹⁰⁷⁾, largely in line with sustainable use of biomass and limiting its possible negative impact on the LULUCF net removals. Total steel and aluminium demand reduce around 15%-20% in 2050 compared to STD: this reduction affects mostly primary production, which reduced for the two materials by around half, while secondary production remains stable or increases due to higher availability of scrap and higher recyclability. Ethylene demand, which already decreases in STD due to the high recycling rates, shows a possible additional reduction of around 20% in CIRC. The demand in the paper and pulp sector by around 20-25% until 2050 in CIRC, driven mostly by an increase market share of reusable packaging and light weighting of paper packaging.

1.4.6.4.Final Energy Consumption

The resulting FEC, FEC-E and FEC-RFNBOs (hydrogen + e-fuels) in STD and CIRC scenarios are shown in Figure 57.

Figure 57: FEC, FEC-E and FEC-RFNBOs as % of 2019



Note: 2019 is taken as the calibration year for the FORECAST model.

Source: FORECAST.

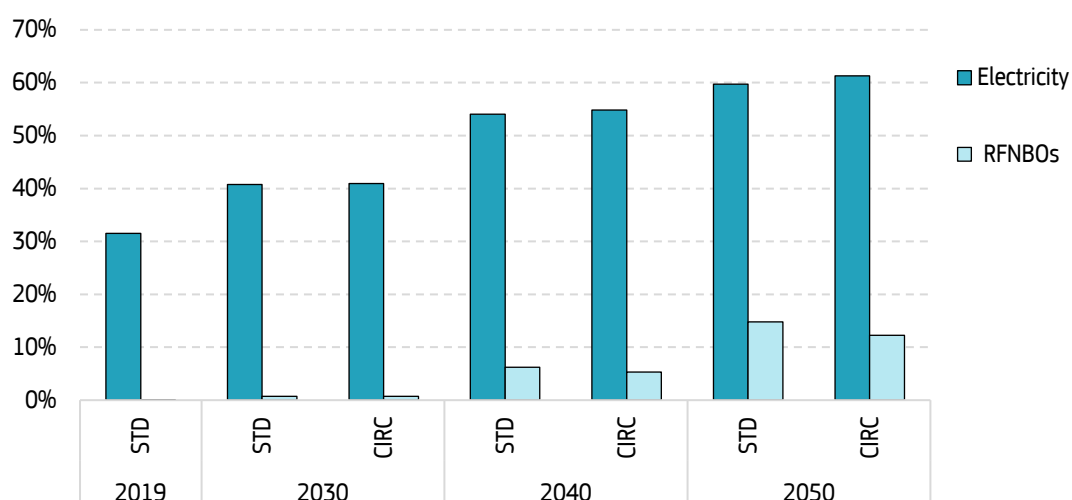
A significant decrease in FEC in STD occurs until 2040 (around -10% vs 2019) and stabilises until 2050. This decline is given mainly by efficiency gains from the electrification of processes or the shift to hydrogen-based production, which in part compensate for the assumed growth in industrial value added. Additional savings of 3%, 5% and 8% in 2030, 2040 and 2050 are achieved in CIRC compared to STD, leading to an overall decrease of around 20% in 2050 compared to 2019. This trend is attributed to additional energy and material efficiency measures, as well as the increase in recycling-based processes, and confirm that impact of CE actions becomes more visible on the long term. Electricity and RFNBOs consumptions in the sector under analysis increase considerably both in STD and CIRC. In STD, FEC-E grows by around 21%, 55% and 68% in 2030, 2040 and 2050 compared to 2019, and FEC-RFNBOs rises from 0 to 1%, 6% and 15% in the same years. CIRC allows for lower consumption, leading to

⁽¹⁰⁷⁾ Nemry, F.; Uihlein, A. (2008): Environmental Improvement Potentials of Residential Buildings (IMPRO-Building).

electricity savings of around 3-4% in 2030-2040 and up to 6% in 2050, and RFNBOs savings of around 1% in 2040 and 3% in 2050 (with respect to STD).

The share of FEC across energy carriers also changes (Figure 58). As result of decrease of FEC and increase of FEC-E, electricity becomes the dominant energy carrier, growing from around 30% of FEC share in 2019, to above 50% already in 2040 and up to around 65% in 2050. To replace fossil fuels in processes where electrification is currently not viable, the amount of RFNBOs increases in absolute terms and as share of FEC, growing from around 1% in 2030, to above 5% in 2040 and above 10% in 2050. When comparing the two scenarios in relative terms⁽¹⁰⁸⁾, the shares for the two energy carriers behave differently: in CIRC, CE actions boost electricity share by around 1% in 2040 and 2050 when compared to the shares of the same years in STD, while share of RFNBOs reduces by 1% and 3% respectively in 2040 and 2050. This indicates that CE actions, in addition to reducing overall FEC, especially contributes to reduce the final energy demand (and relative FEC shares) for carriers that are more expensive or more complex to implement, like hydrogen and e-fuels. A similar effect of reduction of hydrogen and e-fuels due to circular economy actions could be witnessed also in the final non-energy consumption (see 1.4.4 in this Annex).

Figure 58: Share of electricity and RFNBOs in FEC



Note: STD and CIRC shows different FEC, meaning that the comparison between FEC shares in STD and CIRC can only apply in relative terms. A phase out of fossil fuel to less than 3% share of FEC in 2050 is projected, and the rest of FEC is covered by other RES sources. 2019 is taken as the calibration year for the FORECAST model.

Source: FORECAST.

1.4.6.5. GHG Emissions

Figure 59 shows the evolution of GHG emissions in the industrial sector. In STD, net GHG emissions reduce by 29%, 69% and 90% in 2030, 2040 and 2050 compared to

⁽¹⁰⁸⁾ Comparison in absolute terms is not possible since the total FEC in CIRC and BENCH is different.

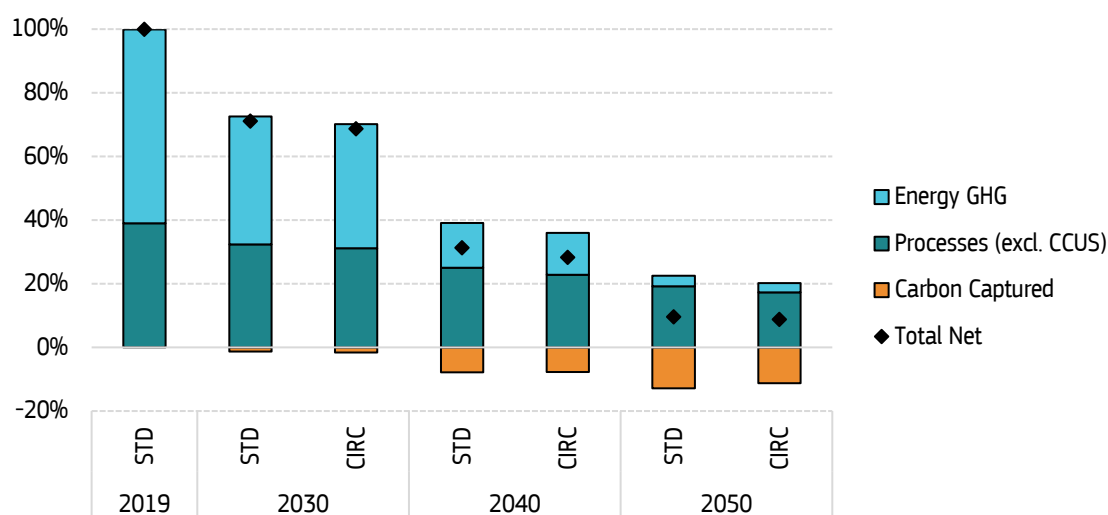
2019. GHG emissions in the CIRC scenario reduce by 31%, 72% and 91% for the same years.

Energy-related emissions decrease in STD in line with the strong electrification of the power system and the reduction of energy needs. In an already well decarbonised sector, the CIRC assumptions can further decrease energy-related emissions by around 7% and 12% compared to STD in 2040 and 2050. The use of alternative processes also reduces significantly process emissions in comparison with today level: process changes in the steel and chemical industries, reduced use of hydrofluorocarbons (HFCs) and additives or low-CO₂ binders in cement and lime production can cut by around 50% process-related emissions (excl. carbon capture) in 2050 compared 2019 in the industrial sector considered. Implementation of the selected list of CE action leads to additional savings in 2040-2050 compared to STD of around 10%. Carbon capture also plays a role in the decarbonisation of process emissions, and CE actions help slightly reduce the carbon capture needs.

The differences in GHG emissions between STD and CIRC only capture a fraction of the positive impact of CE on the decarbonisation of the economy for two main reasons. First, part of the CE impact is already covered in the STD, which assumes implementation of the CEAP; second, the additional CE actions apply into an already well decarbonised energy system, limiting their potential to cut emissions. The contribution to emission reduction of the CE actions can be disaggregated from the one of the decarbonisation of the energy system by assuming a constant carbon intensity in the period from the year of reference (2019) until 2050. In constant carbon intensity settings, the analysis shows that selected list of CE actions could reduce industrial emissions in the sectors under scrutiny by around 20% in the CIRC scenario with respect to STD (in 2050).

Net residual emissions of around 10% of 2019 values are projected in 2050 (see Figure 59). This is explained mainly by the assumptions taken on the role of carbon capture in these scenarios, which has been applied only to the emissions of processes where other mitigation strategies (e.g., fuel and process switch) are lacking today, i.e., in the cement sector. Residual emission confirms that a larger deployment of carbon capture in additional (e.g., steel, chemical) and emerging (e.g., DACC) sectors, or compensation of emission by other sectors (e.g. LULUCF) are needed to reach climate neutrality in industry.

Figure 59: GHG emissions by type in % of 2019 values



Note: 2019 is taken as the calibration year for the FORECAST model.

Source: FORECAST.

1.5. Transport

1.5.1. Introduction

All the decarbonisation pathways for the transport sector ⁽¹⁰⁹⁾ analysed in this impact assessment show a sustained growth in transport activity at EU level, as well as a modal shift to rail, from now to 2040 and 2050 (see Section 1.5.2). Nevertheless, as explained in Section 1.5.3, the total amount of energy consumed by the EU's transport sector is projected to decline significantly because of large-scale electrification (notably in road transport) and implementation of technological and operational measures to improve energy efficiency (notably in maritime and air transport). Furthermore, the fuel mix of the transport sector is projected to undergo a deep transformation characterised by a significant reduction in the consumption of fossil fuels, which are largely replaced by zero- and low-emission energy carriers (i.e., electricity, advanced liquid biofuels and biogas, e-fuels and hydrogen) by 2040 and almost fully replaced by them by 2050. In terms of decarbonisation options deployed, road and rail transport are largely electrified over time, whereas the maritime and air transport sectors, which are hard to electrify, deploy measures to improve energy efficiency combined with a significant uptake of zero- and low-emission fuels, particularly liquid biofuels, biogas and e-fuels (see Section 1.5.4). Consequently, direct CO₂ emissions from the EU's transport sector are projected to decrease dramatically in the next decades, especially after 2030 (see Section 1.5.5). Road and maritime transport are the modes reducing their CO₂ emissions the most by 2040, and most of the transport-related emissions remaining in 2050 are projected to come from the international aviation sector.

The decarbonisation pathways for the transport sector are in line with the results of the public consultation. The participants to the “expert section” of the public consultation think that the transport sector will be one of the key sectors affected by the green transition after 2030, particularly because of the transition to electric vehicles and

⁽¹⁰⁹⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

alternative fuels (this is mentioned by 20% of the respondents). The results of the public consultation also show that, amongst all economic sectors, the respondents give the highest priority to reduce emissions caused by the transport sector, particularly “aviation and maritime transport” (with an average priority of 4.42 between 1 and 5, 5 being the highest priority level) and “road transport” (with an average priority of 4.39 between 1 and 5). However, overall, the respondents think that “aviation and maritime transport” will be the last economic sectors to become climate neutral, compared to “production of electricity and district heating”, “industrial processes and waste”, “buildings”, “agriculture, forestry and other land use” and “road transport”.

1.5.2. Activity

A sustained growth in transport activity at EU level is observed in all scenarios, following the post-COVID recovery. Total **passenger transport** activity (expressed in passenger-km, excluding international navigation and extra-EU aviation), increases to a similar extent in the main scenarios (S1, S2 and S3). As shown in Figure 60 and Figure 61, in these scenarios, total activity increases by 26-27% (depending on the scenario) in 2040 and 32% in 2050 compared to 2015. However, there are differences between transport modes with respect to activity growth. The modes showing the greatest increase in activity relative to 2015 are rail (65-67% in 2040 and 83-86% in 2050), driven mainly by the revision of the TEN-T Regulation, CEF funding, the proposal for the increase in railway capacity use and the action plan to boost long-distance and cross-border passenger rail, and intra-EU aviation (56-57% increase in 2040 and 74% increase in 2050), driven by the sustained economic growth and the post-COVID recovery. Road transport activity grows by 20-21% between 2015 and 2040 (see Figure 61) and then mostly stabilises (between 2015 and 2050, activity grows by 23%, see Figure 60). Domestic navigation activity is projected to increase by 12-17% in 2040 and by 20-23% in 2050, relative to 2015 ⁽¹¹⁰⁾. There are slight differences between the three main scenarios. The S3 scenario shows the highest increase in rail transport activity and the lowest increase in road and air transport activity over time, whereas the S1 scenario shows the lowest increase in rail transport activity and the highest increase in road and air transport activity.

In LIFE, total passenger transport activity (excluding international navigation and extra-EU aviation) still increases over time, but less than in the three main scenarios ⁽¹¹¹⁾. As shown in Figure 60 and Figure 61, total passenger activity increases by 22% in 2040 and 27% in 2050 compared to 2015 (i.e., 4-5 and 5-6 percentage points less than in the other scenarios, respectively). If one looks at the activity per mode, intra-EU aviation shows much lower activity growth rates relative to 2015 than the other scenarios (42% in 2040, i.e., 15-16 pp less than in S2 and S3, and 47% in 2050, i.e., 27 pp less), driven by the assumed substitution of some business trips with video conferences, reduction in the

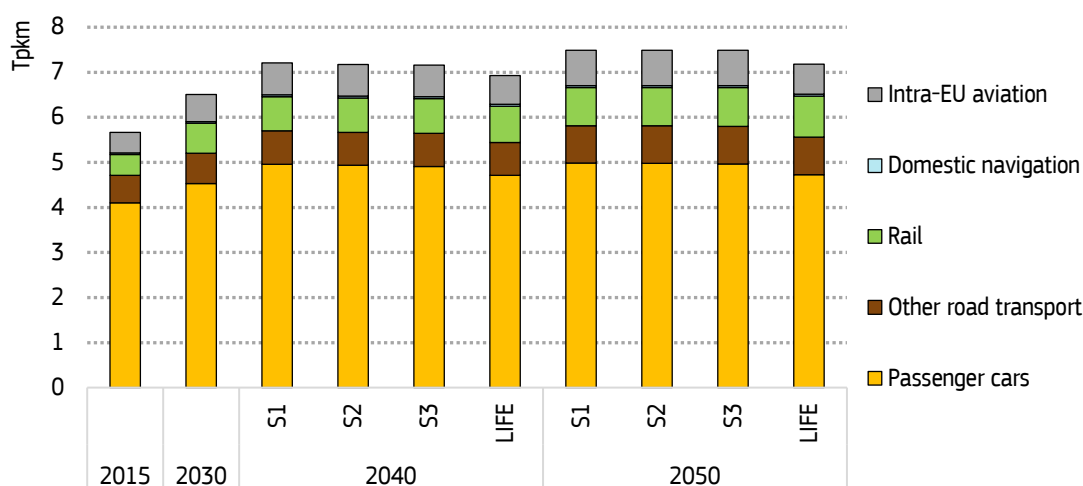
⁽¹¹⁰⁾ In this impact assessment, the term *domestic navigation* includes inland waterway transport and national maritime transport. These two waterborne transport modes are grouped together because a split between inland waterway and national maritime transport is currently not available in the official energy statistics, so the PRIMES model takes them together.

⁽¹¹¹⁾ Other analyses look at much stronger changes in mobility patterns. For instance, the CLEVER scenario published in “*Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables*” projects a 21% reduction in passenger traffic between 2019 and 2050. However, the costs associated to these changes are not assessed.

distance travelled for trips for personal purposes, and modal shift towards high-speed rail where available. Passenger road transport also shows lower activity growth rates relative to 2015 than in the other scenarios (15% in 2040 and 18% in 2050, i.e., 4-5 pp less than in S2 and S3 in both years). Note that it is assumed that part of this difference in road transport activity growth is replaced by an increased use of active modes, which is not represented in the PRIMES model. Instead, passenger rail activity increases much more than in the other scenarios (74% in 2040, i.e., 7-9 pp more than in S2 and S3, and 97% in 2050, i.e., 10-13 pp more). Domestic navigation activity is projected to increase by 12% in 2040 and by 22% in 2050, relative to 2015, that is to say, similarly to the main scenarios. Consequently, in LIFE, air transport represents a lower share of the total passenger transport activity (9% in 2040 and 2050) than in the other scenarios (10% in 2040 and 2050), whereas rail transport represents a higher share of the total passenger transport activity (12% in 2040 and 13% 2050) than in the other scenarios (11% in 2040 and 2050). This indicates a modal shift to rail.

International extra-EU aviation activity (expressed in passenger-km) increases by 62% in 2040 and 80-81% in 2050 compared to 2015 in the three main scenarios (S1, S2 and S3), whereas in LIFE it increases to a lesser extent (46% in 2040 and 57% in 2050 relative to 2015, i.e., 16 and 23-24 percentage points less than in S2 and S3 in 2040 and 2050, respectively) ⁽¹¹²⁾.

Figure 60: Passenger transport activity in the EU disaggregated by mode

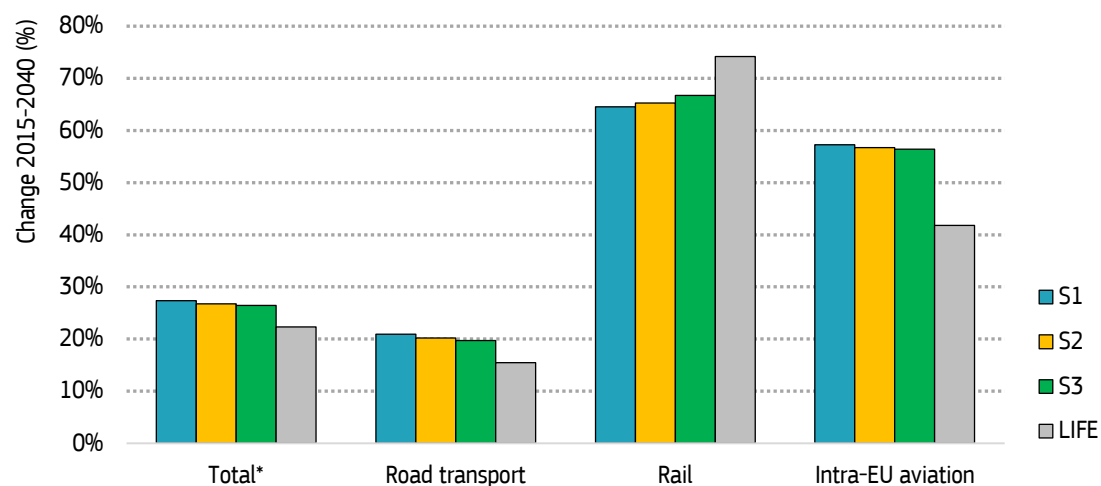


Note: The y-axis label ("Tpkkm") stands for trillion passenger-kilometres.

Source: PRIMES.

⁽¹¹²⁾ In its "Aviation Outlook 2050 – Main Report, 2022" report EUROCONTROL looks at scenarios on the evolution of the number of flights in Europe between 2019 (the year with the highest number of flights) and 2050, reaching +44% in the "base" (or most-likely) scenario, ranging from +54% in the "high" scenario to +20% in the "low" scenario.

Figure 61: Change in passenger transport activity between 2015 and 2040 by mode



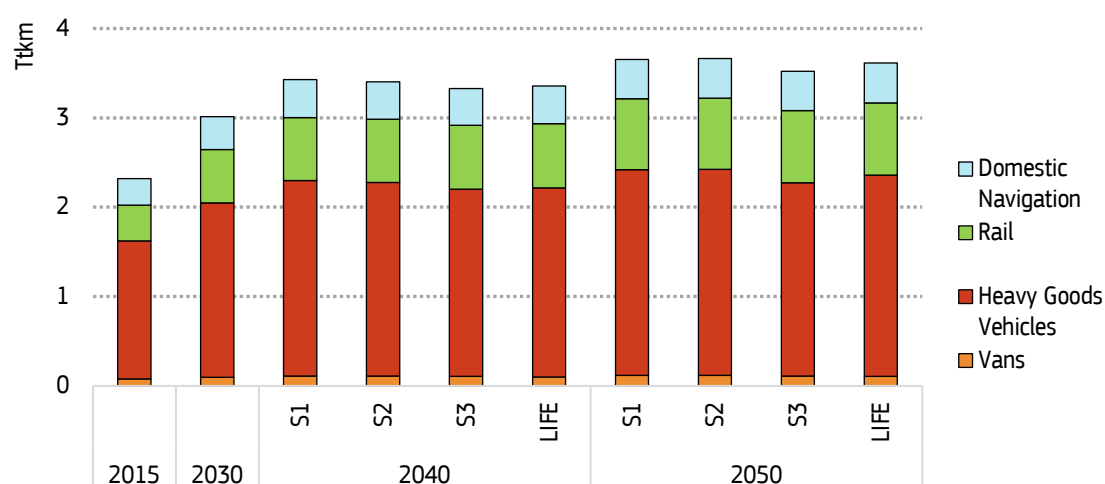
Note: *The total passenger transport activity excludes international navigation and extra-EU aviation.

Source: PRIMES.

Total **freight transport** activity (expressed in tonnes-km, including international shipping), also increases to a similar extent in the S1, S2 and S3 scenarios. As shown in Figure 63, in these scenarios, total activity increases by 35-36% in 2040 and 51% in 2050 compared to 2015. Note, however, that there are significant differences in activity growth between transport modes. The activity of international navigation increases by 34% in 2040 and by 50-51% in 2050 compared to 2015, and the activity growth is slightly higher in the S3 scenario than in the S1 and S2 scenarios. Rail shows the greatest increase in freight transport activity relative to 2015 amongst all modes (77-79% in 2040 and 99-102% in 2050), driven mainly by the revision of the TEN-T Regulation, CEF funding, the proposal for the increase in railway capacity use, and the proposed revision of the Combined Transport Directive. The S3 scenario shows the highest increase in rail transport activity over the 2015-2040 and 2015-2050 periods, and the S1 scenario shows the lowest increase over the same periods (see Figure 62 and Figure 63). Regarding road transport, the S3 scenario shows a lower increase in activity over the 2015-2040 and 2015-2050 periods (36% and 40%, respectively) than the S1 and S2 scenarios. Instead, the S1 scenario shows the highest growth in activity between 2015 and 2040 (41%). Road transport activity increases to a similar degree over the 2015-2050 period in the S1 and S2 scenarios (49%), which is greater than that of the S3 scenario. All three scenarios reflect the proposed revision of the Weights and Dimensions Directive. Domestic navigation activity is projected to grow by 40-44% over the 2015-2040 period and by 48-51% over the 2015-2050 period.

In LIFE, the increase in total freight transport activity (expressed in tonnes-km) is similar to the other scenarios. However, there are small differences between modes. As shown in Figure 63, road transport shows an increase in activity compared to 2015 that is lower than in S2 but higher than in S3 (36% in 2040 and 45% in 2050, i.e., 4 percentage points less than S2 in both years, 1 pp more than in S3 in 2040 and 5 pp more than in S3 in 2050). Instead, rail transport shows slightly higher activity growth rates relative to 2015 than the S2 scenario (80% in 2040 and 102% in 2050, i.e., up to 2 pp more than S2 and S3 in both years). Furthermore, the increase in domestic navigation activity between 2015 and 2040 is also slightly higher in LIFE than in S2 and S3. This indicates a modal shift to rail and domestic navigation.

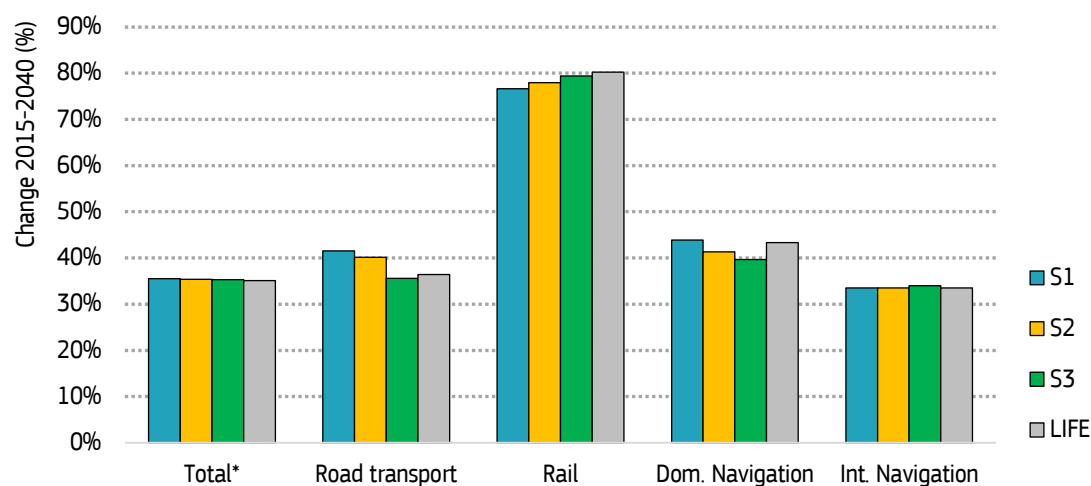
Figure 62: EU freight transport activity by mode (excluding international navigation)



Note: The y-axis label ("Ttkm") stands for trillion tonne-kilometres.

Source: PRIMES.

Figure 63: Change in EU freight transport activity between 2015 and 2040 by mode



Note: *The total freight transport activity includes international navigation.

Source: PRIMES.

1.5.3. Energy consumption and fuel mix

The total amount of energy consumed by the transport sector in the EU significantly decreases between 2015 and 2050 in all scenarios (even though transport activity increases over that period, as discussed in Section 1.5.2), thanks to major energy consumption reductions in road transport. The main reasons are electrification⁽¹¹³⁾ (notably in road transport) and energy efficiency improvements. As shown in Figure 64 and Figure 65, in the S1, S2 and S3 scenarios, total energy consumption (expressed in Mtoe, including international aviation and navigation) decreases by 33-35% in 2040 and

⁽¹¹³⁾ In general, electric engines are 3-4 times more energy-efficient than internal combustion engines.

by 42-44% in 2050 compared to 2015. The greatest reduction is observed in the S3 scenario, whereas the lowest reduction is observed in the S1 scenario.

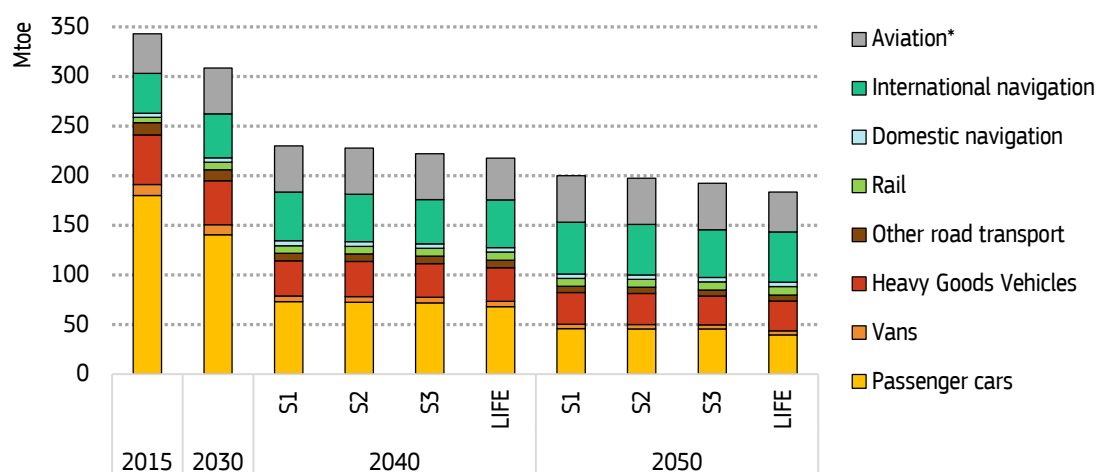
There are significant differences between transport modes. As shown in Figure 64 and Figure 65, a large reduction in energy consumption is observed in **road transport** (by 52-53% in 2040 and 65-67% in 2050 relative to 2015, depending on the scenario). The main reason is the large-scale electrification of the fleet. As a result, the percentage of the total energy consumption in the transport sector attributable to road transport drops from 74% in 2015 to 53-54% in 2040 and around 44% in 2050. The decrease in energy consumption is especially significant for passenger cars: roughly 105 Mtoe in 2040 compared to 2015 (i.e., 60% reduction) and 135 Mtoe in 2050 relative to 2015 (i.e., around 75% reduction). For trucks, the reduction is significant but more moderate, because of lower levels of electrification (see Figure 64).

All **modes other than road transport** increase their energy consumption. These are modes for which the shift to electrification is less prominent than for road transport ⁽¹¹⁴⁾, so their energy consumption increases mainly because of the increased transport activity. However, in relative terms, the increase in energy consumption is significantly lower than the increase in transport activity (see Section 1.5.2), which indicates important energy efficiency gains over time in these transport modes.

In LIFE, the total amount of energy consumed by the transport sector decreases over time a bit more than in the other scenarios, mainly because of a different transport activity pattern (including a higher shift to rail transport, which is a very energy-efficient mode, and to active modes). As shown in Figure 64 and Figure 65, total energy consumption drops by 37% in 2040 and 46% in 2050 compared to 2015 (i.e., 1-3 percentage points more than in S2 and S3 in 2040, and 3-4 pp more in 2050). Road transport shows a slightly greater decrease in energy consumption relative to 2015 than the other scenarios (55% in 2040 and 69% in 2050, i.e., 2 pp more than in S2 and S3 in 2040 and 2-3 pp more than in S2 and S3 in 2050), while aviation shows a much lower increase (6% in 2040, i.e., 11 pp less than in S2 and S3, and 0.5% in 2050, i.e., 16-17 pp less). Instead, energy consumption in rail transport increases more in LIFE than in the other scenarios (by 48% in 2040, i.e., 4-5 pp more than in S2 and S3, and by 54% in 2050, i.e., 4-6 pp more), driven by the higher increase in activity.

⁽¹¹⁴⁾ In the case of rail transport, the shift to electrification is less prominent than for road transport only because currently the sector is already largely electrified.

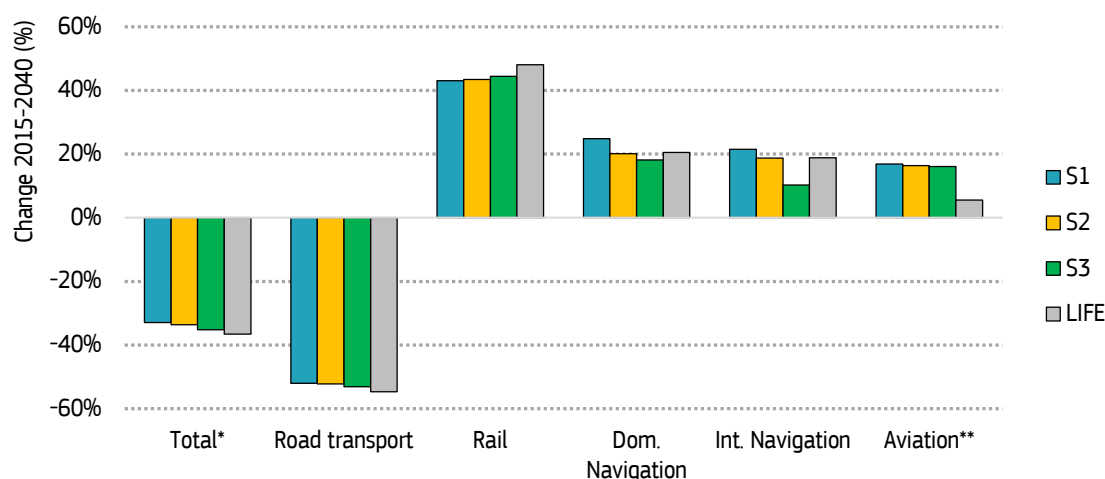
Figure 64: EU energy consumption in the transport sector by mode



Note: *Aviation includes domestic aviation as well as international intra-EU and extra-EU aviation.

Source: PRIMES.

Figure 65: Change in EU energy consumption between 2015 and 2040 by mode



Note: *The total energy consumption includes international transport. **Aviation includes domestic aviation as well as international intra-EU and extra-EU aviation.

Source: PRIMES.

The analysis of the fuel mix in the transport sector shows a significant reduction in the consumption of fossil fuels (i.e., oil products and natural gas) between 2015 and 2050, which are partially replaced by electricity, advanced liquid biofuels and biogas, e-fuels and hydrogen. As shown in Figure 66, in the S1, S2 and S3 scenarios, fossil fuel consumption in the EU drops from almost 326 Mtoe in 2015 to 12-16 Mtoe in 2050 (i.e., 95-96% reduction). Most of the fossil fuel consumption remaining in 2050 occurs in the aviation sector. In 2040, fossil fuel consumption is 68% to 77% lower than in 2015, depending on the scenario (68% in S1, 74% in S2 and 77% in S3). Fossil fuel consumption constituted 95% of the total energy consumption in 2015, but this share drops to 33-45% in 2040 and 6-8% in 2050, depending on the scenario.

Instead, electricity consumption in the EU's transport sector increases from less than 5 Mtoe in 2015 to 42-43 Mtoe in 2040 and 53-54 Mtoe in 2050 in the S1, S2 and S3 scenarios (see Figure 66). This represents 15-16% of the EU's total final electricity

consumption across all sectors in 2040 and around 17% in 2050 (with small differences between the scenarios). The main driver is the electrification of road transport; however, it should be noted that electricity consumption in rail transport also increases significantly (it almost doubles between 2015 and 2050). As a result, the share of electricity in the total energy consumption of the transport sector increases from around 1% in 2015 to 19% in 2040 and 27-28% in 2050, depending on the scenario (the highest shares are observed in S3, and the lowest shares are observed in S1).

Hydrogen consumption in the EU's transport sector increases from almost zero in 2015 to 14-16 Mtoe in 2040 and 35-40 Mtoe in 2050 in the S1, S2 and S3 scenarios (see Figure 66). Based on the assumptions on hydrogen production pathways and efficiency, producing this amount of hydrogen will require around 17-19 Mtoe of (renewable) electricity in 2040 and 42-48 Mtoe in 2050. In 2040, almost all hydrogen used in the transport sector (more than 90%) is consumed by road transport alone. In 2050, this percentage drops to 75-80% (depending on the scenario), because the navigation and aviation sectors also consume significant amounts of hydrogen. The use of hydrogen in rail transport is more limited; it is mainly used where electrification is not possible. In the S1, S2 and S3 scenarios, the share of hydrogen in the total energy consumption of the transport sector increases from almost zero in 2015 to 6-7% in 2040 and 18-21% in 2050 (the highest shares are observed in S3, and the lowest shares are observed in S1).

As shown in Figure 66, the consumption of liquid biofuels and biogas increases from around 13 Mtoe in 2015 (mostly bioliquids used in road transport) to 48-52 Mtoe in 2040 in the three main scenarios, mainly because of increased consumption in the navigation and aviation sectors ⁽¹¹⁵⁾, which are generally considered hard to decarbonise through electrification. In 2050, instead, the consumption of liquid biofuels and biogas decreases to 41-47 Mtoe, depending on the scenario. The main reason is a strong reduction in liquid biofuel consumption in the road transport sector relative to 2040 (due to growing electrification and use of hydrogen), even if consumption in the navigation and aviation sectors continues to rise. In the S1, S2 and S3 scenarios, the consumption of liquid biofuels and biogas represents 21 to 23% of the total energy consumption of the transport sector (depending on the scenario) in 2040, and 22-23% in 2050. Bioliquids dominate, but the importance of biogas, which is mostly used in the navigation sector, grows over time: biogas use constitutes 7-8% of the total consumption of bioliquids and biogas in 2040 (depending on the scenario), but this share increases to 16% in 2050 (in all three main scenarios).

In the S1, S2 and S3 scenarios, the consumption of e-fuels (including e-gas and e-liquids ⁽¹¹⁶⁾) in the EU rises from zero in 2015 to 22-40 Mtoe in 2040 and 45-49 Mtoe in 2050 (depending on the scenario), which are mainly consumed by road transport, navigation and aviation ⁽¹¹⁷⁾. Based on the assumptions on e-fuel production pathways and efficiency, producing this amount of e-fuels will require around 38-69 Mtoe of (renewable) electricity in 2040 and 76-84 Mtoe in 2050. Note that there are significant differences in e-fuel use between scenarios in 2040: 22 Mtoe in S1, 34 Mtoe in S2 and 40

⁽¹¹⁵⁾ Only bioliquids are used in aviation.

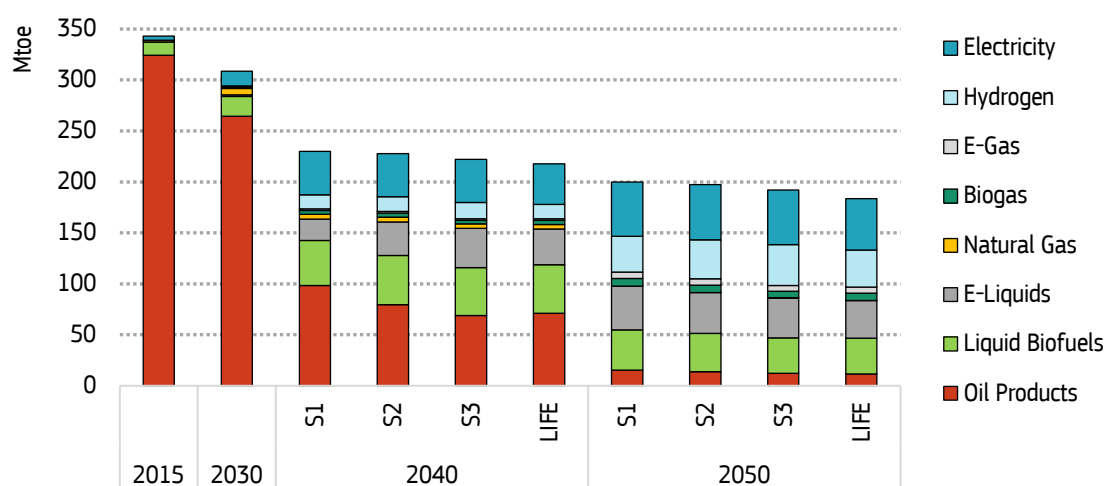
⁽¹¹⁶⁾ E-liquids include e-ammonia and e-methanol.

⁽¹¹⁷⁾ Only e-liquids are used in aviation.

Mtoe in S3 (see Figure 66). These differences are caused mainly by differences in e-fuel consumption in the road transport sector, in which reduced consumption of fossil fuels in the most ambitious scenarios is mostly compensated by increased consumption of e-fuels. E-fuel consumption in road transport in 2040 is rather small in the S1 scenario (roughly 3 Mtoe), but it is significantly higher in the S2 and S3 scenarios (12 and 17 Mtoe, respectively). As a result of the above, in the S1, S2 and S3 scenarios, the share of e-fuels in the total energy consumption of the transport sector increases from zero in 2015 to 10-18% in 2040 and 23-25% in 2050. The consumption of liquid e-fuels is much higher than that of gaseous e-fuels. However, the importance of e-gas, which is mostly used in the navigation sector, increases over time: 4-6% of e-fuel consumption in 2040 corresponds to e-gas, depending on the scenario, whereas in 2050 this share is 13-14%.

In LIFE, the total amount of energy consumed by the transport sector decreases over time a bit more than in the other scenarios, mainly because of the different transport activity pattern, as already explained above. However, in relative terms, the fuel mix of the transport sector is very similar to that of the S2 and S3 scenarios (see Figure 66). More specifically, in LIFE, in 2040, fossil fuel and e-fuel shares are in between those observed in S2 and S3, whereas electricity, hydrogen and liquid biofuel and biogas shares are similar in S2, S3 and LIFE.

Figure 66: EU energy consumption in the transport sector by fuel/energy carrier type



Note: Energy consumption including international aviation and navigation.

Source: PRIMES.

1.5.4. Technology developments per transport mode

1.5.4.1. Passenger cars and vans

A deep transformation of the EU's car and van fleet occurs between 2015 and 2050, driven mainly by the new regulation strengthening the CO₂ emission performance standards applicable to these types of vehicles. In 2015, the fleet consists practically only of conventional ICE cars and vans. Over time, however, the share of ICE vehicles rapidly declines, and these vehicles are replaced by battery-electric vehicles and, to a lesser

degree, fuel-cell and plug-in hybrid vehicles ⁽¹¹⁸⁾ ⁽¹¹⁹⁾. As a result, the EU's car and van fleet goes from consuming almost only fossil fuels in 2015 to consuming energy mostly in the form of electricity and hydrogen in 2050.

As shown in Figure 67, in the S1, S2 and S3 scenarios, the share of ICE **passenger cars** (including diesel, gasoline, LPG and CNG vehicles) in the EU's car stock declines from practically 100% in 2015, to 26% in 2040 and 2% in 2050. These vehicles are substituted by battery-electric, fuel-cell and plug-in hybrid cars. The share of battery-electric cars increases to 57-58% in 2040 and 79-80% in 2050 (depending on the scenario), and the share of fuel-cell cars increases to 5% in 2040 and 14% in 2050. The share of plug-in hybrids increases to 11% in 2040, which indicates that this technology has a role to play in the transition away from fossil fuels. However, in 2050, the share of plug-in hybrids decreases to 5%, as zero-emission powertrains become dominant. As a result of the above, the passenger car fleet goes from consuming mostly only fossil fuels in 2015 (95% of the total amount of energy consumed by cars) to consuming mostly electricity and hydrogen (91% of the total energy consumption) and almost no fossil fuels in 2050 (see Figure 68). Finally, it should be noted that the total energy consumption by cars drops from around 180 Mtoe in 2015 to 72-73 Mtoe in 2040 and 45-46 Mtoe in 2050 (which means it decreases by roughly 60% and 75% in 2040 and 2050, respectively, relative to 2015). This occurs even if transport activity by car (expressed in passenger-km) increases by 20-21% and 21-22% over the 2015-2040 and 2015-2050 periods, respectively (see Section 1.5.2). This can be explained by the significant energy efficiency gains related to electrification.

The picture looks similar for **vans**, although in this case the switch to alternative drivetrains is slightly more moderate than for cars in 2040. In the S1, S2 and S3 scenarios, the share of ICE vehicles in the EU's van stock declines from virtually 100% in 2015, to 38% in 2040 and 3% in 2050, as ICE vans are replaced by battery-electric, fuel-cell and plug-in hybrid vans. The share of battery-electric vehicles increases to 39-40% in 2040 (depending on the scenario) and 74% in 2050, and the share of fuel-cell vans rises to 5% in 2040 and 15-16% in 2050. As a result, the van fleet goes from consuming mostly only fossil fuels in 2015 (94% of the total amount of energy consumed by vans) to consuming mainly electricity and hydrogen (91% of the total energy consumption) and almost no fossil fuels in 2050, similarly to passenger cars. Also, the total amount of energy consumed by vans in the EU drops by 47-48% in 2040 and by 60-63% in 2050, relative to 2015, even though transport activity by vans actually increases

⁽¹¹⁸⁾ The electric passenger car and van market is growing rapidly. According to IEA's 'Global EV Outlook 2023', in Europe, electric passenger car sales increased by more than 15% in 2022 relative to 2021 to reach 2.7 million units (including battery-electric and plug-in hybrid cars). As a result, 21% of all new cars sold in Europe in 2022 were electric, up from 18% in 2021, 10% in 2020 and less than 3% prior to 2019. Electric van sales increased by around 50% in 2022 relative to 2021 to reach 95 000 units (including battery-electric and plug-in hybrid vehicles). As a result, 5% of all new vans sold in Europe in 2022 were electric, up from 3% in 2021 and less than 2% prior to 2020. Note that, in IEA's study, "Europe" includes the EU countries, Iceland, Israel, Norway, Switzerland, Türkiye, and the UK.

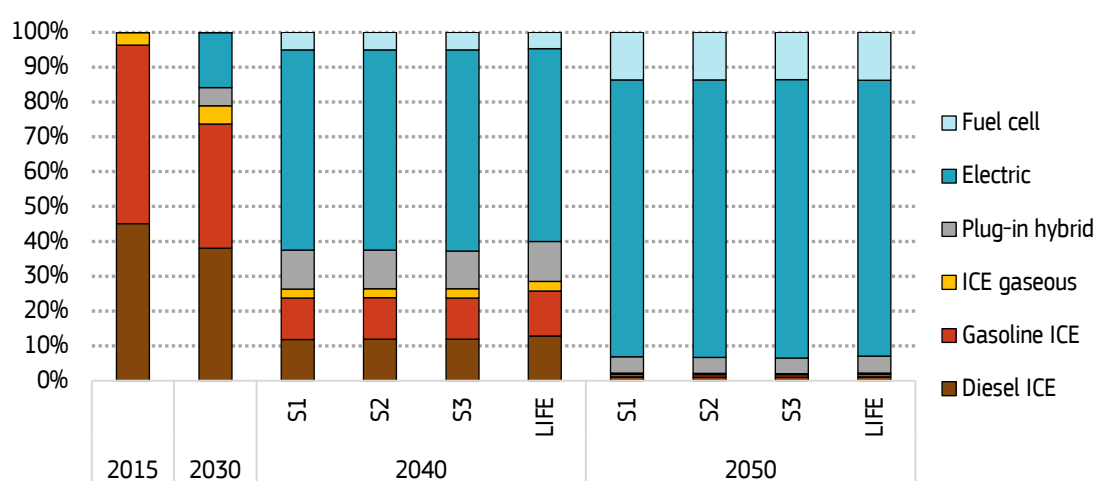
⁽¹¹⁹⁾ The share of electric vehicles (including battery-electric and plug-in hybrid vehicles) in the annual amount of cars and vans sold in Europe is expected to continue rising in the next years, reaching more than 40% in 2026 (according to BNEF's 'Electric Vehicle Outlook 2023') and around 60% in 2030 (according to IEA's 'Global EV Outlook 2023', in the Stated Policies Scenario).

over the same periods (see Section 1.5.2). Again, this can be explained by the significant energy efficiency gains related to electrification.

It should be noted that the carbon intensity of the fuels used by ICE cars and vans is significantly lower in 2040 and 2050 than in 2015, owing to the increased consumption of liquid biofuels, biogas and e-fuels relative to fossil fuels. This is particularly important in 2040, with significant differences between the S1, S2 and S3 scenarios (see Figure 68). The total amount of fossil fuels, liquid biofuels, biogas and e-fuels consumed by passenger cars and vans in 2040 is similar in the three main scenarios (45-46 Mtoe). However, disaggregating per fuel shows that, in 2040, fossil fuel consumption is higher, and liquid biofuel and e-liquid consumption is lower in the S1 scenario than in the S2 and S3 scenarios. Instead, the S3 scenario shows a lower consumption of fossil fuels and a greater consumption of liquid biofuels and e-liquids than the S1 and S2 scenarios. Biogas and e-gas consumption is similar in the three main scenarios. This implies that the carbon intensity (expressed in tCO₂/toe) of fuels used by the ICE passenger cars and vans remaining in the fleet in 2040 is highest in the S1 scenario (21% lower intensity than in 2015) and lowest in the S3 scenario (49% lower intensity than in 2015). In 2050, the carbon intensity is 89-93% lower than in 2015 in the main scenarios, with S3 scenario showing the largest decrease (93%).

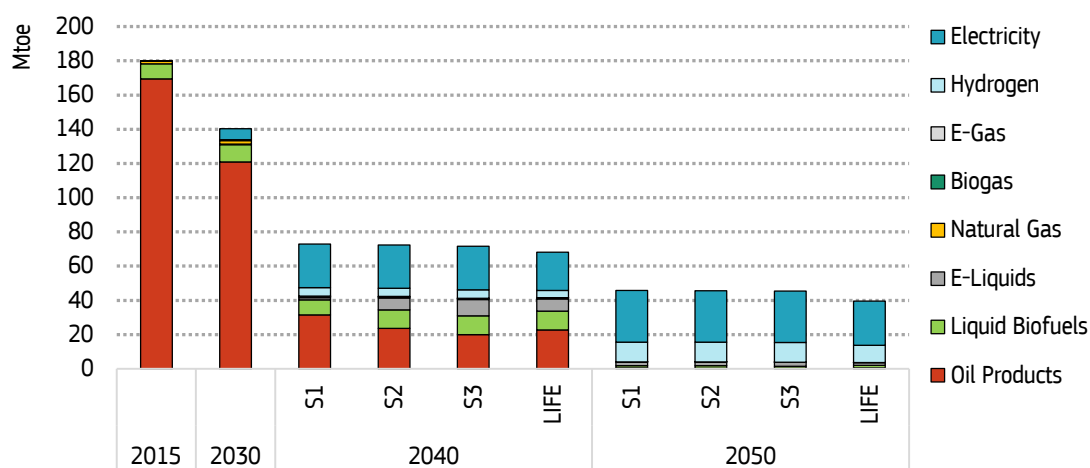
In LIFE, the total amount of energy consumed by cars and vans decreases over time a bit more than in the other scenarios, mainly because of the lower transport activity (expressed in passenger-km for cars, and in tonnes-km for vans). For passenger cars, total energy consumption drops by 62% in 2040 and by 78% in 2050 compared to 2015 (i.e., 2 percentage points more than in the S2 and S3 scenarios in 2040, and 3 pp more in 2050). For vans, energy consumption drops by 52% in 2040 and 63% in 2050 compared to 2015 (i.e., 4-5 pp more than in the S2 and S3 scenarios in 2040, and 1-3 pp more in 2050). In 2040, both for cars and vans, the fuel mix is similar to that of the S2 scenario (in relative terms).

Figure 67: Distribution of the EU passenger car stock per type of drivetrain



Source: PRIMES.

Figure 68: EU energy consumption by passenger cars by fuel/energy carrier type



Source: PRIMES.

1.5.4.2. Heavy Goods Vehicles (HGVs)

The EU's HGV stock undergoes a deep transformation between 2015 and 2050, driven mainly by the proposed revision of the regulation on CO₂ emission standards for heavy duty vehicles ⁽¹²⁰⁾. In 2015, the fleet consisted almost entirely of diesel conventional ICE vehicles, but over time their share is projected to decline, and these vehicles are largely replaced by battery-electric vehicles and hydrogen vehicles (the latter, mostly for long-haul transport) ⁽¹²¹⁾. Consequently, the EU's HGV fleet goes from consuming almost only fossil fuels in 2015 to consuming mostly electricity and hydrogen in 2050.

As shown in Figure 69, in the S1, S2 and S3 scenarios, the total share of diesel conventional, diesel hybrid ⁽¹²²⁾, LPG and LNG vehicles in the EU's HGV stock drops from virtually 100% in 2015, to 62-64% in 2040 and 21-29% in 2050 (depending on the scenario). These vehicles are replaced mostly by battery-electric and hydrogen HGVs. The share of battery-electric vehicles in the HGV stock increases to 24-25% in 2040 and 45-48% in 2050, and the share of hydrogen HGVs increases to 12-14% in 2040 and 26-31% in 2050. As already mentioned above, however, there is still a significant percentage of diesel conventional, diesel hybrid and ICE gaseous vehicles left in 2050 (21-29% of the HGV stock, depending on the scenario). The differences between scenarios, particularly observed in 2050, are mainly due to different assumptions on HDV CO₂ standards from 2040 onwards (see Annex 6). S1 is the scenario assuming the least

⁽¹²⁰⁾ COM(2023) 88 final.

⁽¹²¹⁾ Electric truck sales are currently low, but this market is growing. According to IEA's 'Global EV Outlook 2023', 0.5% of all new trucks sold in Europe in 2022 were electric (including battery-electric and plug-in hybrid vehicles). This is a small share, but an increasing trend is observed in the last years (the share of electric truck sales was almost zero in 2017 and 0.2% in 2020). Furthermore, the share of electric truck sales is projected to continue rising in the next years, reaching 10% in Europe and 13% in the EU in 2030 (in the Stated Policies Scenario). Note that, in IEA's study, "Europe" includes the EU countries, Iceland, Israel, Norway, Switzerland, Türkiye, and the UK.

⁽¹²²⁾ Here, diesel hybrid vehicles include plug-in hybrids. The share of plug-in hybrids in the HGV stock is limited (below 2% of the fleet in all years up to 2050).

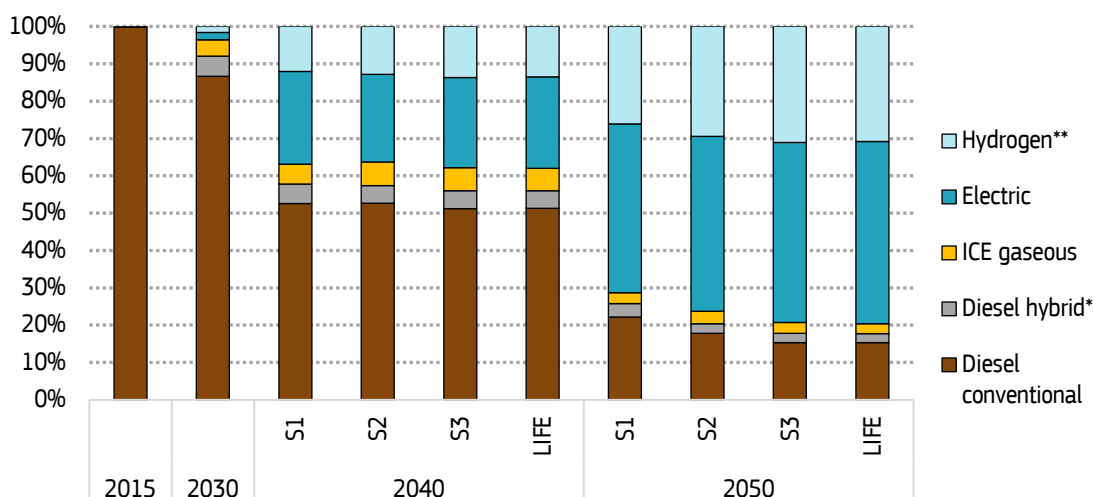
stringent CO₂ standards in the 2040-2050 period, and S3 is the scenario assuming the most stringent ones. This is why the S1 scenario shows the largest share of diesel conventional, diesel hybrid and ICE gaseous vehicles (29%) and the smallest share of battery-electric and hydrogen vehicles (71% taken together) in 2050, whereas S3 is the scenario showing the smallest share of diesel conventional, diesel hybrid and ICE gaseous vehicles (21%) and the biggest share of battery-electric and hydrogen vehicles that year (79% in aggregate).

As a result of the fleet transformation described above, the HGV fleet goes from consuming mostly only fossil fuels in 2015 (94% of the total amount of energy consumed by HGVs) to consuming mostly hydrogen and electricity (70-84% of the total energy consumption, depending on the scenario) and almost no fossil fuels in 2050 (see Figure 70). Moreover, as in the case of passenger cars and vans, the diesel conventional, diesel hybrid and ICE gaseous vehicles remaining in the fleet in 2040 and 2050 use fuels that have a significantly lower carbon intensity than in 2015, owing to the increased consumption of liquid biofuels, biogas and e-fuels relative to fossil fuels. This is particularly important in 2040, with significant differences in carbon intensity between the S1, S2 and S3 scenarios. More specifically, the carbon intensity of fuels used by diesel conventional, diesel hybrid and ICE gaseous vehicles in 2040 is highest in the S1 scenario (24% lower intensity than in 2015) and lowest in the S3 scenario (52% lower intensity than in 2015). In 2050, instead, the remaining diesel conventional, diesel hybrid and ICE gaseous vehicles use almost no fossil fuels in all three scenarios (see Figure 70); hence, the carbon intensity is similar in the three main scenarios (95-98% lower than in 2015).

Furthermore, it should be noted that the total amount of energy consumed by HGVs in the EU, which is almost 50 Mtoe in 2015, decreases by 29% in S1 and S2 and 32% in S3 in 2040, and by 36% in S1, 37% in S2 and 42% in S3 in 2050, compared to 2015 (see Figure 70). This occurs even if the HGV transport activity (expressed in tonnes-km) increases by 35-41% and 40-49% (depending on the scenario) over the 2015-2040 and 2015-2050 periods, respectively (see Section 1.5.2). This is mostly explained by the energy efficiency gains linked to electrification.

In LIFE, the total amount of energy consumed by HGVs decreases over time a bit more than in the S1 and S2 scenarios, mainly because of a slightly lower level of HGV transport activity (expressed in tonnes-km), due to a shift to other modes, such as rail. However, the total energy consumption in LIFE is slightly higher than in S3, mainly because of the somewhat higher level of HGV transport activity. More specifically, the total energy consumption drops by 32% in 2040 and 40% in 2050 compared to 2015 (i.e., 3 percentage points more than in S1 and S2 in 2040 and 3-4 pp more in 2050, and 0.1 pp less than in S3 in 2040 and 2 pp less in 2050). In 2040, the fuel mix in LIFE has similar characteristics to the fuel mix of both the S2 and S3 scenarios (in relative terms).

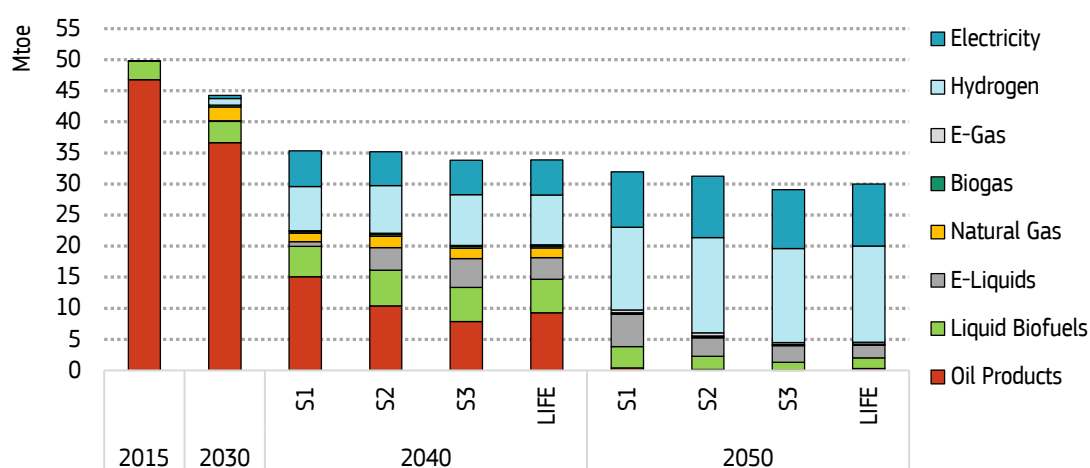
Figure 69: Distribution of the EU HGV stock by type of drivetrain



Note: *Diesel hybrid vehicles include plug-in hybrids. **Hydrogen vehicles include fuel-cell vehicles and hydrogen ICE vehicles.

Source: PRIMES.

Figure 70: EU energy consumption by HGVs by fuel/energy carrier type



Source: PRIMES.

1.5.4.3. Other road transport

The EU's fleet of buses and coaches is projected to undergo significant changes between 2015 and 2050, driven mainly by the proposed revision of the regulation on CO₂ emission standards for heavy duty vehicles⁽¹²³⁾. In 2015, the fleet consisted almost entirely of diesel ICE vehicles. However, battery-electric and hydrogen vehicles are expected to largely replace this type of vehicles by 2050⁽¹²⁴⁾. Buses are used mostly

⁽¹²³⁾ COM(2023) 88 final.

⁽¹²⁴⁾ Electric bus and coach sales are growing. According to IEA's 'Global EV Outlook 2023', around 9% of all new buses and coaches sold in Europe in 2022 were electric (including battery-electric and plug-in hybrid vehicles), up from around 7% in 2021, 4% in 2020 and less than 3% prior to 2019. Furthermore, the share of electric bus and coach sales is projected to continue rising in the next years,

within urban areas, where battery-electric vehicles are generally a fully viable alternative, and this allows high shares of this type of vehicles. Instead, coaches are mainly used for long inter-urban trips, which imposes operational limitations on the use of battery-electric vehicles; as a result, the share of hydrogen vehicles in the fleet is higher for coaches than for buses. In the S1, S2 and S3 scenarios, the share of battery-electric vehicles in the bus and coach fleet increases to 36-37% in 2040 and 43-44% in 2050, while the share of hydrogen vehicles reaches 15-16% in 2040 and 32-37% in 2050 (the exact share depends on the scenario). It is important to note that, even though the total share of diesel conventional, diesel hybrid ⁽¹²⁵⁾ and ICE gaseous buses and coaches is projected to decline over time, their share remains significant in 2040 and 2050. More specifically, the share of diesel conventional, diesel hybrid and ICE gaseous vehicles in the EU's bus and coach fleet is 47-49% in 2040 and 20-25% in 2050. Note that the exact fleet composition shares differ per scenario. In particular, significant differences can be observed in 2050, which is mainly due to different assumptions on CO₂ emission standards for coaches from 2040 onwards (see Annex 6). As a result of the fleet transformation described above, the EU's bus and coach fleet goes from consuming almost only fossil fuels in 2015 (94% of the total energy consumption) to using mostly alternative energy carriers in 2050 (electricity, hydrogen, liquid biofuels, biogas and e-fuels represent 95-96% of the total energy consumption in that year).

The EU's fleet of powered 2-wheelers becomes largely electrified between 2015 and 2050 ⁽¹²⁶⁾. In the S1, S2 and S3 scenarios, the share of ICE 2-wheelers in the EU's stock declines from virtually 100% in 2015, to 32% in 2040 and 10% in 2050, as ICE vehicles are rapidly replaced by battery-electric vehicles. On the other hand, the share of battery-electric vehicles increases to 68% in 2040 and 90% in 2050. As a result, the 2-wheeler fleet goes from consuming mostly only fossil fuels in 2015 (97% of the total energy consumption) to consuming mainly electricity (78-79% of the total energy consumption) and almost no fossil fuels in 2050.

It should be noted that the total amount of energy consumed by buses, coaches and powered 2-wheelers taken together decreases by 39-40% in 2040 and 49-51% in 2050 compared to 2015. This occurs even if transport activity (expressed in passengers-km) by these transport modes taken together increases by 19-21% and 35-36% over the 2015-2040 and 2015-2050 periods, respectively (see Section 1.5.2). This can be explained by the significant energy efficiency gains related to electrification.

Finally, the diesel conventional, diesel hybrid and ICE gaseous buses and coaches and the ICE 2-wheelers that remain in the fleet in 2040 and 2050 use fuels that have a significantly lower carbon intensity than in 2015, due to the increased consumption of

reaching 40% in Europe and 55% in the EU in 2030 (in the Stated Policies Scenario). Note that, in IEA's study, "Europe" includes the EU countries, Iceland, Israel, Norway, Switzerland, Türkiye, and the UK.

⁽¹²⁵⁾ Diesel hybrid vehicles include plug-in hybrids.

⁽¹²⁶⁾ The electric two- and three-wheeler market is growing. According to IEA's 'Global EV Outlook 2023', in Europe, 8% of all new powered two-wheelers and 7% of all new powered three-wheelers sold in 2022 were electric, up from around 5% and 4%, respectively, in 2020. The share of electric two- and three-wheeler sales is projected to continue rising in the next years, reaching more than 90% in 2040 (according to BNEF's 'Electric Vehicle Outlook 2023').

liquid biofuels, biogas and e-fuels relative to fossil fuels. This is particularly important in 2040, with significant differences in carbon intensity between scenarios. More specifically, the carbon intensity of fuels used by ICE vehicles in 2040 is highest in the S1 scenario (22% lower intensity than in 2015) and lowest in the S3 scenario (51% lower intensity than in 2015), while in 2050 the carbon intensity is similar in all scenarios (88-91% lower intensity than in 2015).

In LIFE, the total amount of energy consumed by buses, coaches and 2-wheelers taken together is similar to that of the other scenarios both in 2040 and 2050 (around 8 and 6 Mtoe, respectively). Furthermore, in 2040, the combined fuel mix for all these modes is similar to that of the S2 scenario.

1.5.4.4. Rail

The EU's rail transport sector is projected to undergo significant further electrification between 2015 and 2050. In 2015, around 67% of the rolling stock used for passenger transport was already electric, while in the case of freight transport this share was a bit lower (55%). The remainder was internal combustion rolling stock. The proportion of electrified lines in use in the EU is increasing gradually (56% in 2015, 57% in 2020), and the share of electric rolling stock is projected to increase considerably by 2040 and 2050. More specifically, in the S1, S2 and S3 scenarios, the share of electric rolling stock used for passenger transport increases to 85-86% in 2040 and 95% in 2050, and the share of electric rolling stock used for freight transport increases to 76-77% in 2040 and 88-89% in 2050 (the exact shares differ slightly per scenario). At the same time, the share of internal combustion rolling stock used for passenger transport drops to 12-13% in 2040 and 4% in 2050, and in the case of freight rail transport, it goes down to 21-22% in 2040 and 10% in 2050. The share of hydrogen rolling stock is projected to be limited; it will be mainly used where electrification is not possible. This transformation requires substantial investments in electric rolling stock as well as significant efforts to largely electrify the European rail infrastructure by 2050 ⁽¹²⁷⁾, and it is supported by the assumed completion of the core TEN-T network by 2030 and the comprehensive TEN-T network by 2050.

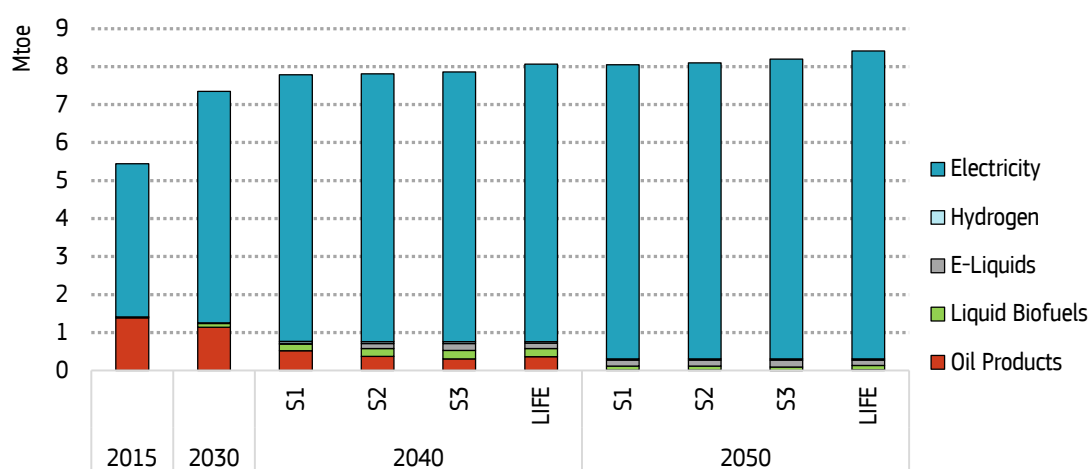
As a result of the transformation described above, in the S1, S2 and S3 scenarios, the EU's rail transport sector transitions from meeting 25% of its energy demand with fossil fuels in 2015 (the remainder being electricity), to using almost only electricity and no fossil fuels in 2050 (see Figure 71). Note that, although the share of internal combustion rolling stock is projected to decline over time, there is still some left both in 2040 and in 2050; however, in these two years, and particularly in 2050, the internal combustion rolling stock uses a fuel blend that has a significantly lower carbon intensity than in 2015, due to the increased consumption of liquid biofuels and e-fuels relative to fossil fuels (see Figure 71). More specifically, in 2040, this carbon intensity is 26% lower in S1, 46% lower in S2 and 56% lower in S3 than in 2015. In 2050, it is more than 95% lower than in 2015 in all three scenarios. Furthermore, it should be noted that the total amount of energy consumed by rail transport in the EU increases by around 43-44% in 2040 and 48-51% in 2050 compared to 2015 (see Figure 71), mainly due to increased rail transport activity (see Section 1.5.2). However, these energy consumption growth rates

⁽¹²⁷⁾ The investment costs corresponding to the electrification of the rail network are not included in the modelling. Instead, the investment costs related to rolling stock are included.

are lower than the activity growth rates observed over the same period. The main reason is that the rail sector is projected to be further electrified during the next decades, which brings significant energy efficiency gains.

In LIFE, the total amount of energy consumed by the rail sector increases over time a bit more than in the S1, S2 and S3 scenarios, mainly because of a higher level of rail transport activity (both in passenger-km and tonnes-km) due to a higher shift from other modes to rail. The total energy consumption increases by 48% in 2040 and 54% in 2050 compared to 2015 (i.e., 4-5 percentage points more than in the core scenarios in 2040, and 4-7 pp more in 2050). Nevertheless, the fuel mix remains similar to that of the core scenarios (in relative terms), particularly S2 and S3.

Figure 71: EU energy consumption in the rail sector by fuel/energy carrier type



Note: Energy consumption including passenger and freight rail transport.

Source: PRIMES.

1.5.4.5. Domestic navigation

As explained in Section 1.5.2, in this impact assessment, the term *domestic navigation* includes inland waterway transport and national maritime transport⁽¹²⁸⁾. The composition of the vessel fleet used for domestic navigation in the EU is projected to undergo significant changes between 2015 and 2050, in a similar way across all scenarios. In 2015, the fleet consisted almost entirely of conventional vessels powered by liquid fossil fuels (i.e., diesel, gasoline and fuel oil). However, the share of vessels using alternative propulsion technologies is expected to grow in the next decades. More specifically, in the S1, S2 and S3 scenarios, the share of battery-electric vessels in the fleet increases to 14% in 2040 and 24% in 2050, while the share of fuel-cell ships, which are deployed only after 2040, becomes 6% in 2050. Furthermore, the share of vessels using gaseous fuels grows over time, reaching 8% of the fleet in 2040 and 11-12% in 2050. It is important to note that, even though the share of vessels equipped with

⁽¹²⁸⁾ These two waterborne transport modes are grouped together because a split between inland waterway and national maritime transport is currently not available in the official energy statistics, so the PRIMES model takes them together.

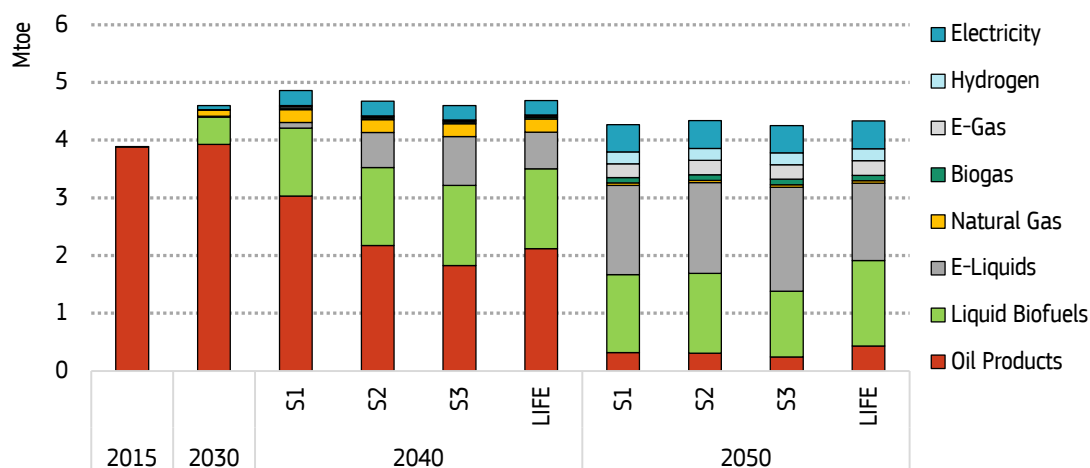
conventional propulsion systems using liquid fuels is projected to decline over time, this ship type remains the predominant one, representing 78% of the EU fleet in 2040 and 58% in 2050.

As a result of the fleet composition changes described above, along with a significant uptake of liquid biofuels, biogas and e-fuels after 2030, the EU's fleet goes from consuming almost only fossil fuels in 2015 to using mostly zero- and low-emission energy carriers in 2050. In the S1, S2 and S3 scenarios, projections show that liquid oil products and natural gas represent only 6-7% and 1% of the total amount of energy consumed by domestic navigation in 2050, respectively (see Figure 72). Instead, liquid biofuels, biogas and e-fuels (in gaseous or liquid form) are projected to represent 76-77% of the total energy consumption in 2050, while the share of electricity and hydrogen taken together reaches 16%. Note that the fuels used by conventional vessels have a significantly lower carbon intensity in 2040 and 2050 than in 2015, due to the increased consumption of liquid biofuels, biogas and e-fuels (both in gaseous and liquid form) relative to fossil fuels (see Figure 72). This is particularly important in 2040, with significant differences in carbon intensity between scenarios. More specifically, the carbon intensity of fuels used by conventional vessels in 2040 is highest in the S1 scenario (31% lower intensity than in 2015) and lowest in the S3 scenario (54% lower intensity than in 2015), while in 2050 it is 91-93% lower than in 2015 in the three main scenarios.

Furthermore, it should be noted that, in S1, S2 and S3, the total amount of energy consumed by domestic navigation in the EU increases by around 18-25% in 2040 and 9-11% in 2050 compared to 2015 (see Figure 72). This occurs in parallel to the deployment of technological and operational measures to improve energy efficiency (e.g., hull design, slow steaming, optimisation of cargo capacity utilisation, etc.) as well as the energy efficiency gains linked to the partial electrification of the fleet.

In LIFE, the total amount of energy consumed in the domestic navigation sector evolves over time in the same way as in the core scenarios (reaching almost 5 Mtoe in 2040 and a bit more than 4 Mtoe in 2050). In 2040, the fuel mix is similar to that of the S2 scenario.

Figure 72: EU energy consumption in domestic navigation by fuel/energy carrier type



Note: Including passenger and freight transport. The category «E-Liquids» includes e-methanol, e-ammonia, synthetic diesel and synthetic fuel oil.

Source: PRIMES.

1.5.4.6. International navigation

The composition of the vessel fleet used for international maritime transport in the EU is projected to change considerably between 2015 and 2050. The transformation is driven by policy measures aimed at decarbonising this sector adopted by the EU (e.g., FuelEU Maritime) and by the International Maritime Organisation (see Annex 6). In 2015, the EU's fleet consisted almost entirely of vessels with conventional engines powered by liquid fossil fuels (i.e., diesel and fuel oil). However, the number of ships using alternative propulsion technologies is projected to grow in the next decades. More specifically, in the S1, S2 and S3 scenarios, the share of battery-electric vessels in the fleet increases to 2-3% in 2040 and 6-7% in 2050, while the share of fuel-cell ships increases to 3-7% in 2040 and 21-29% in 2050 (depending on the scenario), as shown in Figure 73. Furthermore, the share of vessels powered by engines that can use gaseous fuels (which are gradually decarbonised over time) grows significantly until 2040 (reaching 20-21% in 2040) and it remains relatively stable after that year (reaching 21-23% in 2050). It is important to remark that, even though the share of vessels equipped with conventional propulsion systems using liquid fuels is projected to decline over time, this ship type remains the predominant one, representing 71-74% of the EU fleet in 2040 and 44-49% in 2050 (depending on the scenario). Note also that the fleet composition is similar in the S1 and S2 scenarios, whereas in the S3 scenario it shows slightly lower shares of ships with conventional engines along with slightly higher shares of fuel-cell vessels (see Figure 73).

As a result of the fleet composition changes described above, combined with a significant uptake of liquid biofuels, biogas and e-fuels⁽¹²⁹⁾ after 2030, the EU's fleet goes from consuming almost only liquid fossil fuels in 2015 to using almost exclusively zero- and

⁽¹²⁹⁾ Including e-ammonia, e-methanol and other e-fuels.

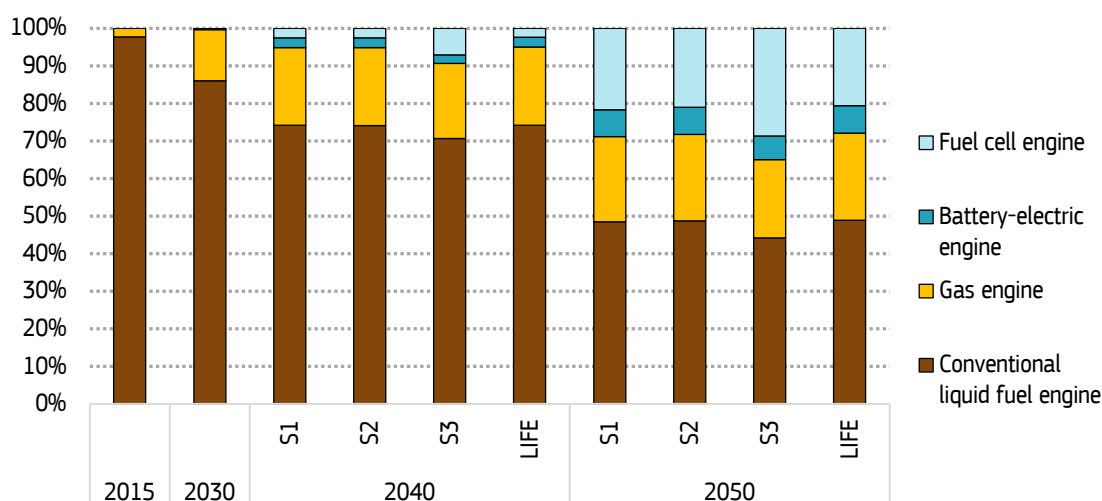
low-emission energy carriers in 2050 ⁽¹³⁰⁾. In the S1, S2 and S3 scenarios, liquid oil products are projected to represent almost 0% of the total amount of energy consumed by international navigation in 2050 (see Figure 74). The use of gaseous fuels (LNG, biogas and e-gas) is projected to increase gradually this decade and the next one, reaching 23-24% of the total energy consumption in 2050. It should be noted that gaseous fuels are gradually decarbonised over time: biogas and e-gas taken together represent 63-70% of the consumption of gaseous fuels in the international navigation sector in 2040, whereas in 2050 this share is close to 100%, as biogas and e-gas progressively replace LNG (see Figure 74). Liquid biofuels and e-liquids are projected to represent 61-62% of the total energy consumption in 2050, whereas electricity and hydrogen represent the remaining 14-16%. Note that the fuels used by vessels equipped with conventional liquid fuel engines or engines that can use gaseous fuels have a significantly lower carbon intensity in 2040 and 2050 than in 2015, due to the increased consumption of liquid biofuels, biogas and e-fuels (both in gaseous and liquid form) relative to fossil fuels. This is particularly important in 2040, with significant differences in carbon intensity between scenarios. More specifically, the carbon intensity of liquid and gaseous fuels in 2040 is highest in the S1 scenario (73% lower intensity than in 2015) and lowest in the S3 scenario (82% lower intensity than in 2015). In 2050, the carbon intensity of these fuels is projected to be almost zero in all scenarios, due to the very low share of fossil fuels in the fuel blend.

It should be noted that the total amount of energy consumed by international navigation in the EU increases by around 10-21% in 2040 and 19-30% in 2050 compared to 2015 in the S1, S2 and S3 scenarios (see Figure 74). However, these growth rates are lower than the increase in international navigation activity projected over the same period (see Section 1.5.2). This can be explained mainly by the deployment of technological and operational measures to improve the energy efficiency of maritime transport (e.g., hull design, slow steaming, optimisation of cargo capacity utilisation, increased vessel size, etc.). The energy intensity of international navigation (expressed in toe/tkm) decreases by 9-18% between 2015 and 2040 and by 13-21% between 2015 and 2050 (the exact rate depends on the scenario), mostly as a result of these measures. Note that there are significant differences between scenarios, with S3 showing the lowest increase in total energy consumption relative to 2015 (see Figure 74), although it is the scenario with the highest level of transport activity (see Section 1.5.2). The main reason for this difference is a larger deployment of energy efficiency measures compared to the S1 and S2 scenarios.

In LIFE, the total amount of energy consumed in the international navigation sector evolves over time in the same way as in S2. However, in 2040, the fuel mix is similar to that of the S3 scenario (in relative terms).

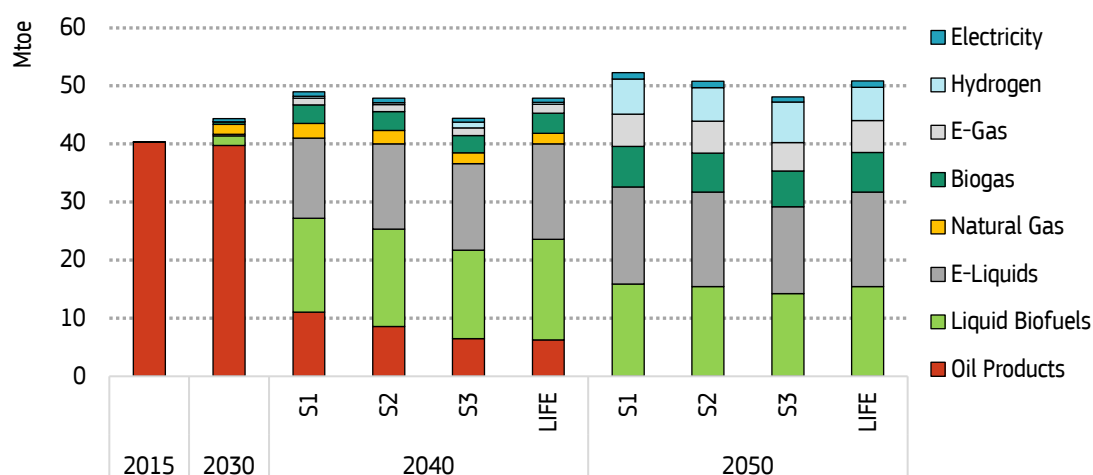
⁽¹³⁰⁾ Projections made by other studies also show an increasing use of zero- and low-emission energy carriers over the next decades. For example, IEA's 'Net Zero Road Map' (2023 update) shows an increase in the use of bioenergy, hydrogen and e-fuels in international shipping at global level, with bioenergy representing 8% and 19% of the energy consumed in 2030 and 2050, respectively, hydrogen representing 4% and 19% in 2030 and 2050, respectively, and e-fuels (mostly, ammonia), representing 7% and 47% in the same years. Similarly, DNV's 'Energy Transition Outlook 2023' argues that the main decarbonisation opportunity for the international maritime sector is switching to low- and zero-carbon fuels such as ammonia, e-methanol, e-methane, and various forms of biofuel.

Figure 73: Composition of the EU vessel fleet used for international navigation



Source: PRIMES.

Figure 74: EU energy consumption in international navigation by fuel/energy carrier type



Note: The category «E-Liquids» includes e-methanol, e-ammonia, synthetic diesel and synthetic fuel oil.

Source: PRIMES.

1.5.4.7. Aviation

The European aviation sector is projected to undergo a significant transformation over the next decades, driven by policy measures aimed at decarbonising this sector, such as the EU Emissions Trading System and ReFuelEU Aviation, which mandates the supply of Sustainable Aviation Fuels (SAF) (see Annex 6). This transformation is multi-dimensional, mainly driven by significant improvements in energy efficiency and a large

uptake of zero- and low-emission fuels (such as liquid biofuels and e-fuels) ⁽¹³¹⁾, along with a moderate deployment of battery-electric and fuel-cell-electric aircraft.

In the S1, S2 and S3 scenarios, the total amount of energy consumed by the aviation sector in the EU (including domestic and international intra-EU and extra-EU aviation) is projected to increase by around 16-17% between 2015 and 2040, remaining relatively stable after 2040 (see Figure 75). This increase is much lower than the growth in air transport activity (expressed in passenger-km) over the same period (see Section 1.5.2). There is a decoupling between energy consumption and market growth. The difference between transport activity growth and energy consumption growth is mainly due to the large-scale deployment of technological and operational measures to improve energy efficiency (e.g., measures related to aircraft structure design and aerodynamics, propulsion system technology, and transport capacity utilisation). The energy intensity of air transport (expressed in toe/pkm) decreases by 27-28% between 2015 and 2040, and by 34-35% between 2015 and 2050, mostly as a result of these measures.

Furthermore, the S1, S2 and S3 scenarios show an increasing use of zero- and low-emission energy carriers (particularly after 2030), which partially replaces the consumption of fossil fuels in the EU aviation sector. In this respect, the sector transitions from consuming almost only fossil fuels (kerosene) in 2015 to using mostly zero- and low-emission energy carriers in 2050. As shown in Figure 75, oil products are projected to represent 62-66% of the total amount of energy consumed by the aviation sector in 2040, and 24-30% in 2050 (the exact shares depend on the scenario). Thanks to the mandates in ReFuelEU Aviation, the share of liquid biofuels in the total energy consumption increases to 24% in 2040 and 35% in 2050, and the share of e-fuels grows to 10-13% in 2040 and 33-34% in 2050. In addition, hydrogen is projected to represent 0.2-1.1% of the aviation fuel mix in 2040 and 1.6-6% in 2050. The use of electricity as an energy carrier in the aviation sector remains limited to very specific niche markets; consequently, it represents a very small share of the total amount of energy consumed by the aviation sector by 2050 (see Figure 75). Note that the fuel mix in 2040 and 2050 differs between scenarios: S1 is the scenario showing the highest share of oil products and the lowest shares of e-fuels and hydrogen, whereas S3 shows the lowest share of oil products and the highest shares of e-fuels and hydrogen. The liquid biofuel shares in 2040 and 2050, instead, are almost the same across scenarios.

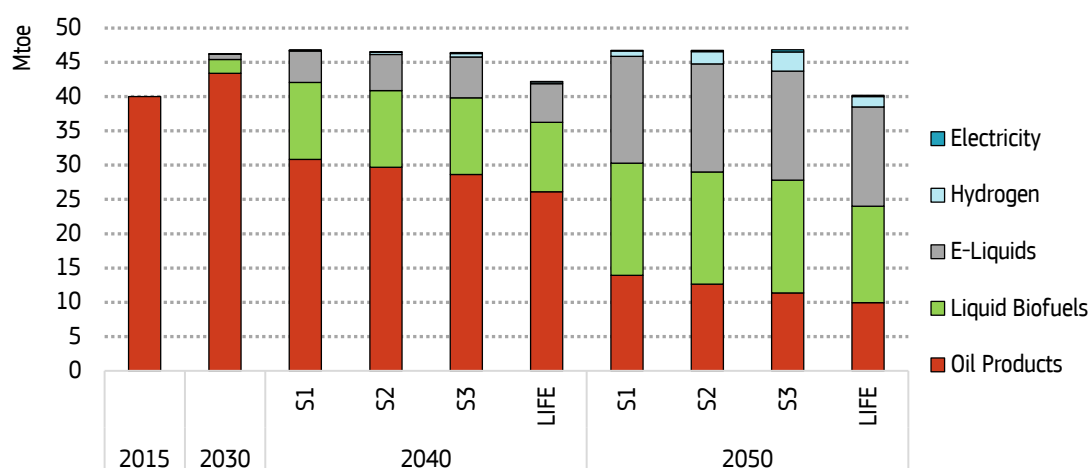
It is important to remark that the aviation fuel blend (excluding electricity and hydrogen) is projected to have a considerably lower carbon intensity in 2040 and 2050 than in 2015, mainly because of the increased consumption of liquid biofuels and e-fuels relative to fossil fuels. There are significant differences between scenarios; more specifically, the carbon intensities are highest in the S1 scenario (34% lower intensity in 2040 than in

⁽¹³¹⁾ Projections made by other studies also show an increasing use of zero- and low-emission fuels over the next decades. For instance, IEA's 'Net Zero Road Map' (2023 update) projects an increase in the use of sustainable aviation fuels (SAF) at global level, with biofuels representing 10% and 33% of the energy consumed in 2030 and 2050, respectively, and synthetic hydrogen-based fuels representing 1% in 2030 and 37% in 2050. Similarly, both DNV's 'Energy Transition Outlook 2023' and ITF's 'Decarbonising Air Transport' (published in 2021) expect a large uptake of sustainable aviation fuels (biofuels and e-fuels) over the next decades, which will play a key role in decarbonising air transport (together with technological and operational measures to improve energy efficiency, which will play a smaller role).

2015, and 70% lower intensity in 2050 than in 2015) and lowest in the S3 scenario (37% lower intensity in 2040 than in 2015, and 74% lower intensity in 2050 than in 2015).

In LIFE, the total amount of energy consumed by the aviation sector increases over time less than in the core scenarios, mainly because of lower levels of air transport activity, as explained in Section 1.5.2. In LIFE, total energy consumption is 6% higher in 2040 and 0.5% higher in 2050 relative to 2015 (i.e., 11 percentage points less than in the main scenarios in 2040, and 16-17 pp less in 2050), as shown in Figure 75. However, the energy efficiency of air transport (expressed in toe/pkm) is very similar in all scenarios. Furthermore, the fuel mix in LIFE is similar to that of the S3 scenario (in relative terms), although showing a somewhat lower uptake of hydrogen.

Figure 75: EU energy consumption in aviation by fuel/energy carrier type



Note: Energy consumption including domestic and international (intra-EU and extra-EU) aviation.

Source: PRIMES.

1.5.5. CO₂ emissions from transport

Direct CO₂ emissions from the EU transport sector are projected to decrease dramatically between 2015 and 2050, especially after 2030. It should be noted that this occurs within a context of increased transport activity (see Section 1.5.2). Even so, emissions drop because of a sharp decline in fossil fuel consumption, which is mainly caused by a decrease in energy consumption in the transport sector (resulting mainly from electrification and measures to improve energy efficiency) combined with an increased use of zero- and low-emission energy carriers, i.e., electricity, hydrogen, liquid biofuels, biogas and e-fuels (see Section 1.5.3). As a result of the latter, the carbon intensity (expressed in tCO₂/toe) of all the energy carriers employed in the transport sector taken together decreases by more than 90% between 2015 and 2050 in all scenarios.

As shown in Figure 76, in the S1, S2 and S3 scenarios, the total CO₂ emissions from the EU transport sector (including international navigation and aviation) are projected to drop from almost 1000 MtCO₂ in 2015 to 37-46 MtCO₂ (depending on the scenario) in 2050, i.e., a 95-96% reduction. It should be noted that, in 2015, almost 74% of the transport-related CO₂ emissions were caused by road transport; instead, roughly 90% of the emissions remaining in 2050 are projected to come from the aviation sector, particularly from the international aviation sector. In 2040, the total amount of transport-related emissions differs significantly between scenarios (see Figure 76 and Figure 77):

310 MtCO₂ in the S1 scenario (i.e., a 69% reduction relative to 2015), 252 MtCO₂ in the S2 scenario (-75% compared to 2015), and 219 MtCO₂ in the S3 scenario (-78% compared to 2015). Relative to 1990, this means CO₂ emissions reductions of 62% in S1, 69% in S2 and 73% in S3 by 2040. Emissions are lower in S2 compared to S1, and in S3 compared to S2, mainly because of a greater consumption of e-fuels, hydrogen and electricity taken together, which replace fossil fuels (see Figure 66).

In the S1, S2 and S3 scenarios, emissions from road and rail transport decrease by 77-86% and 62-78% in 2040 compared to 2015, respectively, and they are almost fully eliminated by 2050 (see Figure 76 and Figure 77). In 2040, both modes show the highest level of emissions in the S1 scenario, and the lowest level in the S3 scenario. These emissions reductions are driven mostly by large-scale electrification combined with a switch to zero- and low-emission fuels (i.e., advanced liquid biofuels, biogas and e-fuels) to power the remaining internal-combustion engine vehicles and rolling stock (see Sections 1.5.4.1 to 1.5.4.4). As shown in Figure 76 and Figure 77, direct emissions from the international navigation sector decrease by 68-81% in 2040 compared to 2015 and they are almost fully eliminated by 2050. The aviation sector (including both domestic and international air transport) is projected to reduce its CO₂ emissions by 23-28% in 2040 and 65-72% in 2050 relative to 2015, thanks mainly to the uptake of SAF as a major emissions reduction driver. In 2040, both modes show the highest level of emissions in the S1 scenario and the lowest level in the S3 scenario. The emissions reductions in the maritime and air transport sectors are driven mainly by the uptake of zero- and low-emission fuels and the deployment of zero-emission airplanes and vessels, along with further improvements in energy efficiency (see Sections 1.5.4.6 and 1.5.4.7). If one analyses domestic and international transport emissions separately, domestic transport emissions decrease by 76-85% in 2040 compared to 2015 and they reach very low levels in 2050, whereas international transport emissions (including navigation and aviation) decrease by 47-56% in 2040 and by 84-87% in 2050 compared to 2015. However, as already mentioned above, in 2050, most emissions are caused by international air transport, while the international navigation sector is fully decarbonised.

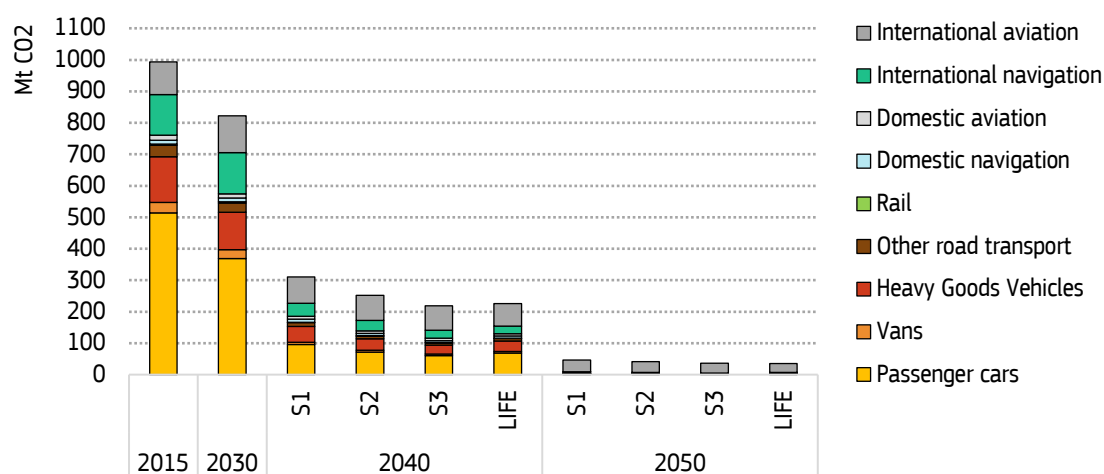
In LIFE, which is designed to meet the same climate target in 2040 as the S3 scenario, transport-related CO₂ emissions are in between those observed in S2 and S3 (although closer to S3) in 2040 (226 MtCO₂)⁽¹³²⁾, and similar to those observed in the other scenarios in 2050 (35 MtCO₂). This is driven by a combination of two factors: a) lower energy consumption compared to the S2 and S3 scenarios, which is caused by a different transport activity pattern including a higher modal shift to rail and to active modes; b) a fuel mix combining characteristics from S2 and S3 (see Sections 1.5.2 and 1.5.3).

In addition to the above, it should be noted that the transport sector also has significant non-CO₂-related impacts on the climate. These effects are caused by emissions of non-CO₂ greenhouse gases such as methane and nitrogen oxides, but also by emissions of black carbon from maritime transport, and various types of particles from air transport causing the formation of contrail cirrus. Methane and nitrous oxides emissions from the

⁽¹³²⁾ Although S3 and LIFE are designed to meet the same climate target in 2040, transport-related CO₂ emissions are higher in LIFE. Other sectors (e.g., agriculture) have lower GHG emissions in LIFE than in S3, which compensates for the higher transport-related CO₂ emissions.

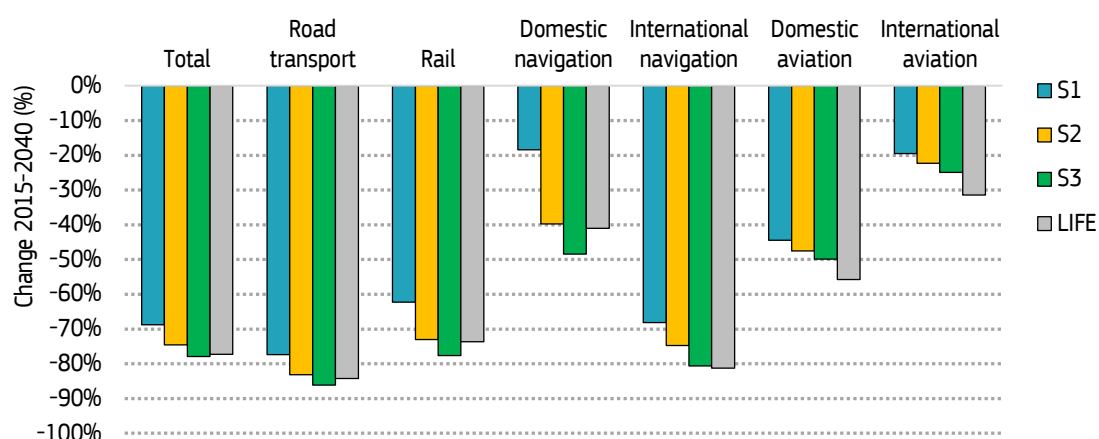
EU transport sector are presented in Section 1.6. Other non-CO2 effects are not quantified in this impact assessment, but they are discussed in Annex 12.

Figure 76: Direct CO2 emissions from the EU transport sector by mode



Source: PRIMES.

Figure 77: Change in EU transport direct CO2 emissions between 2015 and 2040 by mode



Source: PRIMES.

1.6. Non-CO2 GHG emissions in non-land-related sectors

1.6.1. Evolution of emissions without additional mitigation

For non-land-related sectors, the concept of “non-CO2 GHG emissions without additional mitigation” refers to the emissions trajectory resulting from applying a carbon value equal to zero to non-CO2 GHG emissions up to 2050. Thus, this emissions

trajectory results solely from the combination of the following two types of drivers for emissions reductions: a) transformation of the energy system on its way to meet climate neutrality by 2050; and b) relevant existing and proposed legislation, particularly the Landfill Directive⁽¹³³⁾, the Waste Framework Directive⁽¹³⁴⁾, and the proposals for a regulation to reduce methane emissions in the energy sector⁽¹³⁵⁾, a revised Urban Wastewater Treatment Directive⁽¹³⁶⁾ and a revised F-gas regulation⁽¹³⁷⁾. In this impact assessment, the non-CO2 GHG emissions without additional mitigation in the non-land-related sectors are assumed to be the same in all scenarios. There is, however, significant mitigation potential beyond this level of emissions. This additional mitigation potential is discussed in Section 1.6.2.

The non-CO2 GHG emissions without additional mitigation corresponding to all non-land-related sectors taken together equal 116 MtCO₂-eq in 2040, which represents a 65% reduction relative to 2015 levels. The degree of reduction varies across sectors (see Table 10), but all of them reduce their non-CO2 GHG emissions by more than 40% in 2040 compared to 2015. In the energy and transport sector, non-CO2 GHG emissions drop by 71% in 2040 compared to 2015. Heating and cooling is the sector showing the largest decline in emissions (97% reduction in 2040 relative to 2015, close to the maximum mitigation potential), mainly due to the impact of the proposal for a revised F-gas regulation. Finally, in industry and other sectors, emissions decrease by 50% over the same period.

⁽¹³³⁾ Directive 1999/31/EC and Amending Directive (EU) 2018/850.

⁽¹³⁴⁾ Directive 2008/98/EC.

⁽¹³⁵⁾ COM(2021) 805 final.

⁽¹³⁶⁾ COM(2022) 541 final.

⁽¹³⁷⁾ COM(2022) 150 final.

Table 10: Non-CO2 GHG emissions without add. mitigation in non-land-related sectors

	Non-CO2 GREENHOUSE GAS EMISSIONS (MtCO2-eq)*					CHANGE IN EMISSIONS (%)		
	2005	2015	2030	2040	2050	2015-30	2015-40	2015-50
Waste treatment**								
CH4	145	109	78	59	47	-29%	-46%	-57%
N2O	10	9.2	9.2	9.1	9.1	0%	-1%	-1%
Total (all gases)	155	118	87	68	56	-27%	-42%	-53%
Energy and transport								
CH4	110	86	38	20	14	-56%	-76%	-83%
N2O	24	23	18	11	8.1	-22%	-52%	-65%
Total (all gases)	135	109	56	31	23	-49%	-71%	-79%
Heating and cooling								
F-gases	43	76	21	2.6	0.7	-72%	-97%	-99%
Total (all gases)	43	76	21	2.6	0.7	-72%	-97%	-99%
Industry and other								
N2O	48	8.3	6.9	7.2	7.6	-16%	-13%	-8%
F-gases	28	18	8.9	6.1	6.8	-51%	-67%	-63%
Total (all gases)	76	27	16	13	14	-41%	-50%	-46%
Total								
CH4	255	196	116	80	61	-41%	-59%	-69%
N2O	83	41	34	27	25	-16%	-33%	-39%
F-gases	71	94	30	8.7	7.6	-68%	-91%	-92%
Total (all gases)	409	330	180	116	93	-46%	-65%	-72%

*Note: *Non-CO2 GHG emissions without additional mitigation, i.e., assuming a carbon value equal to zero. **The waste treatment sector includes solid waste and wastewater treatment.*

Source: GAINS.

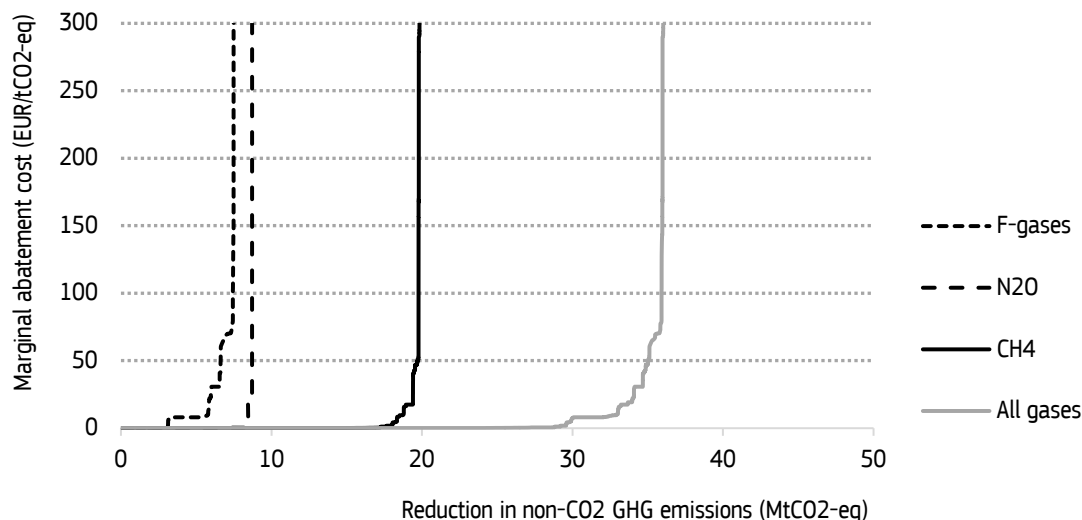
1.6.2. Additional mitigation potential

Figure 78 and Figure 79 show the 2040 marginal abatement cost curves (MACC) corresponding to non-land-related sectors specified per gas and per sector, respectively. These curves indicate the marginal cost of the additional reductions in non-CO2 GHG emissions, which come on top of the “emissions without additional mitigation” described in Section 1.6.1. Similarly, Table 11 and Table 12 show the reductions in emissions achievable at various marginal abatement cost levels. Note that the marginal abatement cost curves corresponding to non-land-related sectors are assumed to be the same in all scenarios.

Table 11 and Table 12 show that, in the non-land-related sectors, there is significant additional mitigation potential: 41 MtCO2-eq in 2040, considering all sectors and gases. If fully achieved, this mitigation potential would reduce the EU’s total non-land-related non-CO2 GHG emissions to 79 MtCO2-eq by 2040 (i.e., 76% less than in 2015). It is important to mention that 61% of this maximum mitigation potential (i.e., 25 MtCO2-eq) could be reached at a marginal cost close to zero. Note, however, that even in cases where marginal abatement costs are nearly zero, policy intervention is usually needed to overcome market barriers, lack of information and split incentives. The largest share of this near-zero-cost potential is found in the waste treatment sector. The remaining share

of the maximum mitigation potential (39%) comes at a marginal cost significantly higher than zero. Nevertheless, 80% and 85% of the maximum mitigation potential (including all sectors and gases) may be reached at a marginal cost lower than 10 and 50 EUR/tCO₂-eq, respectively, leaving only a small part of the maximum mitigation potential untapped (8 and 6 MtCO₂-eq, respectively).

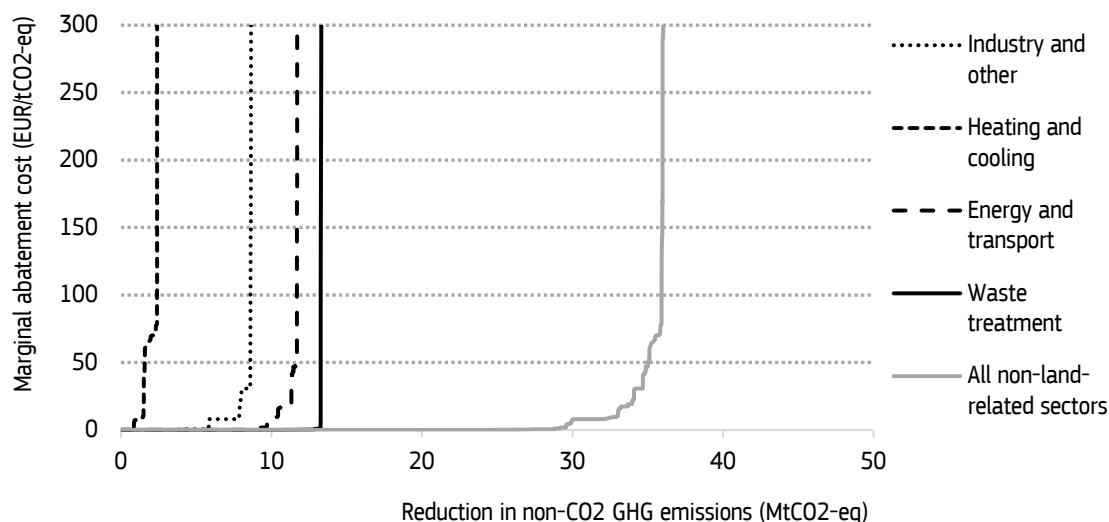
Figure 78: MACC across all non-land-related sectors in 2040 (per gas)



Note: MACC including all non-CO₂ greenhouse gases, and MACCs per gas. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

Figure 79: MACC across all non-CO₂ greenhouse gases in 2040 (per sector)



Note: MACC including all non-land-related sectors, and MACCs per sector. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

By analysing the additional mitigation potential across all non-land-related sectors separately for each gas, one can see that in all cases most of the maximum mitigation potential could be tapped at a low marginal cost. For instance, there exists potential to reduce methane emissions by as much as 23 MtCO₂-eq below the “emissions without additional mitigation” in 2040 (see Table 11). Around 82% of this maximum mitigation

potential could be tapped at a marginal abatement cost lower than 10 EUR/tCO₂-eq, mainly in the waste treatment sector and the energy and transport sector. In the case of nitrous oxide, there exists potential to reduce emissions by as much as 10 MtCO₂-eq below the “emissions without additional mitigation” in 2040, about half of which is to be found in the waste treatment sector, and the other half is to be found in industry and other sectors. Around 82% of the maximum mitigation potential for N₂O emissions could be reached at a marginal abatement cost lower than 10 EUR/tCO₂-eq. Finally, for fluorinated gases, the maximum additional mitigation potential is around 8 MtCO₂-eq in 2040 (see Table 11), which is to be found mostly in heating and cooling, industry and other sectors. About 70% of this maximum mitigation potential could be reached at a marginal cost lower than 10 EUR/tCO₂-eq and 80% may be tapped at a marginal cost lower than 50 EUR/tCO₂-eq, leaving only a very small part of the maximum mitigation potential untapped (3 and 2 MtCO₂-eq, respectively).

Table 11: Additional mitigation potentials of non-CO₂ GHG emissions across all non-land-related sectors in 2040 (by gas)

	Marginal abatement cost for non-CO ₂ GHG emissions (EUR/tCO ₂ -eq)**						
	0*	0.1	10	50	100	300	Max
Emissions mitigation in 2040 (MtCO₂-eq)							
CH ₄	0	16	19	20	20	20	23
N ₂ O	0	6.6	8.4	8.7	8.7	8.7	10
F-gas	0	2.7	5.8	6.7	7.5	7.5	8.3
Total	0	25	33	35	36	36	41
Share of maximum mitigation potential achieved in 2040 (%)							
CH ₄	0%	71%	82%	86%	87%	87%	100%
N ₂ O	0%	64%	82%	85%	85%	85%	100%
F-gas	0%	33%	70%	80%	90%	90%	100%
Total	0%	61%	80%	85%	87%	87%	100%

*Note: *In this table, the non-CO₂ GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. **Marginal abatement costs are expressed in constant EUR 2015.*

Source: GAINS.

By analysing the mitigation potential separately for each non-land-related sector, one can see that in almost all cases most of the maximum mitigation potential could be reached at a low marginal cost. In the **waste treatment** sector, there exists potential to reduce emissions by as much as 14 MtCO₂-eq below the “emissions without additional mitigation” in 2040. Around 96% of this maximum mitigation potential could be tapped at a marginal abatement cost lower than 10 EUR/tCO₂-eq (see Table 12), mainly through process optimisation and deployment of anaerobic digestion technology with biogas recovery. In the **energy and transport** sector, the maximum additional mitigation potential is 14 MtCO₂-eq in 2040. About 73% of this mitigation potential could be achieved at a marginal cost lower than 10 EUR/tCO₂-eq, and 82% could be tapped at a marginal cost below 50 EUR/tCO₂-eq (in both cases, mostly through implementation of best available technology in bunker fuel use and leak detection and repair programs, and by flooding abandoned coal mines). Higher emission reductions could be achieved only at very high marginal costs, mainly by upgrading long-distance gas pipelines to minimum leakage rates, replacing steel gas distribution networks by PE/PVC networks, and additional leak detection and repair. Non-CO₂ GHG emissions from the **heating and**

cooling sector are mostly F-gas emissions. In this sector, the “emissions without additional mitigation” are already very low in 2040 (less than 3 MtCO₂-eq); however, there is enough additional mitigation potential in 2040 to almost eliminate these emissions fully (by using alternative agents). Around 57% of the maximum mitigation potential could be tapped at a marginal cost lower than 10 EUR/tCO₂-eq, and 62% could be reached at a marginal cost below 50 EUR/tCO₂-eq, leaving only a small part of the maximum mitigation potential untapped (around 1 MtCO₂-eq in both cases). Finally, in **industry and other** sectors, the maximum additional mitigation potential is 11 MtCO₂-eq in 2040. About 72% of this potential could be tapped at a marginal abatement cost lower than 10 EUR/tCO₂-eq, while 79% may be reached at less than 50 EUR/tCO₂-eq.

Table 12: Additional mitigation potentials of non-CO₂ GHG emissions in 2040 (by non-land-related sector)

	Marginal abatement cost for non-CO ₂ GHG emissions (EUR/tCO ₂ -eq)**						
	0*	0.1	10	50	100	300	Max
Emissions mitigation in 2040 (MtCO₂-eq)							
Waste treatment***	0	12	13	13	13	13	14
Energy and transport	0	9	10	12	12	12	14
Heating and cooling	0	0.8	1.4	1.6	2.4	2.4	2.5
Industry and other	0	3.5	7.8	8.6	8.6	8.6	11
Total	0	25	33	35	36	36	41
Share of maximum mitigation potential achieved in 2040 (%)							
Waste treatment***	0%	85%	96%	96%	96%	96%	100%
Energy and transport	0%	65%	73%	82%	83%	83%	100%
Heating and cooling	0%	33%	57%	62%	94%	94%	100%
Industry and other	0%	32%	72%	79%	79%	79%	100%
Total	0%	61%	80%	85%	87%	87%	100%

*Note: *In this table, the non-CO₂ GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. **Marginal abatement costs are expressed in constant EUR 2015. ***The waste treatment sector includes solid waste and wastewater treatment.*

Source: GAINS.

1.6.3. Emissions projections

As described in the previous section, the non-land-related sectors show relatively low-cost mitigation potentials, which translates into very close emission profiles across all scenarios except S1 (see Table 13). The S1 scenario assumes a carbon value equal to zero up to 2040. Therefore, in this scenario, the non-CO₂ GHG emissions trajectory is the emissions trajectory without additional mitigation (see Section 1.6.1) until 2040. The level of non-CO₂ GHG emissions in 2050 is the same across all scenarios (since the carbon value assumed is also the same).

The non-CO₂ GHG emissions from the **waste management** sector in 2040 are projected to be 42% lower than in 2015 in S1, and 54% lower in the other scenarios. In 2050, emissions from the waste management sector are 73% lower than in 2015 in all scenarios. In 2040, in S2, S3 and LIFE, the additional mitigation is achieved mainly through the implementation of: a) source separation and anaerobic digestion with biogas recovery to treat solid waste; and b) 2-stage treatment (anaerobic with biogas recovery

and then aerobic) combined with process optimisation to treat wastewater. In 2050, energy recovery technologies are used in addition to the above-mentioned ones in all scenarios.

The non-CO₂ GHG emissions from the **energy and transport** sector go down to 31 MtCO₂-eq in S1 and 24 MtCO₂-eq in the other scenarios in 2040, which means a decrease by 71% and 78%, respectively, compared to 2015. In 2050, emissions are projected to be 83% lower than in 2015 in all scenarios. This mitigation is largely driven by the evolution of the energy system and the lower consumption of fossil fuels, complemented in S2, S2 and LIFE by implementation of technologies to improve bunker fuel use, leak detection and repair programs in gas networks, leakage control and gas recovery in crude oil and natural gas production sites, oxidation of ventilation air methane in coal mines, and flooding of abandoned coal mines.

Non-CO₂ GHG emissions from the **heating and cooling** sector are projected to decrease to around 2.5 MtCO₂-eq in S1 and to almost zero in the other scenarios in 2040, largely driven by the impact of the proposal for a revised F-gas regulation (reflected already in the S1 scenario, which assumes no additional mitigation). Emissions from this sector are almost fully eliminated by 2050 in all scenarios. Finally, the non-CO₂ GHG emissions from **industry and other** sectors are projected to be around 13 MtCO₂-eq in S1 and 5 MtCO₂-eq in the other scenarios in 2040 (i.e., 50% and 82% less than in 2015, respectively). In 2050, non-CO₂ GHG emissions from this sector remain at around 5 MtCO₂-eq in all scenarios.

Table 13: Non-CO2 GHG emissions from the non-land-related sectors

Non-CO2 greenhouse gas emissions (MtCO2-eq)						Change in emissions (%)		
	2005	2015	2040		2050	2015-40		2015-50
			S1	S2, S3 & LIFE	S1, S2, S3 & LIFE	S1	S2, S3 & LIFE	S1, S2, S3 & LIFE
Waste management*								
CH4	145	109	59	51	28	-46%	-53%	-74%
N2O	10	9.2	9.1	4.2	3.8	-1%	-54%	-59%
Total (all gases)	155	118	68	55	32	-42%	-54%	-73%
Energy and transport								
CH4	110	86	20	14	10	-76%	-84%	-88%
N2O	24	23	11	11	7.9	-52%	-53%	-66%
Total (all gases)	135	109	31	24	18	-71%	-78%	-83%
Heating and cooling								
F-gases	43	76	2.6	0.2	0.1	-97%	-100%	-100%
Total (all gases)	43	76	2.6	0.2	0.1	-97%	-100%	-100%
Industry and other								
N2O	48	8.3	7.2	3.7	4.0	-13%	-55%	-52%
F-gases	28	18	6.1	1.0	0.7	-67%	-94%	-96%
Total (all gases)	76	27	13	4.7	4.7	-50%	-82%	-82%
Total								
CH4	255	196	80	64	38	-59%	-67%	-80%
N2O	83	41	27	19	16	-33%	-54%	-61%
F-gases	71	94	8.7	1.2	0.8	-91%	-99%	-99%
Total (all gases)	409	330	116	84	55	-65%	-74%	-83%

*Note: *The waste management sector includes solid waste and wastewater treatment.*

Source: GAINS.

1.7. Agriculture

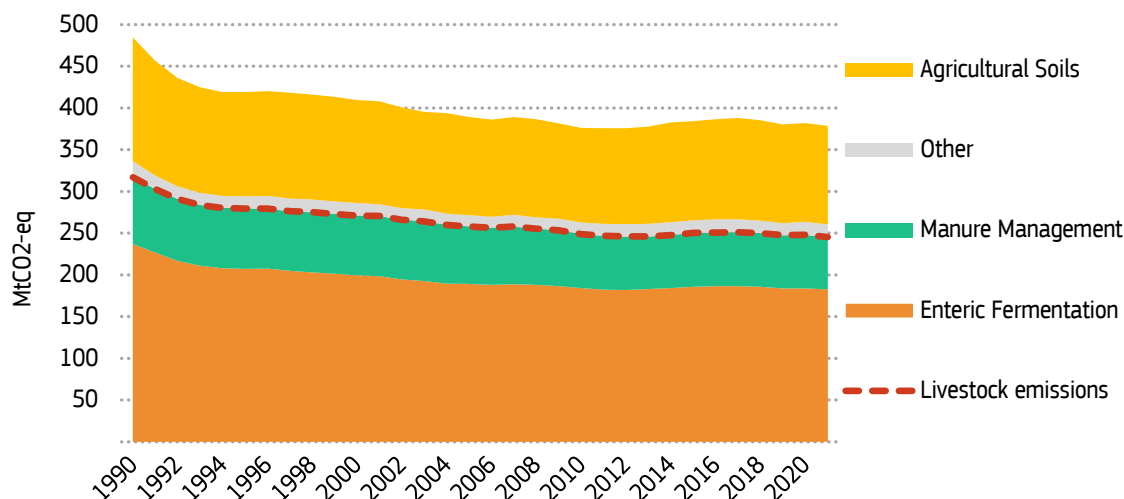
1.7.1. Introduction

Emissions in the agricultural sector declined since 1990 by 23% with an increase in output efficiency (i.e., lower emissions per unit of output), but remained stable over the last 10 years (see Figure 80). This relative stability in emissions also applies to livestock emissions, which throughout the average 2019-2021 compared to 10 years ago only reduced emissions by around 1%. Since 1990, livestock emissions consistently make up around 65% of all emissions in the agriculture sector. Emissions from agricultural soil management increased in the last 10 years by about 4% (on a three-year average) and make up around 30% of all emissions in the agriculture sector.

Although agricultural GHG emissions changed very little at EU level in the past, the trend shows considerable variation between Member States, with some decreasing or increasing by about 20%, which highlights the dynamic of emissions from agriculture

and the room for additional emission reduction in some Member States in relation to their specific emission profiles and sectorial context ⁽¹³⁸⁾. It is important to note that the reduction of uncertainty in the GHG inventories in the agricultural sector, which does not fully capture the implementation of emission reduction practices at farm level, remains a significant challenge.

Figure 80: Emissions from Agriculture in the EU by sector



Note: Emissions based on UNFCCC categories. 'Livestock' depicts category 3.1 (3.A+3.B) 'enteric fermentation' 3.A, 'manure management' 3.B, 'agricultural soils' 3.D. 'Other' summarises emissions from 3.C Rice Cultivation, 3.F - Field Burning of Agricultural Residues, 3.G - Liming, 3.H - Urea Application, 3.I - Other Carbon-containing Fertilisers, 3.J - Other agriculture emissions.

Source: UNFCCC 2023.

Opinions on whether the land sector should do more to reduce GHG emissions were divided among stakeholders responding to the Public Consultation questionnaire. On a 5-point scale from 'can reduce little more' (1) to 'can reduce a lot more' (5), on average all respondents found that the land sector could do somewhat more to reduce emissions (Average: 3.96). But civil society organisations (Average: 4.59) and academic/research institutions (Average: 4.28) find that the land sector could contribute much more, while SME's, EU citizens and public authorities assessed the sector's potential for further reduction less positive (Average: 3.53 to 3.81). This divided assessment was also reflected in the question on which sector would achieve climate neutrality first. While about 22% of the respondents believed that the land sector will be the first one to achieve climate neutrality, 30% believed that it will be the last sector, a division presumably due to different expectations about the potential of nature-based removals and the potential to reduce agricultural emissions.

⁽¹³⁸⁾ European Environment Agency, 'Agricultural emissions and projected emissions by EU Member State', https://www.eea.europa.eu/ds_resolveuid/KPQBZ3Y6T9, 2022.

1.7.2. Activity

1.7.2.1. Mitigation options in the food system

Agricultural and forest land are the two primary users of land in the EU. A conversion of agricultural land has impacts on GHG emissions when forests or grasslands are converted into croplands and carbon stored in vegetation and soil is released into the atmosphere. However, current trends show a positive trend with a slow decline of cropland and a slow increase of forest land.

Implementing sustainable land management practices in agriculture, such as agroforestry, conservation agriculture practices, and proper land-use planning, can help minimise impacts of land use change and deforestation and thus preserving carbon stocks. Promoting carbon farming practices under the Common Agricultural Policy (CAP) and other EU and national programmes with financial incentives to farmers and foresters can enhance practices such as afforestation, reforestation, agroforestry, conservation agriculture practices and soil protection, appropriate peatland management, and sustainable and precision farming, which contribute to carbon removals with the potential to offset agricultural emissions. Throughout a combination of mandatory and voluntary interventions, Member States planned significant support to farmers in the approved Common Agricultural Policy Strategic Planning Regulation, for the uptake of carbon farming practices, protection of carbon in soil and reduction of emissions.

Livestock production, particularly from ruminant animals like cows, sheep, and goats, is a significant contributor to GHG emissions in the EU's agriculture sector. Ruminant animals produce methane through enteric fermentation, a natural digestive process, responsible for roughly 38% of emissions in the agriculture sector. Additionally, the management of manure from livestock releases methane and nitrous oxide and is responsible for about 13% of emissions throughout the last 10 years⁽¹³⁹⁾. Implementing practices such as optimised fodder, feed additives, more favourable animal genetics⁽¹⁴⁰⁾, and improved herd management help reduce enteric fermentation and, consequently, methane emissions from the livestock. Anaerobic digestion of manure and other biomass does not only mitigate emissions but also provides a new source of income for farmers (since it produces biogas, which can be recovered and used for energy production or other purposes) and can help to prevent excessive nutrient losses.

Nitrogen fertilisers are widely used in agriculture to enhance crop production. However, the excessive or inefficient application of nitrogen fertilisers leads to the release of N₂O into the atmosphere and losses of other nitrogen components to water and atmosphere. Utilisation of precision agriculture techniques⁽¹⁴¹⁾, such as site-specific fertiliser management with variable rate distribution techniques, can help optimise fertiliser

⁽¹³⁹⁾ UNFCCC inventory data 2023

⁽¹⁴⁰⁾ Wall, E., Simm, G., & Moran, D. (2010). Developing breeding schemes to assist mitigation of greenhouse gas emissions. *Animal*, 4(3), 366-376.

⁽¹⁴¹⁾ for overview on precision agriculture technologies: Balafoutis, A.; Beck, B.; Fountas, S.; Vangeyte, J.; Wal, T.V.d.; Soto, I.; Gómez-Barbero, M.; Barnes, A.; Eory, V. Precision Agriculture Technologies Positively Contributing to GHG Emissions Mitigation, Farm Productivity and Economics. *Sustainability* 2017, 9, 1339.

application and minimise nitrogen losses, reducing N₂O emissions. Moreover, the use of N₂O stabilisers ⁽¹⁴²⁾, inhibitors and nitrogen in more complex formulation (such as in organic fertilisers) can enhance fertiliser efficiency and reduce nitrogen losses, ultimately lowering nitrous oxide emissions. With regard to nutrients and the objective to reduce nutrient losses within the EU ⁽¹⁴³⁾, implementing precision nutrient management and optimising the use of organic fertiliser improves the nutrient cycle and provides co-benefits for environmental protection.

It's worth noting that the effectiveness and feasibility of these mitigation options depends on local conditions, farm-scale factors, and policy support. Ongoing research and innovation play a crucial role in further developing and implementing these technologies to achieve sustainable agricultural practices with reduced emissions.

Importantly, action addressing primary agriculture is necessary to drive down emissions from the food system. But for the EU to achieve climate neutrality in 2050, the food system needs to take action along the entire value chain, which goes beyond primary agriculture and includes secondary agriculture ⁽¹⁴⁴⁾, retail, and consumption ⁽¹⁴⁵⁾. In other words, the adoption of certain practices and technologies can reduce GHG emissions from agriculture, but reducing food loss and food waste, dietary shifts away from animal protein and use of land resources for nature-based mitigation solutions is unavoidable to get to climate neutrality ⁽¹⁴⁶⁾.

1.7.2.2.Sustainable Agriculture and bioeconomy

A living and functioning environment is vital for a functioning and resilient food system. Agriculture needs pollinators, healthy soils and functioning ecosystems. A more sustainable agricultural production will increase resilience and protect the food system in the long term. But sustainable agricultural practices may reduce agricultural intensity and agricultural output, which in turn may affect economic income in the sector. It is therefore important to ensure adequate support and discuss new business models, such as the provision of biogenic carbon as industrial feedstock and the remuneration of ecosystem services as additional income opportunities for European farmers (see Annex 9 for more details).

⁽¹⁴²⁾ Panchasara, H.; Samrat, N.H.; Islam, N. Greenhouse Gas Emissions Trends and Mitigation Measures in Australian Agriculture Sector—A Review. *Agriculture* 2021, 11, 85.

⁽¹⁴³⁾ COM(2020) 381 final.

⁽¹⁴⁴⁾ Secondary agriculture is defined as processing and adding value to the basic agriculture commodities (O'Shea et al. Dietary fibre and phytochemical characteristics of fruit and vegetable by-products and their recent applications as novel ingredients in food products. *Innov Food Sci Emerg Technol* 2012, 16).

⁽¹⁴⁵⁾ Mc Kinsey & Company, 'The agricultural transition: Building a sustainable future', 2023.

⁽¹⁴⁶⁾ Ibid.

1.7.3. Evolution of emissions without additional mitigation measures

1.7.3.1.S1, S2 and S3 scenarios

In this impact assessment, the concept of “emissions without additional mitigation” in the agriculture sector refers to the emissions trajectory resulting from applying a carbon value equal to zero to non-CO₂ GHG emissions up to 2050. Thus, this emissions trajectory results solely from the combination of two main types of drivers for emissions reductions: a) agriculture policy as reflected in the EU Agricultural Outlook 2022 ⁽¹⁴⁷⁾; and b) relevant existing and proposed legislation, particularly the proposal for a revised Industrial Emissions Directive ⁽¹⁴⁸⁾ (see Annex 11). The “emissions without additional mitigation” do not consider any other policies that would enable the implementation of extra practices and technologies.

In the S1, S2 and S3 scenarios, the GHG emissions without additional mitigation from the agriculture sector are 351 MtCO₂-eq in 2040 and 347 MtCO₂-eq in 2050 (including all greenhouse gases), which implies a 9% reduction by 2040 and a 10% reduction by 2050 relative to 2015 levels (see Table 14). It should be noted that, in all scenarios, there exists significant additional mitigation potential through different practices and technological solutions. This additional mitigation potential is discussed in Section 1.7.4.

Table 14: GHG emissions in agriculture without additional mitigation in S1, S2, S3

	GREENHOUSE GAS EMISSIONS (MtCO ₂ -eq)					CHANGE IN EMISSIONS (%)		
	2005	2015	2030	2040	2050	2015-30	2015-40	2015-50
Agriculture								
CH ₄	242	237	223	214	213	-6%	-10%	-10%
N ₂ O	138	138	128	127	124	-7%	-8%	-10%
CO ₂	9	10	10	10	10	3%	3%	3%
Total (all gases)	390	385	361	351	347	-6%	-9%	-10%

Source: GAINS.

1.7.3.2.LIFE scenario

LIFE considers a more sustainable lifestyle guided by consumer climate-friendly choices and a more efficient use of the resources. Besides the impact of the existing policy framework, LIFE assumes changes in the food system in terms of dietary changes, food waste reduction and a gradual implementation by 2040 of the objectives of the Farm to Fork Strategy ⁽¹⁴⁹⁾. This leads to changes in sectoral activity (notably in livestock of cattle and other animals as well as in use of manure and mineral fertilisers) compared to the main scenarios (S1, S2 and S3).

⁽¹⁴⁷⁾ The Agricultural Outlook 2022 is assumed to reflect the Common Agricultural Policy at the time of publication in 2022.; European Commission, DG Agriculture and Rural Development, ‘EU agricultural outlook for markets, income and environment, 2022-2032’, Brussels, 2022.

⁽¹⁴⁸⁾ COM(2022) 156 final. Note that this impact assessment takes into account the changes made to the European Commission’s proposal during the co-decision process up to July 2023.

⁽¹⁴⁹⁾ COM(2020) 381 final.

As a result, assuming no deployment of additional mitigation practices and technologies, the GHG emissions from the agriculture sector are lower in LIFE than in the other scenarios (around 80 MtCO₂-eq less, both in 2040 and 2050). More specifically, the level of emissions in LIFE is projected to be around 271 MtCO₂-eq in 2040 and 269 MtCO₂-eq in 2050 (i.e., 30% lower than in 2015 in both years), as shown in Table 15. Note that both CH₄ and N₂O emissions are lower than in scenarios S1, S2 and S3; for instance, in 2040, CH₄ emissions are 48 MtCO₂-eq (22%) lower, while N₂O emissions are 32 MtCO₂-eq (25%) lower.

Table 15: GHG emissions in the agriculture without additional mitigation in LIFE

	GREENHOUSE GAS EMISSIONS (MtCO ₂ -eq)			CHANGE IN EMISSIONS (%)		DIFFERENCE COMPARED TO S1, S2 & S3 (MtCO ₂ -eq)	
	2015	2040	2050	2015-40	2015-50	2040	2050
Agriculture							
CH ₄	237	166	167	-30%	-29%	-48	-46
N ₂ O	138	95	92	-31%	-33%	-32	-32
CO ₂	10	10	10	3%	3%	0	0
Total (all gases)	385	271	269	-30%	-30%	-80	-78

Source: GAINS.

1.7.4. Mitigation potential for non-CO₂ GHG emissions

The GAINS model provides marginal abatement cost ⁽¹⁵⁰⁾ curves (MACC) for non-CO₂ GHG emissions corresponding to the agriculture sector, specified per gas and per type of source, coming on top of the “emissions without additional mitigation” described in Section 1.7.3. Note that the S1, S2 and S3 scenarios are assumed to share the same MACCs, whereas LIFE has scenario-specific MACCs. Figure 81 shows the MACC applicable to the agriculture sector in 2040 in the different scenarios.

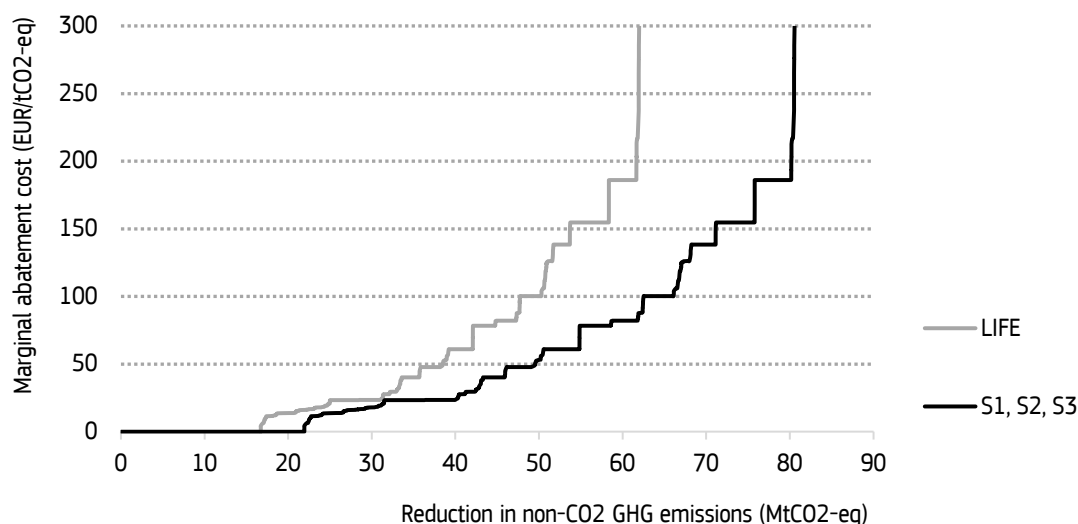
For the S1, S2 and S3 scenarios, the maximum abatement potential is estimated to be 83 MtCO₂-eq in 2040, which would bring total non-CO₂ GHG emissions down to 258 MtCO₂-eq (i.e., a level 31% lower than in 2015). A bit more than 25% of this mitigation potential may be tapped at near-zero cost ⁽¹⁵¹⁾, mainly by introducing breeding through selection to enhance productivity, fertility and longevity, and farm-scale anaerobic digestion with biogas recovery, which reduce CH₄ emissions. Almost 40% of the maximum mitigation potential could be reached at a marginal abatement cost lower than 20 EUR/tCO₂-eq, mainly by using feeding additives that reduce CH₄ emissions in addition to the near-zero-cost mitigation options. Finally, around 85% of the maximum mitigation potential can be achieved with a marginal cost lower than 140 EUR/tCO₂-eq, mostly by scaling up the use of various mitigation options to reduce N₂O emissions (such as nitrification inhibitors and variable rate technology) on top of the options mentioned above.

⁽¹⁵⁰⁾ Marginal abatement costs are defined using the *opportunity cost* approach.

⁽¹⁵¹⁾ Note that even in cases where marginal abatement costs are nearly zero, policy intervention is often needed to overcome market barriers, lack of information and split incentives.

In LIFE, starting with lower emissions than in the S1, S2 and S3 scenarios, the additional mitigation potential for non-CO₂ GHG emissions stemming from the deployment of extra mitigation practices and technologies is estimated to be still 64 MtCO₂-eq in 2040. Fully reaching this potential would reduce total non-CO₂ GHG emissions from the agriculture sector to 198 MtCO₂-eq in that year, which implies a 47% reduction relative to 2015.

Figure 81: MACC of the agriculture sector in 2040 per scenario



Note: Marginal abatement costs are expressed in constant EUR 2015.

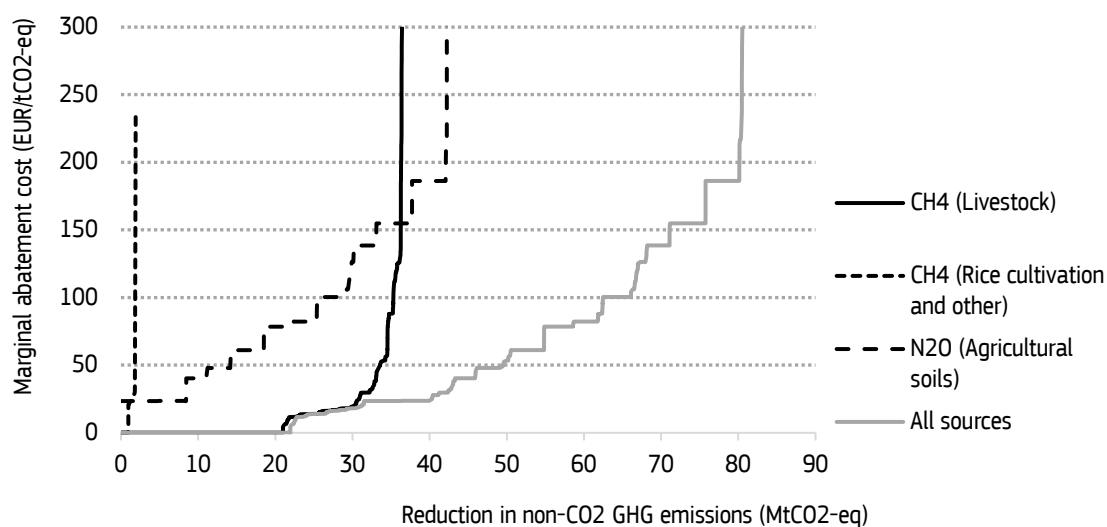
Source: GAINS.

By analysing the additional mitigation potential separately for each gas, one can see that most of the mitigation potential associated to CH₄ emissions may be tapped at a relatively low marginal cost; instead, in the case of N₂O emissions, higher marginal costs are observed (see Table 16 and Table 17).

For CH₄, the abatement potential is mostly linked to mitigation options to reduce livestock emissions, with a small contribution from mitigation options to reduce emissions from rice cultivation and other activities (see Figure 82 and Figure 83). In 2040, the total maximum additional potential to reduce CH₄ emissions is 38 MtCO₂-eq in the three main scenarios (30 MtCO₂-eq in LIFE, which starts from lower emissions). Around 57% of this potential would be accessible at near-zero marginal abatement cost (mainly through breeding through selection to enhance productivity, fertility and longevity, and farm-scale anaerobic digestion with biogas recovery), and 90% could be achieved at a marginal cost lower than 35 EUR/tCO₂-eq (by including feeding additives).

For N₂O, the abatement potential is entirely linked to mitigation practices and technologies to reduce emissions from agricultural soils, such as nitrification inhibitors and variable rate technology. In 2040, the maximum additional potential to reduce N₂O emissions is 44 MtCO₂-eq in the three main scenarios (34 MtCO₂-eq in LIFE, starting from lower emissions). Around 32% of this potential could be reached at a marginal cost between 25 and 50 EUR/tCO₂-eq, while 75% could be reached at a marginal cost below 140 EUR/tCO₂-eq and 95% could be reached at a marginal cost below 190 EUR/tCO₂-eq.

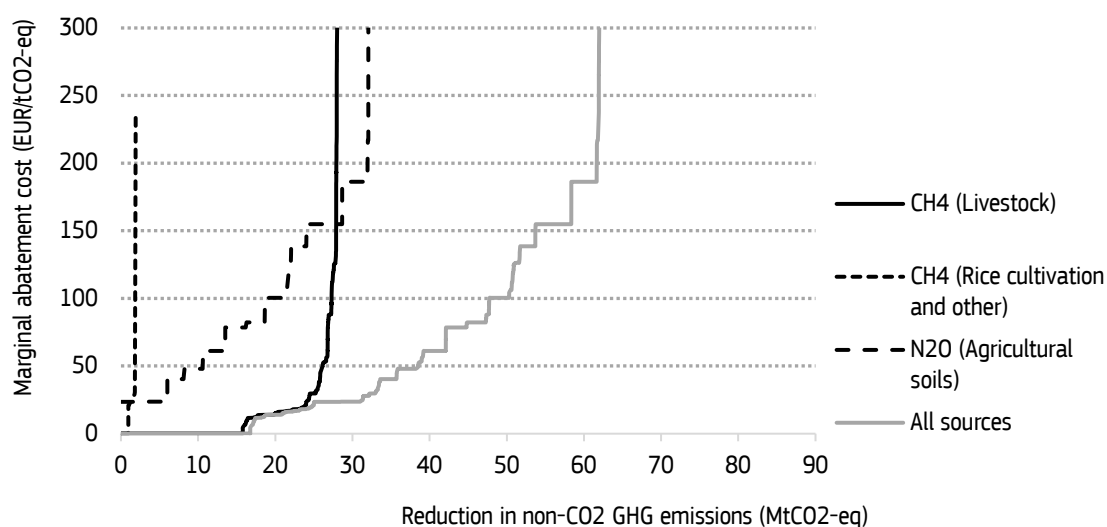
Figure 82: MACC of the agriculture sector in 2040 in S1, S2 and S3 (by gas and area of application)



Note: The MACCs include all non-CO₂ greenhouse gases. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

Figure 83: MACC of the agriculture sector in 2040 in LIFE (by gas and area of application)



Note: The MACCs include all non-CO₂ greenhouse gases. Marginal abatement costs are expressed in constant EUR 2015.

Source: GAINS.

Table 16: Mitigation potential in the agriculture sector in S1, S2 and S3

	Marginal abatement cost for non-CO2 GHG emissions (EUR/tCO2-eq)**						
	0*	0.1	10	50	100	300	Max
Emissions mitigation in 2040 (MtCO2-eq)							
CH4 (Livestock)	0	21	22	34	35	36	37
CH4 (Rice cultivation and other)	0	1	1	2	2	2	2
N2O (Agricultural soils)	0	0	0	14	25	42	44
Total	0	22	23	50	62	81	83
Share of maximum mitigation potential achieved in 2040 (%)							
CH4 (Livestock)	0%	57%	59%	92%	97%	100%	100%
CH4 (Rice cultivation and other)	0%	50%	50%	94%	94%	100%	100%
N2O (Agricultural soils)	0%	0%	0%	32%	57%	95%	100%
Total	0%	27%	27%	60%	76%	97%	100%

*Note: *In this table, the non-CO2 GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. **Marginal abatement costs are expressed in constant EUR 2015.*

Source: GAINS.

Table 17: Mitigation potential in the agriculture sector in LIFE

	Marginal abatement cost for non-CO2 GHG emissions (EUR/tCO2-eq)						
	0*	0.1	10	50	100	300	Max
Emissions mitigation in 2040 (MtCO2-eq)							
CH4 (Livestock)	0	16	16	26	27	28	28
CH4 (Rice cultivation and other)	0	1	1	2	2	2	2
N2O (Agricultural soils)	0	0	0	11	19	32	34
Total	0	17	17	39	48	62	64
Share of maximum mitigation potential achieved in 2040 (%)							
CH4 (Livestock)	0%	56%	58%	93%	97%	100%	100%
CH4 (Rice cultivation and other)	0%	50%	50%	94%	94%	100%	100%
N2O (Agricultural soils)	0%	0%	0%	32%	56%	96%	100%
Total	0%	26%	27%	61%	75%	98%	100%

*Note: *In this table, the non-CO2 GHG emissions at zero marginal abatement cost correspond to the emissions without additional mitigation in 2040. Marginal abatement costs are expressed in constant EUR 2015.*

Source: GAINS.

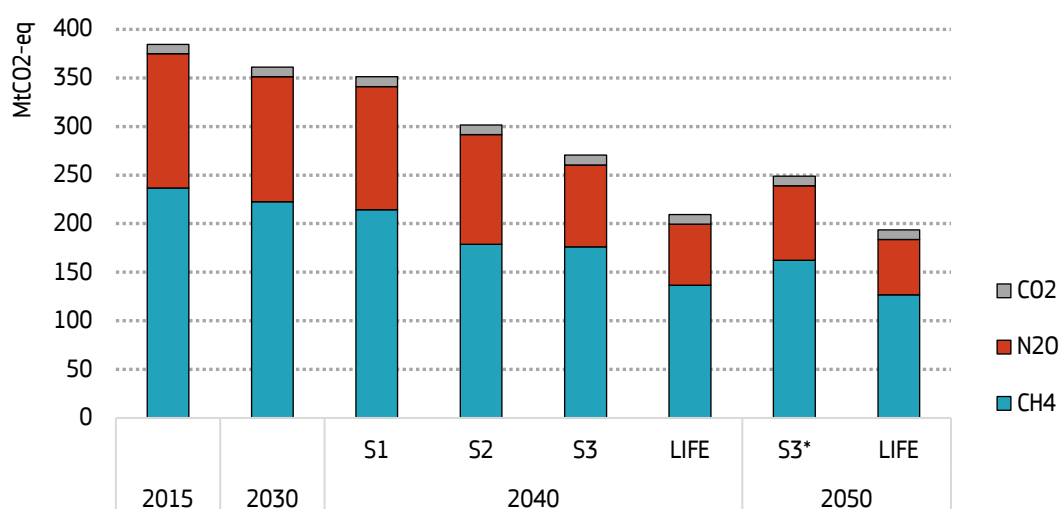
1.7.5. GHG emissions projections

This section presents the agriculture GHG emissions trajectory in each scenario.

Currently, almost all GHG emissions from agriculture that are not related to energy consumption (i.e., all category 3 of the UNFCCC inventory) are CH4 and N2O emissions (see Table 18 and Figure 84). CO2 emissions included in category 3 are very small and are assumed to remain constant at historical level (10 MtCO2). CO2 emissions from agriculture related to energy consumption (i.e., those included in category 1 of the UNFCCC inventory) are not analysed in this section, but in Section 1.1.3.

The S1 scenario assumes that no additional mitigation measures are deployed by 2040. In the S2 scenario, reductions take place, mostly through the deployment by 2040 of technologies reducing CH₄ emissions (such as feeding additives, farm-scale anaerobic digestion with biogas recovery, and breeding through selection to enhance productivity, fertility and longevity), while technologies to reduce N₂O emissions from agriculture are only partially deployed in 2040. S3 and LIFE assume the full deployment of all additional mitigation measures (including nitrification inhibitors, variable rate technology and restoring drained organic soils) by 2040, thus contributing to the overall net GHG reductions. In modelling terms, the extra mitigation to the baseline is realised through the application of a “carbon value” to GHG emissions applied to the sector (see Annex 6 and previous section on mitigation potential in the sector).

Figure 84: GHG emissions from agriculture by gas



*Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **CO₂ emissions include only emissions in category 3 ("Agriculture").*

Source: GAINS.

The amount of GHG emissions⁽¹⁵²⁾ generated by the agriculture sector in 2040 is projected to be 351 MtCO₂-eq in S1 (9% lower than in 2015), 302 MtCO₂-eq in S2 (22% lower than in 2015), and 271 MtCO₂-eq in S3 (30% lower than in 2015) (see Table 18). LIFE, which combines a different evolution of the food system and the application of technologies, shows a much lower level of emissions (209 MtCO₂-eq, i.e., 46% lower than in 2015). In 2050, GHG emissions are projected to reach 249 MtCO₂-eq (a 35% reduction relative to 2015) in the three main scenarios, and 194 MtCO₂-eq in LIFE (a 50% decrease compared to 2015).

⁽¹⁵²⁾ Including CO₂, CH₄ and N₂O emissions in category 3 of the UNFCCC inventory.

Table 18: GHG emissions from the agriculture sector (by gas and type of source)

Greenhouse gas emissions (MtCO2-eq)								
	2015	2030	2040			2050		
			S1	S2	S3	LIFE	S3*	LIFE
Disaggregated per gas								
CH4	237	223	214	179	176	137	162	127
N2O	138	128	127	113	85	63	77	57
CO2**	10	10	10	10	10	10	10	10
Total (all gases)	385	361	351	302	271	209	249	194
Disaggregated per type of source								
Livestock	244	230	221	188	185	143	171	134
Agricultural soils	127	118	116	102	74	55	66	49
Other	13	14	14	12	12	12	12	12
Total (all sources)	385	361	351	302	271	209	249	194

*Note: *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario. **CO₂ emissions include only emissions in category 3 ("Agriculture").*

Source: GAINS.

The analysis of emissions per type of source shows that, in 2040, GHG emissions caused by **livestock** (which are mostly CH₄ emissions ⁽¹⁵³⁾) are projected to be 221 MtCO₂-eq (10% lower than in 2015) in the S1 scenario, 188 MtCO₂-eq (23% lower than in 2015) in the S2 scenario, and 185 MtCO₂-eq (24% lower than in 2015) in the S3 scenario (see Table 18 and Figure 85). In 2050, GHG emissions from livestock are 171 MtCO₂-eq (i.e., 30% lower than in 2015) in these three scenarios. These emissions reductions (compared to 2015) are achieved mainly by implementing the following technologies: a) breeding through selection to enhance productivity, fertility and longevity; b) farm-scale anaerobic digestion with biogas recovery; and c) feed additives. Note that, in the S1 scenario, these technologies are only deployed after 2040.

In addition to the implementation of these technologies, LIFE assumes changes in sectoral activity compared to the other scenarios (notably, a decrease in livestock leading to a lower production of manure). As a result, GHG emissions caused by livestock decrease further: they are projected to be 143 MtCO₂-eq in 2040 (i.e., 41% lower than in 2015) and 134 MtCO₂-eq in 2050 (i.e., 45% lower than in 2015).

GHG emissions from **agricultural soils** (which are entirely N₂O emissions ⁽¹⁵⁴⁾) are projected to be 116 MtCO₂-eq in S1 (8% lower than in 2015), 102 MtCO₂-eq (19% lower than in 2015) in the S2 scenario, and 74 MtCO₂-eq (42% lower than in 2015) in S3 in 2040 (see Table 18 and Figure 85). In 2050, emissions from agricultural soils are 66 MtCO₂-eq (48% lower than in 2015) in these three scenarios. These emissions reductions (compared to 2015) are achieved mainly through the large-scale implementation of

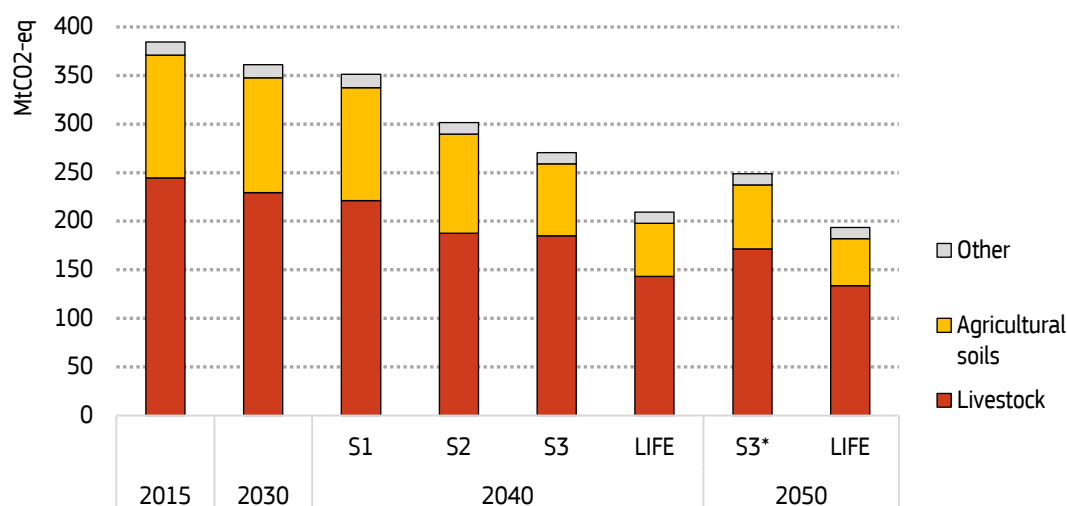
⁽¹⁵³⁾ According to the UNFCCC inventory, around 93% of the GHG emissions from livestock in the EU in 2021 were CH₄ emissions, whereas the remainder (7%) were N₂O emissions.

⁽¹⁵⁴⁾ According to the UNFCCC inventory, 100% of the GHG emissions from agricultural soils in the EU in 2021 were N₂O emissions.

technologies to improve fertiliser application (notably, nitrification inhibitors and variable rate technology) and by restoring drained organic soils. The S1 scenario assumes that these technologies are only deployed after 2040 (see Annex 6).

In addition to the implementation of these technologies, LIFE assumes changes in sectoral activity compared to the other scenarios, with a decrease in the use of mineral fertilisers. Consequently, GHG emissions from agricultural soils decrease further: they are projected to be 55 MtCO₂-eq in 2040 (57% lower than in 2015) and 49 MtCO₂-eq in 2050 (62% lower than in 2015).

Figure 85: GHG emissions from agriculture by type of source



*Note: GHG emissions include CO₂ (category 3), CH₄ and N₂O emissions. *In the S1 and S2 scenarios, emissions in 2050 are equal to those in the S3 scenario.*

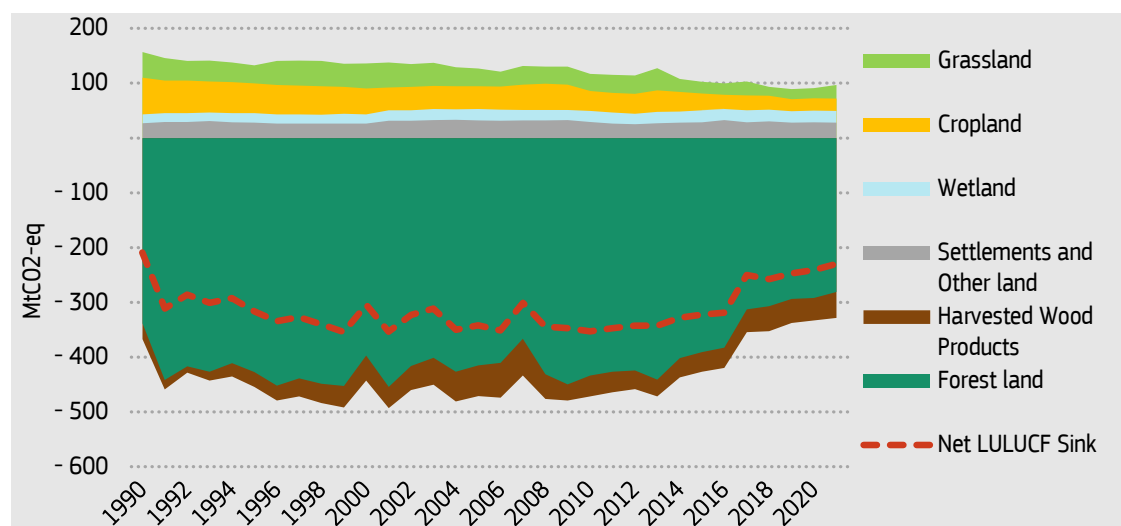
Source: GAINS.

1.8. LULUCF

1.8.1. Introduction

Figure 86 shows the evolution of the EU LULUCF net removals over 1990-2021. They have been on average about -325 MtCO₂-eq between 1990 and 2016, and declining since, down to -230 MtCO₂-eq in 2021.

Figure 86: Historical LULUCF emissions, removals and net carbon removals



Source: UNFCCC 2023

The LULUCF sector generates emissions from wetland, cropland, and grassland, settlements and other land (69 MtCO₂-eq in 2021), which are counterbalanced with removals from forest land (-281 MtCO₂) and through harvested wood products (-47 MtCO₂).

The different categories show relatively stable development for settlements and other land as well as wetland with changes below 10% throughout the average 2019-2021 compared to 10 years before. Cropland emissions (-44%) and grassland emissions (-36%) decreased considerably and removals from harvested wood products increased at the same time (+26%). However, in absolute terms the change in these sectors plays a minor role with a total change of -38 MtCO₂-eq. The changes in forest land are the decisive factor for the change in the net LULUCF net removal with a change of -34% in the last ten years of about -148 MtCO₂-eq (average 2019-2021 compared to 10 years before). Ageing forests, increased wood harvest for material and energy purposes, as well as impacts of climate change and natural hazards are responsible for the variations of the carbon removals from forests ⁽¹⁵⁵⁾ ⁽¹⁵⁶⁾ ⁽¹⁵⁷⁾.

⁽¹⁵⁵⁾ JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report*, 2023.

⁽¹⁵⁶⁾ ICOS ERIC, 'Forest carbon sinks under pressure' *Fluxes - The European Greenhouse Gas Bulletin Volume 2: Nature-based solutions for net zero*. ICOS ERIC, 2023. <https://doi.org/10.18160/99JW-2D3S>

⁽¹⁵⁷⁾ Ceccherini, G., Duveiller, G., Grassi, G. et al. Abrupt increase in harvested forest area over Europe after 2015. *Nature* 583, 72–77 (2020). <https://doi.org/10.1038/s41586-020-2438-y>

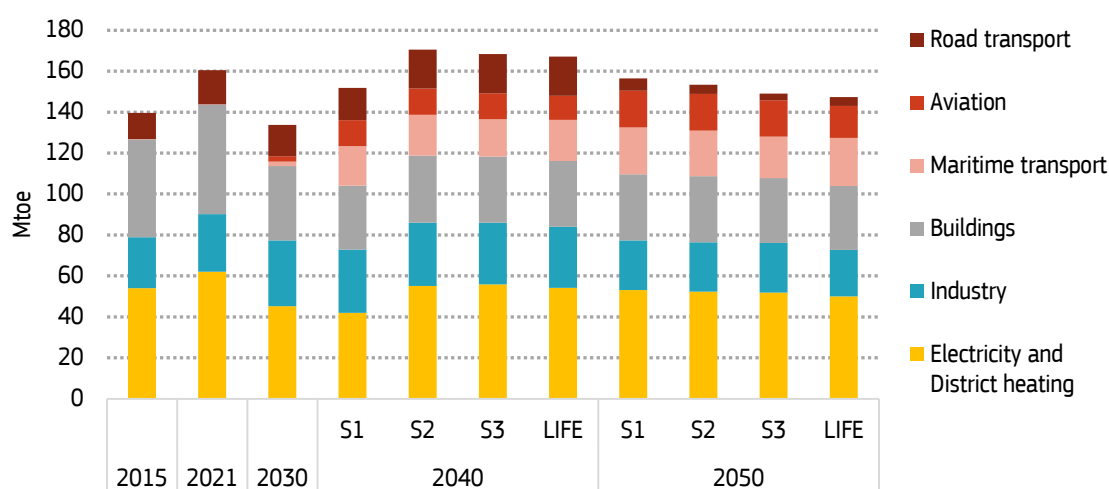
1.8.2. Activity

1.8.2.1. Bioenergy demand

The size of the LULUCF net removals is related to the use of biomass and particularly to the consumption of woody biomass. An important driver for the biomass demand is bioenergy, which made up 22% of the total biomass uses in 2015 ⁽¹⁵⁸⁾. Furthermore, 49% of woody biomass went directly or indirectly into bioenergy in 2015 ⁽¹⁵⁹⁾, underlining the strong relation of bioenergy and LULUCF net removals.

The modelling exercise shows final demand for bioenergy ⁽¹⁶⁰⁾ in 2040 being only slightly higher than in 2021 in scenarios S2 and S3, and lower in scenario S1 (see Figure 87).

Figure 87: Final bioenergy demand by sector and scenario



Note: Graph includes consumption of waste for energy purposes. 'Industry' includes energy sector. 'Buildings' cover household buildings, services, and agriculture.

Source: 2015 and 2021 from Eurostat, projections from PRIMES

However, consumption shifts across sectors. Demand for (mostly solid) biomass for heating reduces strongly in buildings (by about 20 Mtoe, due to energy efficiency gains and electrification of the sector), as well as in electricity and district heating (notably in S1), compared to 2021. Conversely, the demand for (liquid) biofuels develops significantly in aviation and maritime in 2040 by respectively about 15 Mtoe and 20 Mtoe. After 2040, bioenergy demand decreases across all scenarios, which is driven

⁽¹⁵⁸⁾ JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report*, 2023.

⁽¹⁵⁹⁾ Camia, A., Giuntoli, J., Jonsson, K., Robert, N., Cazzaniga, N., Jasinevičius, G., Avitabile, V., Grassi, G., Barredo Cano, J.I. and Mubareka, S., The use of woody biomass for energy production in the EU, EUR 30548 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-27867-2, doi:10.2760/831621, JRC122719.

⁽¹⁶⁰⁾ "Final" demand for bioenergy includes here bioenergy used in final energy consumption sectors (industry, transport, buildings, agriculture, services), in international aviation and maritime and as input to the electricity and district heating. It does not consider transformation process losses to produce biofuels, biogas or biomethane.

notably by reduced demand in road transport where it gets close to zero in a context of electrification of the vehicles fleet and, although to a lesser extent, in industry where it gets to levels observed in 2015.

Net imports of bioenergy (including solid biomass, waste, and liquid biofuels) are limited to 10-13 Mtoe in 2040 before reducing by 2050, against 9 Mtoe in 2021.

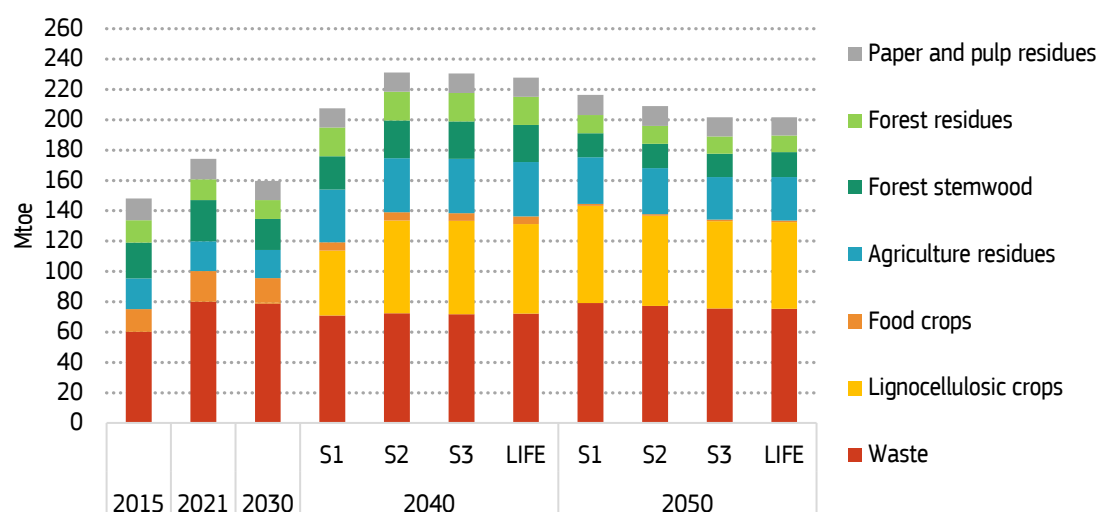
The evolution of bioenergy demand by 2040 towards an increasing role of second generation biofuels converts into higher domestic feedstock supply from lignocellulosic crops (both annual and perennial), while food crops decline. Bioenergy from agriculture residues is expected to also increase reflecting an improved mobilisation of their potential, including manure. S1 shows lower biomass supply needs than S2 and S3 by 2040, reflecting a lower recourse to bioenergy in electricity production and district heating. Woody biomass for bioenergy shows a limited increase to about 25 Mtoe for stemwood ⁽¹⁶¹⁾ and 20 Mtoe for forest residues in 2040, in a context of increasing use of secondary residues and used wood from consumers within the waste category. This has very important implications for the forest sink because primary woody biomass for bioenergy decreases the carbon pool and the LULUCF net removals. Therefore, an increasing use of secondary woody biomass from other uses (bark, secondary residues from material production, recovered post-consumer wood), which substitutes woody biomass coming directly from forests, has an alleviating effect on the LULUCF net removals. In 2040 wood plantations for energy use start to develop and stay stable in size in 2050, which also buffers the required harvest removals for energy use.

The total domestic feedstock for bioenergy and waste (including manure) peaks in 2040, ranging from about 210 Mtoe in S1 to just above 230 Mtoe in S2 and S3. By 2050 the feedstock supply decreases to a level ranging between 200 Mtoe (S3) and 215 Mtoe (S1). ⁽¹⁶²⁾

⁽¹⁶¹⁾ Forest stemwood for bioenergy can be defined as fuelwood and usually consists of roundwood of quality that is in general not suitable for other purposes. It is harvested directly from forests.

⁽¹⁶²⁾ Future analyses may assume other supply levels of biomass to stay within the sustainability boundaries, in view of the on-going scientific debate.

Figure 88: Domestic supply of feedstock for bioenergy and waste



Note: 'Lignocellulosic crops' includes short rotation coppice and lignocellulosic grass. Manure is included in 'Waste'.

Source: PRIMES, GLOBIOM

As shown in section 1.1.2, scenario S3 requires more industrial carbon removals by 2040. This scenario may require higher biomass use for BECCS if the deployment of the other key identified option to generate industrial removals, DACCS, would remain limited in the coming 15 years. Section 1.8.4 below provides a sensitivity analysis on the impact of a higher need for biomass on the LULUCF net removals.

1.8.2.2. Bioeconomy demand

Beyond bioenergy, the role of bioeconomy at large will have impacts on the future LULUCF net removals. Notably, a change from short-term to long-term harvested wood products will increase the temporary carbon stock and lead to a temporary increase in the net removals. Hence, whether biomass from harvests is used for long-term harvested wood products such as furniture or woody elements in buildings or whether it is used for bioplastics, paper or single-use products is important as it has implications on the size of the temporary sink from harvested wood products. Annex 9 discusses the need for healthy nature and a sustainable bioeconomy in view of maintaining and enhancing the LULUCF net removals and other nature services.

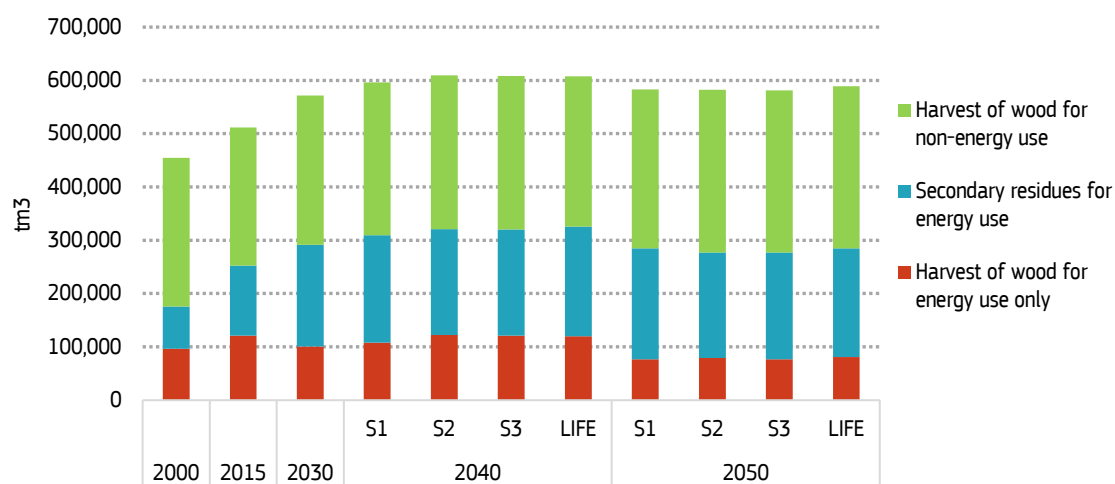
1.8.2.3. Harvest of wood and forest increment

The European forests play a decisive role for the EU LULUCF carbon net removals, as the share from forest land makes up nearly 90% of all carbon removals from the LULUCF sector (see Figure 86). The 'forest sink' depends on the gross annual increment of a forest, the natural mortality and fellings (harvest and logging residues) ⁽¹⁶³⁾. Hence, the demand for woody biomass and the corresponding harvest and overall forest management has a direct impact on the forest sink.

⁽¹⁶³⁾ Korosuo, A. et al., 'The role of forests in the EU climate policy: are we on the right track?', *Carbon Balance and Management*, 18, 15, 2023.

Figure 89 shows the evolution of wood harvest by 2050. Wood production increased significantly since the beginning of this century to satisfy the increasing demand for woody biomass ⁽¹⁶⁴⁾. Compared to 2015, total harvest of wood is expected to be higher in 2040 (ranging from 17% in S1 to 19% in S3), and then decline by 2050. The increase is driven by harvest for elevating demand of biomass for material uses, combined with an improved exploitation of secondary residues used for energy purposes, while direct harvest for energy uses is expected to be similar to 2015 or slightly lower (for S1) in 2040 before declining by 2050.

Figure 89: Harvest of wood for energy and non-energy use



Note: "Secondary residues used for energy use" are forest residues that were initially harvested for material use (e.g., from the production of sawnwood) but then used for energy production.

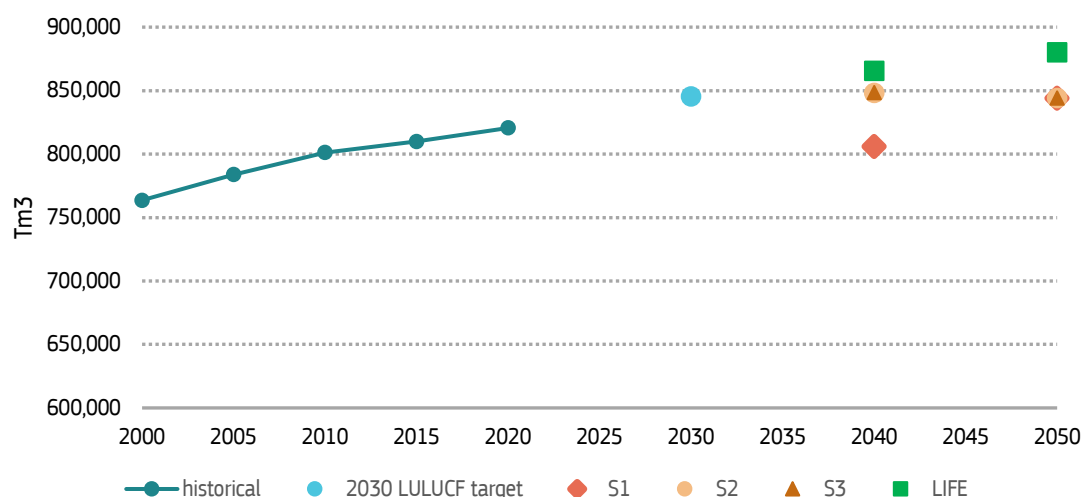
Source: GLOBIOM

The gross annual increment of a forest is the second important factor that determines the forest carbon sink. As an important development, the productivity of the managed forests has peaked, given recent forest management strategies, and given the fact that the increase of the biomass stock in the EU has slowed down in recent years ⁽¹⁶⁵⁾. The slower increase of growth productivity (i.e., the annual increment of the forests) is due to the age structure of the forests, which show a slower growing rate at higher ages. As shown in Figure 90, forest increment of managed forest is projected to reach its maximum around 2030 for S1 and around 2040 for S2 and S3 and will then slowly decline. The difference in forest increment between the scenarios in 2040 is caused by different carbon values to cover mitigation costs, which incentivize improved forest management and afforestation in S2 and S3 (see section 1.8.3). In 2050 S1, S2 and S3 use equal carbon values, resulting in the same forest increment. For LIFE the trend looks more optimistic, because a significant share of new land is used for afforestation, which leads to a greater forest increment compared to S2 and S3. In 2050 the discrepancy to the other scenarios becomes even bigger, because additionally afforested trees achieve high growth rates.

⁽¹⁶⁴⁾ JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report*, 2023.

⁽¹⁶⁵⁾ JRC, 'Biomass production, supply, uses and flows in the European Union', *JRC Science for policy report*, 2023.

Figure 90: Total forest increment of managed forests per year and scenario in EU



Note: The graph depicts the forest increment projections per year for S1, S2, S3 and LIFE. The forest increment does not take natural disturbances or climate change and CO₂ fertilisation effects into account.

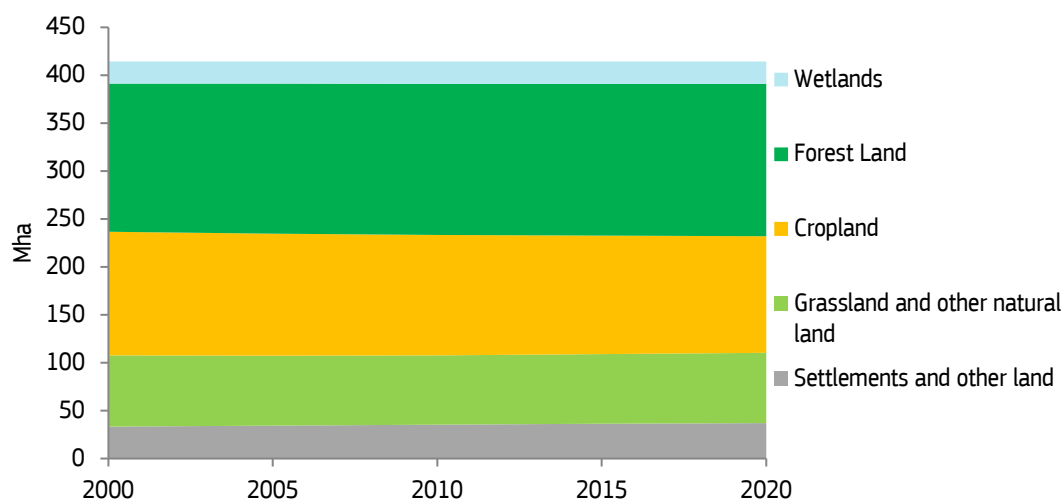
Source: GLOBIOM

1.8.2.4. Land use

The distribution of land for different uses impacts GHG emissions and carbon removals from land but is also influencing the functioning of habitats and ecosystems which play a vital role for biodiversity and climate. The use of land is under high competition in the EU to supply land for food, production of materials, bioenergy, housing and infrastructures, ecosystem services and other purposes. A change in land use for example by reducing the land for settlements or changing land used dedicated to fodder activities for carbon farming activities would reduce emissions or enhance carbon removals and thus have a positive impact on the net removals.

Figure 91 provides an overview of the historic evolution of the land use until 2020. Overall, the share of land use between different sectors appears very stable with a slow increase in managed forest land (+4 Mha) and land for settlements (+3 Mha) and a simultaneous decline of cropland (-7 Mha). The area for settlements has been steadily increasing until today, which is associated with additional emissions.

Figure 91: Evolution of land use in EU by category

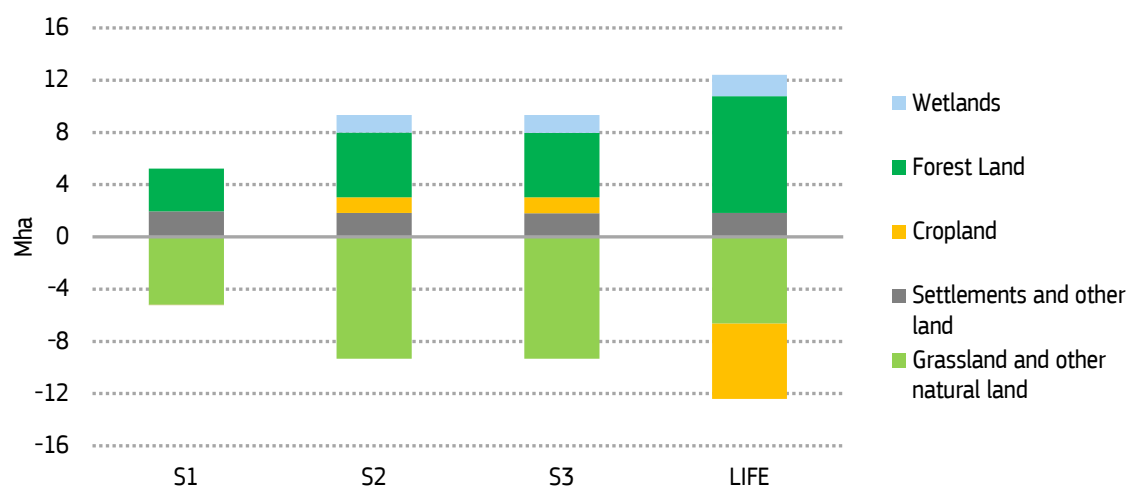


Note: Evolution of land use by land use category from 2000 until 2020.

Source: UNFCCC 2023, GLOBIOM

From 2020 onwards the different scenarios comprise different developments of land use (see Figure 92), although the absolute overall land use changes compared to today remain small in relative terms, which range from 5 Mha (S1) to 9 Mha in S2 and S3 and 12 Mha in LIFE, which corresponds to 1-3% of the total land.

Figure 92: Changes in land use between 2020 and 2040 by scenario



Source: GLOBIOM

Next to the assumed growing land take by settlements (+2 Mha), the land use changes in the scenarios are driven by actions to enhance the LULUCF net removals⁽¹⁶⁶⁾ and changes on energy demand in S2 and S3, which decrease grassland and other natural land

⁽¹⁶⁶⁾ The scenarios assume a marginal mitigation cost covered for additional nature-based removals of EUR 50 for S2, S3, LIFE and no mitigation costs covered in S1. For details see Annex 6, section 3.2.

by 9.3 Mha in S2 and S3 and by 5.2 Mha in S1 ⁽¹⁶⁷⁾. This shift translates for S2 and S3 into more land for forests (+4.9 Mha). Furthermore, additional nature-based removals to increase the LULUCF net removal are implemented through restoration of wetlands, which increase by 1.4 Mha in S2 and S3. Very limited land use changes occur in S1 due to no incentives for additional nature-based removals and lower demand for second generation lignocellulosic crops. In S2 and S3 about 1.2 Mha are converted into additional cropland by 2040, while in S1 no additional cropland is converted. The cropland in S2 and S3 increases by about 1% compared to 2020 and is still substantially smaller than the total cropland area during the period of 2000 and 2015.

Throughout the scenarios, financial incentives for nature-based removals have a higher impact on land-use change than a limited use of lignocellulosic crops for bioenergy. Even though from total cropland area, land for lignocellulosic crops requires 7 Mha in S1 and 10.6 Mha in S2 and S3, the overall land-use change impact from crops for biofuels on total cropland is with an increase in cropland of about 1% relatively small ⁽¹⁶⁸⁾. This is because second-generation lignocellulosic crops replace in 2040 to a large extent cropland from first generation food crops. Lignocellulosic crops for second generation biofuels produce higher yields ⁽¹⁶⁹⁾ and require less land for the same amount of bioenergy ⁽¹⁷⁰⁾.

LIFE has significant effects for agricultural land used for livestock and fodder. Because less livestock and therefore less area for fodder is required, intensively managed grassland and cropland from fodder production are abandoned and converted into natural and set aside land partly covered with buffer stripes, hedges and other landscape elements, extensive grassland, and forests. The additional natural land vegetation is accounted in the grassland and other natural land category ⁽¹⁷¹⁾. In comparison to S2 and S3, the change in the food system in LIFE lead to additional forest land (afforestation;

⁽¹⁶⁷⁾ ‘Grassland and other natural land’ consists of managed pasture land, unmanaged grassland and shrubland. The area of managed pasture land remains relatively stable within the category.

⁽¹⁶⁸⁾ In 2040 total cropland remains unchanged in S1 and increases by 1.2 Mha in S2 and S3, because around 80% of the required area for lignocellulosic crops comes from cropland currently used for first generation biofuels (7.5 Mha) or other cropland (1.9 Mha). The total potential for lignocellulosic crops is however limited. A higher use of biofuels for road transport, maritime transport and aviation than displayed in the scenarios would have a much bigger impact on land use change or food production, because no further areas from first generation lignocellulosic crops could be substituted.

⁽¹⁶⁹⁾ Muylle, H., Van Hulle, S., De Vlieghe, A., Baert, J., Van Bockstaele, E., & Roldán-Ruiz, I., ‘Yield and energy balance of annual and perennial lignocellulosic crops for bio-refinery use: a 4-year field experiment in Belgium’, *European Journal of Agronomy*, 63, 62-70, 2015.

⁽¹⁷⁰⁾ Second-generation biofuel feedstocks often have a higher energy yield per unit of land and water compared to first-generation crops, which means that more energy can be obtained from the same amount of resources, making them more efficient in terms of land and water use. Moreover, these feedstocks are typically non-food feedstocks from energy crops which do not directly compete with food production and can also be produced on marginal lands; Antizar-Ladislao, B., & Turrión-Gómez, J. L. ‘Second-generation biofuels and local bioenergy systems.’ *Biofuels, Bioproducts and Biorefining: Innovation for a sustainable economy*, 2(5), 455-469, 2008.

⁽¹⁷¹⁾ Additional land available from fodder production and for livestock is becoming either afforested land or abandoned land with buffer stripes, hedges or other natural vegetation. This abandoned land is attributed here to the UNFCCC grassland sector which also includes shrubland, hence including some woody vegetation. Some changes in LIFE occur within the grassland sector (from productive to unproductive grasslands) and are therefore not visible as change in the overview on land use changes.

+4.0 Mha), more high-diversity landscape features⁽¹⁷²⁾ which is natural land partly covered with buffer stripes, hedges, fallow land or other natural vegetation (+6.8 Mha) and rewetted organic soils (+0.3 Mha). LIFE produces land use changes which result in less cropland (-7 Mha) and more grassland (+2.7 Mha) compared to S2 and S3. Lignocellulosic crops require a total area of around 10.2 Mha in 2040. The increase in wetlands is possible, because less fodder production and less requirement for agricultural grassland reduce pressure on the food system and make land for rewetting of dried organic soils cheaper.

1.8.3. Options to increase the net LULUCF net removal

As discussed in previous section 1.1 technical and nature-based carbon removals are an essential part in each scenario to achieve net zero emissions in 2050. The share between technical and nature-based removals may vary depending on the development of prices for industrial carbon removal technologies, nature-based removal options and the saturation effect of the land sink. Hence, although nature-based removals are expected to make up the bigger share of carbon removals, it is not clear which options will be more cost efficient at a certain point in time.

Nature-based removal options in the LULUCF sector include interventions in forests (e.g., reduce deforestation and peatland degradation, afforestation, forest management, peatland restoration) and agricultural soils (e.g., soil organic carbon management, agroforestry) and have different mitigation potentials⁽¹⁷³⁾. The costs for different mitigation options are specified as a yearly price per ton CO₂-eq, which are required for the implementation of a certain option. Throughout the public consultation, respondents rated ‘afforestation, reforestation and forest restoration’ as the most relevant solution for limiting climate change⁽¹⁷⁴⁾ (Average: 4.44, on a 5-point scale from ‘very irrelevant’ (1) to ‘very relevant’ (5)), which illustrates the perceived prominent role of forests for climate action among both citizens and organisations. Though other nature-based removals such as peatland restoration (rewetting, revegetating, and paludiculture) (Average: 4.24) as well as Agroforestry and other soil management practices (Average 4.18) were rated second and third among the most relevant solutions for limiting climate change. Thus, nature-based removals in the LULUCF sector are clearly well known and seen as the most promising options throughout the portfolio of mitigation options.

For some nature-based removals to contribute to the long-term enhancement of the LULUCF net removals is a slow process – one that should start now to maximise the 2050 carbon removal potential. However, other options, such as rewetting of peat- and wetlands, quickly reduce emissions, when implemented. Therefore, the mitigation

⁽¹⁷²⁾ Resulting from the goal to return at least 10% of agricultural area under high-diversity landscape features; see COM(2020) 380 final. A share of this natural land is formerly intensively managed grassland which stays within the grassland category.

⁽¹⁷³⁾ For an overview of nature-based removals see: Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., ... Lawrence, D., ‘Land-based measures to mitigate climate change: Potential and feasibility by country.’ *Global Change Biology*, 27, 6025–6058, 2021.

⁽¹⁷⁴⁾ Among a range of possible offered options (e.g., Peatland restoration, Agroforestry, BECCS, Biochar, DACCS, nuclear fusion, solar radiation modification)

potential of rewetting drained organic soils is substantial already in 2030. Forest and agriculture related options can also enhance the LULUCF net removal in the short term but most of their potential plays out in 2040 and 2050. As shown in Figure 93, improved forest management and afforestation, can provide a comparably large mitigation potential already by 2030 and largely to a relatively low price of 20 €/tCO₂-eq⁽¹⁷⁵⁾. Similarly, solutions for agricultural land unfold to a large extent as early as 2030, though mitigation costs are much more heterogeneous across the entire spectrum of mitigation options available in the agriculture sector and range from 5 to 150 €/tCO₂-eq. The potential of avoided deforestation is declining and will be almost exhausted after 2050.

Rewetting of drained organic soils makes up about 30% of the total potential for 50 €/tCO₂-eq or 100 €/tCO₂-eq. It provides a high mitigation potential⁽¹⁷⁶⁾ ⁽¹⁷⁷⁾ but also requires substantial investment⁽¹⁷⁸⁾. It can be achieved by using appropriate forms of agriculture management such as paludiculture or by completely taking the land out of production. The elevation of water levels (i.e., ‘rewetting’) reduces emissions that stem from the organic material in these soils. Notably, a high share of today’s drained peatlands is used for agricultural purposes, which hampers the peatlands from being rewetted. Thus, an important element for rewetting practices may be a compensation of farmers and landowners when switching to other forms of agriculture (e.g., paludiculture) or abandoning agricultural activity on these soils. Consequently, as shown in Figure 93, mitigation options for organic soils unfold their potential mainly at costs between 50 €/tCO₂-eq and 100 €/tCO₂-eq.

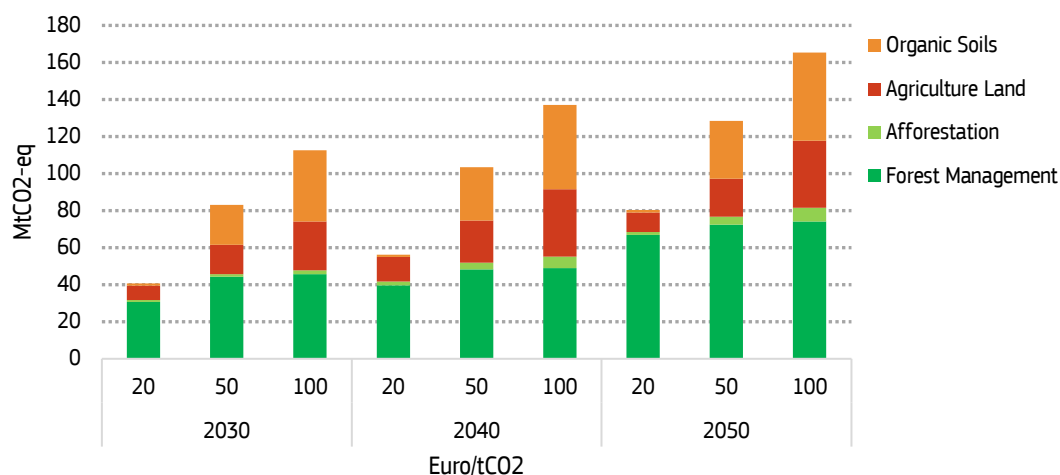
⁽¹⁷⁵⁾ All mitigation costs to cover for nature-based removals in this section are expressed in EUR 2020 values.

⁽¹⁷⁶⁾ CH₄ emissions on rewetted lands decrease the sink potential of active rewetting activities. CH₄ emissions have been included, to avoid an overly optimistic assumption of the potential. However, a high range of uncertainties still exist on CH₄ emissions on rewetted lands and therefore the sequestration potential needs to be interpreted with caution.

⁽¹⁷⁷⁾ Rewetting of drained peatlands overall reduces climate warming despite CH₄ emissions. See for details: Günther, A., Barthelmes, A., Huth, V. et al. ‘Prompt rewetting of drained peatlands reduces climate warming despite methane emissions’, *Nature Communications*, 11, 1644, 2020.

⁽¹⁷⁸⁾ New assumptions on active rewetting and corresponding prices for land acquisition, active rewetting and maintenance have been incorporated for this impact assessment.

Figure 93: Mitigation potentials in LULUCF at different mitigation costs



Note: Nature-based removals show mitigation (including sequestration) potential in MtCO₂ by different mitigation costs. Bars show the accumulated additional LULUCF net removal per year with the respective yearly cost. Costs expressed in EUR2020.

Source: GLOBIOM

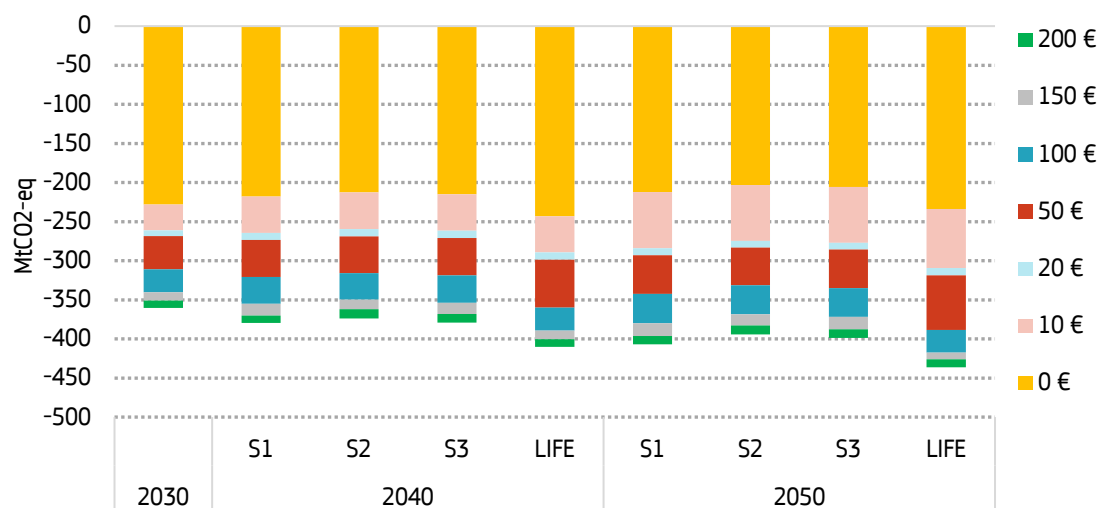
Importantly, many nature-based removals also provide co-benefits for biodiversity as it oftentimes involves a land-use change that can shelter diverse ecosystems and habitats (as in the case of wetlands or when land is converted into primary forest land).

The recently revised LULUCF Regulation sets out a target of -310 MtCO₂-eq of net removals⁽¹⁷⁹⁾ for the LULUCF sector in 2030 as well as corresponding targets for Member States. The modelling results (see Figure 94) indicate that most mitigation options to achieve this target, are available at low mitigation costs (0-20 €/tCO₂-eq), but some nature-based removals with mitigation costs between 40 and 50 €/tCO₂-eq⁽¹⁸⁰⁾ would be required. Implementing these nature-based removal options will also be beneficial beyond 2030 since substantial LULUCF net removals will be required to offset emissions from hard-to-abate sectors in 2040 and 2050.

⁽¹⁷⁹⁾ See LULUCF regulation: Regulation (EU) 2018/841 (amended by Regulation 2023/839)

⁽¹⁸⁰⁾ The Impact Assessment accompanying the proposal for a revised LULUCF Regulation indicated that the target of -310 MtCO₂-eq could be achieved at lower mitigation costs (5-10€/tCO₂-eq), but the starting point for those assumptions was the average LULUCF sink in 2016-2018 which was much larger than the current trend of the LULUCF sink. More importantly, updated mitigation costs have been taken into account in this impact assessment based on the latest scientific literature.

Figure 94: LULUCF net carbon removal potential for different mitigation costs



Note: Mitigation costs specify the price in Euro per tonne CO₂-eq removed by different nature-based removal options. The columns indicate the additional, marginal potential of nature-based mitigation available for the respective prices. Costs expressed in EUR2020.

Source: GLOBIOM

LIFE produces a consistently higher potential of carbon removals compared to S1, S2 and S3. This is because the agricultural area that is freed up in this scenario is expected to be used in part for carbon farming activities.

1.8.4. The LULUCF net removal

1.8.4.1. Analysis of the scenarios

The 2030 LULUCF target of -310 MtCO₂-eq⁽¹⁸¹⁾ is met by applying a carbon value of 50 €/tCO₂-eq⁽¹⁸²⁾. The exact size of the future level of LULUCF net removals bears many uncertainties, depending on the effect of future policy measures in the sector, potential additional nature-based carbon removals through certification schemes, climate change impacts, extreme events, biomass demands, resulting harvesting levels and other factors. A range for the LULUCF net removals is introduced in the analysis to illustrate this uncertainty for the period after 2030, by looking at three levels of net removals:

- A 'lower level', showing a lower boundary for the LULUCF net removals, which is technically implemented in the modelling by applying in the modelling a carbon value of 0 €/tCO₂-eq;
- A 'central level', showing the resulting net LULUCF removals when applying the carbon value of 50 €/tCO₂-eq necessary to meet the 2030 target;

⁽¹⁸¹⁾Regulation (EU) 2018/841 (amended by Regulation 2023/839)

⁽¹⁸²⁾In EUR 2020. The carbon value per tCO₂-eq are calculated as a yearly cost for mitigation. In the following only the marginal carbon values are specified, which means large shares of additional nature-based removals are available at lower costs (see previous section for details).

- An ‘upper level’, showing an upper boundary of the LULUCF net removals, which is technically implemented in the modelling by applying a carbon value of 200 €/tCO₂-eq (which translates into higher net removals than in the “central” level).

To calculate the overall net GHGs of the scenarios across the economy (see section 1.1), the “Central” level of net LULUCF removals is applied for all scenarios in 2040 and 2050, except for S1 in 2040, which applies the “Lower level”.

Figure 95 provides an overview of the LULUCF emissions and removals and the corresponding evolution of the central level as well as the range (i.e., lower and upper level) of the LULUCF net removals for the different scenarios. The difference across scenarios in terms of energy demand translate in differences into forest sink levels as well as different emission levels in cropland. Carbon stored in harvested wood products, and emissions from grassland, settlements and other land, as well as from drained wetlands remain fairly similar across scenarios.

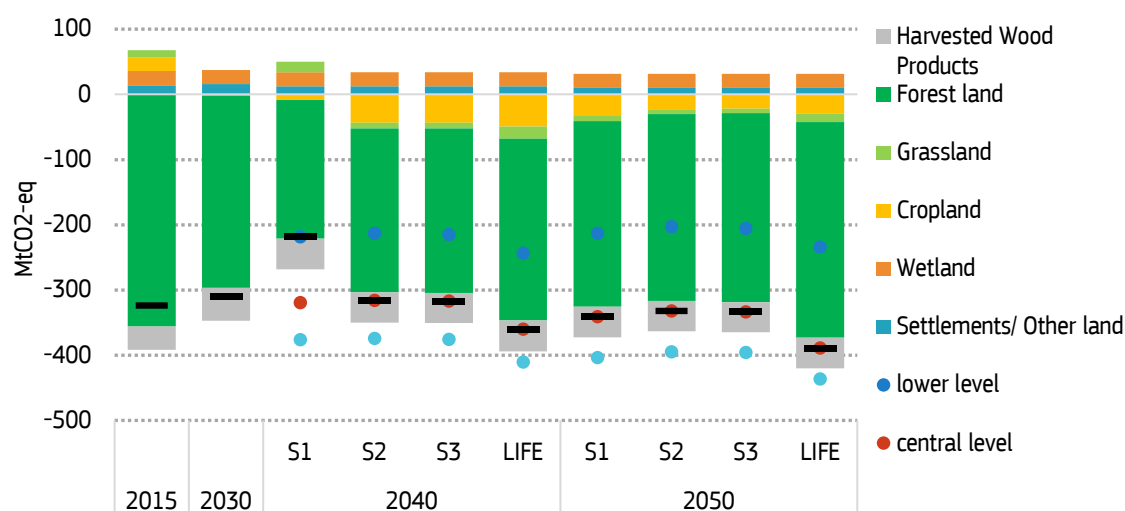
S2, and S3 show very similar net removal levels in 2040 of about -320 MtCO₂-eq. S1 shows much smaller net removals in 2040 of about -220 MtCO₂-eq due to less nature-based removals from cropland, grassland, and forest land. Furthermore, S2 and S3 show higher removals from cropland due to more plantation of lignocellulosic crops in 2040 ⁽¹⁸³⁾.

2050 illustrates a general increase in the net removals across all scenarios by roughly 15 MtCO₂-eq (S2, S3) to 120 MtCO₂-eq (S1), reaching -330 to -340 MtCO₂-eq. Despite this average increase by 2050, the range illustrates that the net removal depends considerably on the capacity of policies to safeguard the net removal to fall below the 2030 target or, conversely, to deliver a stronger contribution towards climate neutrality up of about -400 MtCO₂-eq.

LIFE produces a higher LULUCF net removal, because agricultural land is converted into high-diversity landscape elements covered with buffer stripes, hedges and other landscape elements or provided for carbon farming activity (afforestation) which allows for a considerable increase in the forest sink (30 MtCO₂-eq) and decreases net emissions on agricultural land (15 MtCO₂-eq). The net effect for the LULUCF net removal in LIFE is approximately -45 MtCO₂-eq.

⁽¹⁸³⁾ Lignocellulosic crops create a singular short-term sink effect, when being planted the first time. This growing carbon stock is resulting in carbon removals in cropland starting by 2035 is fading out by 2050 when the carbon pool through these crops has been saturated and no additional carbon removal is achieved. This temporary sink is therefore not a reliable source for the LULUCF sink in the long term. S1 uses less lignocellulosic crops for biofuels compared to S2 and S3.

Figure 95: LULUCF net removal emissions and removals



Note: Emissions and removals include all GHG-emissions from the LULUCF sector and are reported in MtCO₂-eq. For the calculation of LULUCF net removals of the scenarios in 2040, S1 considers the “lower level”, while S2 and S3 the “central level”. All scenarios consider the “central level” in 2050.

Source: UNFCCC 2023, GLOBIOM

The ESABCC analysis defines an environmental risk level of 400 MtCO₂ per year as a maximum net removals level by 2050 ⁽¹⁸⁴⁾. All scenarios analysed in this impact assessment stay below this environmental risk level.

A complementary analysis scenario S2 was run with the JRC forest sector carbon model (FSCM) to crossvalidate the level of the forest sink and the temporary sink of harvested wood products (HWP), which are the main drivers of the LULUCF removals. The results show similar results across both models for these two major carbon removals categories ⁽¹⁸⁵⁾ in the LULUCF sector throughout the period with somewhat higher projections of net removals with the FSCM for 2040: FSCM projects -334 MtCO₂-eq in 2030 (compared to -345 MtCO₂-eq in GLOBIOM model), -331 MtCO₂-eq in 2040 (compared to -298 MtCO₂-eq in GLOBIOM model) and -347 MtCO₂-eq in 2050 (compared to -333 MtCO₂-eq in GLOBIOM model).

1.8.4.2. Sensitivity of the LULUCF net removals to woody biomass use

The scenario S3 relies significantly more than S1 and S2 on industrial carbon removals from DACCS and on e-fuels, two novel technologies with uncertain deployment

⁽¹⁸⁴⁾ This risk level was based on research by Pilli et al. (2022) who provide as a probable range of -100 to -400 MtCO₂-eq for the LULUCF net removals in 2050 taking future climate change impacts based on RCP 2.6 into account. Scenarios exceeding the upper bound of -400 MtCO₂-eq may rely on implausibly high LULUCF net removal levels.

⁽¹⁸⁵⁾ Carbon removals from Forest land and harvested wood products from both models are compared against each other in an aggregated form because neither of the two subcomponents deviated systematically from that aggregate. The numbers are missing emissions from other lands and do not show the total LULUCF net removal. The GLOBIOM model numbers derive from the central level LULUCF case with a carbon value of 50 €/tCO₂, the JRC FSCM does not make these assumptions and assumes a market-driven process.

prospects, which could be substituted by biomass-based options (respectively BECCS and 2nd generation biofuels).

To assess the risks for LULUCF net removals from a higher uptake of biomass, a sensitivity analysis was produced with the GLOBIOM model based on the scenario S3 simulating a higher demand of 20 Mtoe of woody biomass, to showcase the worst possible impact on the LULUCF net removals. The increased demand of woody biomass results in a decrease of the LULUCF net removals by around 100 MtCO₂-eq in 2040, and around 65 MtCO₂-eq in 2050. However, if additional biomass would originate from other sources such as secondary residues, used wood products, lignocellulosic crops, or other waste, the impact on the sink would be much more limited. Still, the analysis shows that the mitigation obtained from a high use of bioenergy, associated to for instance BECCS, needs to be compared with the possible corresponding losses in the LULUCF net removals ⁽¹⁸⁶⁾ ⁽¹⁸⁷⁾, depending on the biomass type.

1.8.5. Analysis of climate change impacts and CO₂ fertilisation

Increasing climate change and GHG emissions have the potential to affect the LULUCF sector, both in a negative (e.g., from lower rainfall, natural disturbances, extreme heat) and beneficial way (e.g., from CO₂ fertilisation, extended growing seasons) ⁽¹⁸⁸⁾. What remains certain however is that the forest net removals are threatened by climate impacts and their future robustness is far from guaranteed. Hence, there exist large uncertainties on the future capacity of the LULUCF net removal due to the complex impacts of both human and natural drivers. Consequently, high uncertainties in current and future levels of nature-based carbon removals mean that it may not be precisely known if the LULUCF net removal is on track to match the required size in the scenarios ⁽¹⁸⁹⁾. It is important to stress that water availability plays a crucial role for EU's forests. It appears that impact of climate change on forest productivity depends strongly on water availability ⁽¹⁹⁰⁾ ⁽¹⁹¹⁾. While the impact of climate change on precipitation levels can be

⁽¹⁸⁶⁾ Because the model assumes only sustainable harvest, yearly harvesting levels cannot exceed the yearly increment from growth. The higher bioenergy demand therefore leads to price feedbacks on biomass for materials, leading to a decline in material demands for harvested wood products.

⁽¹⁸⁷⁾ Merfort, L., et al., 'Bioenergy-induced land-use-change emissions with sectorally fragmented policies' Nature climate change, 2023

⁽¹⁸⁸⁾ It should be noted that the valence of an impact depends on different factors and therefore even natural disturbances may have long-term beneficial effects for the sink. Thus, the listed examples only illustrate the standard case.

⁽¹⁸⁹⁾ Smith, S. M., Geden, O., Nemet, G., Gidden, M., Lamb, W. F., Powis, C., Bellamy, R., Callaghan, M., Cowie, A., Cox, E., Fuss, S., Gasser, T., Grassi, G., Greene, J., Lück, S., Mohan, A., Müller-Hansen, F., Peters, G., Pratama, Y., Repke, T., Riahi, K., Schenuit, F., Steinhauser, J., Streffer, J., Valenzuela, J. M., and Minx, J. C. (2023). The State of Carbon Dioxide Removal - 1st Edition. Available at: <https://www.stateofcdr.org>

⁽¹⁹⁰⁾ Pastor, J., & Post, W. M. (1988). Response of northern forests to CO₂-induced climate change. Nature, 334(6177), 55-58.

⁽¹⁹¹⁾ Ruiz-Benito, P., Madrigal-Gonzalez, J., Ratcliffe, S., Coomes, D. A., Kändler, G., Lehtonen, A., ... & Zavala, M. A. (2014). Stand structure and recent climate change constrain stand basal area change in European forests: a comparison across boreal, temperate, and Mediterranean biomes. Ecosystems, 17, 1439-1454.

modelled, it is difficult to assess the full impact of climate change on regional water availability including groundwater levels because of high cascading uncertainties.

To assess these uncertainties, climate change impacts of different warming potentials were modelled in GLOBIOM, taking different drivers such as an increase of CO₂, extended growing seasons, a higher frequency of natural disturbances and changing precipitation levels into account ⁽¹⁹²⁾. Starting from the evolution of LULUCF net removals in absence of dedicated policies, two different representative concentration pathways for GHG concentrations (RCPs) 2.6 and 7.0 are used to illustrate the range of impacts through different levels of global warming ⁽¹⁹³⁾, and four different climate models were used per RCP to estimate the range of possible outcomes ⁽¹⁹⁴⁾. Furthermore, because the magnitude of the CO₂ fertilisation effect on forest growth is still part of a scientific debate ⁽¹⁹⁵⁾ ⁽¹⁹⁶⁾, the eight trajectories are assessed both with and without persistent CO₂-fertilisation. To illustrate the entire range of uncertainty, all 16 climate impact trajectories entail an additional soil related range due to uncertainty of the heterotrophic respiration (i.e., soil, deadwood and litter decomposition rates), which vary by different degrees of climate change ⁽¹⁹⁷⁾.

Even though climate change impacts vary on the different activities such as forest management, cropland management, grassland management, and harvested wood products the most severe impact is on forests and to a lesser extent on harvested wood products. The impact on forest depends on several factors such as the species used in forests, water availability in different regions, and CO₂ fertilisation.

Figure 96 shows a very wide range for the EU LULUCF net removal due to the effects of climate change. The range shows a deviation from the standard projection in 2040 by 68

⁽¹⁹²⁾ As factors were considered climate change impacts (temperature, precipitation, vapor pressure deficit), increased in damage of wood due to natural disturbances (wind damage, fire, and insect damage) as well as CO₂ fertilisation.

⁽¹⁹³⁾ RCP 2.6 is associated with a best estimate long-term temperature increase until 2100 of 1.8°C, therefore assuming coordinated global action to keep climate change below 2.0°C. RCP 7.0 represents a medium-to-high end of range of emissions and associated global warming, associated to a baseline outcome rather than ambitious climate action on a global level and results in 3.6 °C long-term temperature increase until 2100.

⁽¹⁹⁴⁾ UKESM1-0-LL - The UKESM1.0-N96ORCA1 climate model run by the Met Office Hadley Centre, UK; IPSL-CM6A-LR - The IPSL-CM6A-LR climate model run by the Institut Pierre Simon Laplace, France; GFDL-ESM4 - The GFDL-ESM4 climate model run by the National Oceanic and Atmospheric Administration, Geophysical Fluid Dynamics Laboratory, USA; MPI-ESM1-2-HR - The MPI-ESM1.2-HR climate model run by the Deutsches Klimarechenzentrum, Germany

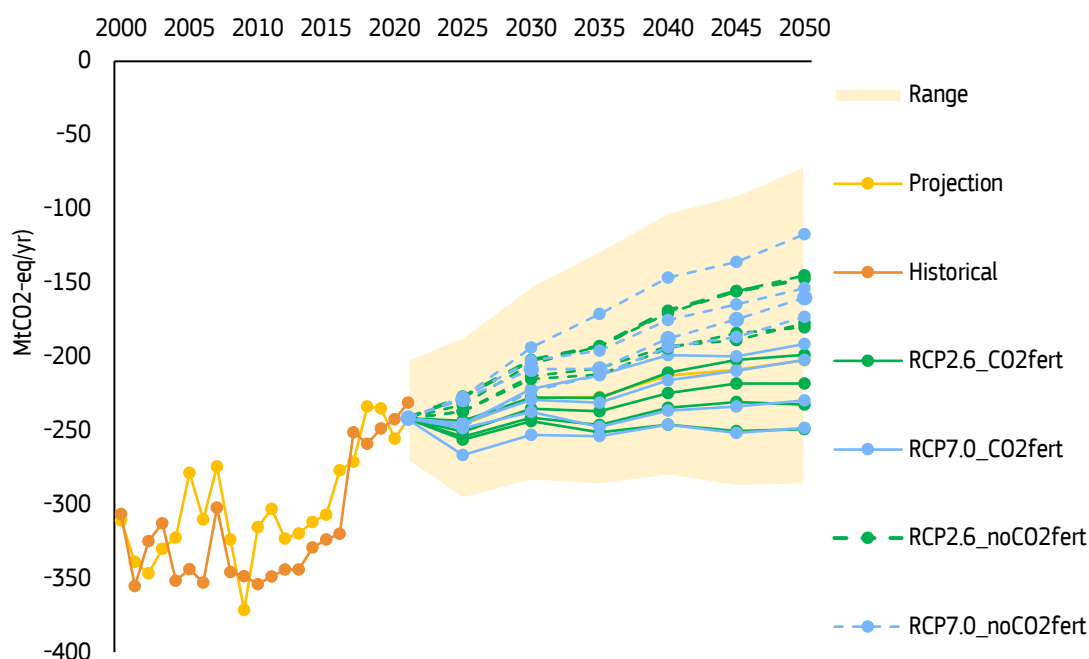
⁽¹⁹⁵⁾ Jiang, M., Medlyn, B.E., Drake, J.E. et al., ‘The fate of carbon in a mature forest under carbon dioxide enrichment’, *Nature*, 580, 227–231, 2020.

⁽¹⁹⁶⁾ Haverd, V., Smith, B., Canadell, J.G., Cuntz, M., Mikaloff-Fletcher, S., Farquhar, G., Woodgate, W., Briggs, P.R. and Trudinger, C.M., ‘Higher than expected CO₂ fertilization inferred from leaf to global observations’, *Global Change Biology*, 26,4, 2390-2402, 2020.

⁽¹⁹⁷⁾ The uncertainty is caused by changes in mortality and foliage/root turnover rates, as well as the influence of temperature and precipitation on the decomposition rates of these carbon pools. The different climate change trajectories entail different rates of carbon input to the soil (due to changes in forest dynamics) and different decomposition rates of deadwood, litter and soil carbon, resulting from changes in temperature and precipitation.

MtCO₂-eq to the upper bound (maximum net removals level) and 111 MtCO₂-eq to the lower bound (minimum net removals level). In 2050 the unsecurity increases further, resulting in a range with a deviation of 84 MtCO₂-eq to the upper bound and 133 MtCO₂-eq to the lower bound. Hence, depending on RCP, climate model and CO₂ fertilisation, the analysis projects for 2050 a possible range of net removals between roughly -70 MtCO₂-eq and -290 MtCO₂-eq (in absence of additional LULUCF policies). The finding is corroborated by other analyses⁽¹⁹⁸⁾ and also roughly concurs with the identified range of -100 to -400 MtCO₂-eq for the LULUCF net removal by 2050, as mentioned by the ESABCC, when taking future impacts of climate change into account.

Figure 96: Estimated climate change impacts on LULUCF net removal in EU



Note: The graph displays a model-based projection of the development of the LULUCF net removal in absence of dedicated mitigation policies [lower level]. The historical trajectory shows the historical inventory data based on UNFCCC 2023. and the 'projection' shows the trajectory of the LULUCF net removal without considering the impact of climate change. The different 16 trajectories show RCP 2.6 vs. 7.0 (2) X different climate models (4) X CO₂ fertilisation vs. no fertilisation (2). The range illustrates the uncertainty due to climate change impacts across all trajectories including uncertainty on carbon storage in soils.

Source: GLOBIOM, UNFCCC 2023

Taking a closer look at the individual climate scenarios, one can see the important role of CO₂ fertilisation⁽¹⁹⁹⁾ and its potential impact on the EU-wide LULUCF net removals. When considering no effect from CO₂ fertilisation, all scenarios show a decline in the LULUCF net removals. When including assumptions on effective CO₂ fertilisation, the

⁽¹⁹⁸⁾ For example: Pilli, R., 'The European Forest carbon budget under future climate conditions and current management practices', *Biogeosciences*, 19, 3263–3284, 2022.

⁽¹⁹⁹⁾ There is a high confidence among the scientific community of the existence of a positive effect of CO₂ fertilisation and extended growing seasons on forests. However, uncertainty remains on the on the size of the effect, IPCC, Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems, 2019.

scenarios show predominantly an increase in the LULUCF net removal in both RCPs. This is because the fertilization effects of increased atmospheric CO₂ lead on average to an increase in forest productivity in future climate scenarios. Considering regional variations in climate change effects, the highest gains occurred in the boreal zone, especially central Sweden and Finland, as well as montane areas in central Europe. Mediterranean forests displayed decreases in standing stocks compared to the reference climate, due to the increase in aridity in the region, with lower precipitation and higher temperatures. Hence, it should be noted that the CO₂ fertilisation effect varies between tree species and regions.

1.8.6. Impacts from simulated extreme events on the LULUCF net removal

European forests are vulnerable to a variety of disturbances such as windstorms, forest fires, pest attacks, and water scarcity. Climate change is closely linked to these disturbances in Europe, making them more frequent and more severe ⁽²⁰⁰⁾. The hotter and drier conditions in the future due to climate change, the more drought and fire disturbances are expected to increase across Europe, especially in the Mediterranean areas ⁽²⁰¹⁾. The last decades brought a variety of extreme events with 2022 showing the second largest wildfire burnt area on record in Europe with a total of 900 000 ha burnt across EU countries ⁽²⁰²⁾ and unprecedented droughts since 2018 leading to large outbreaks of bark beetles in Northern and Central Europe. Importantly, different regions within the EU are not expected to be affected similarly by the same type of disturbances. General hotspots of damage may be located in Scandinavia and mountain forests of Central Europe, which are particularly exposed to the impacts of winter storms, leading to higher risk of wind damage in forests ⁽²⁰³⁾. Modelling results also point to future damage hotspots in Portugal, Spain, southern France and Greece corresponding to regions with high wildfire activity in recent years. Annex 7 provides a more in-depth analysis on how disturbances affect different regions.

While climate change impacts including the increase of natural disturbances unfold their detrimental effects evenly in the mid- and long-term, extreme weather events have an uneven and short-term impact on net removals from the LULUCF sector in general and on the forest sink in particular. In other words, these exceptional events add an additional layer of uncertainty on the evolution of forest stocks particularly for individual member states.

To illustrate the potential impacts for the LULUCF net removal, the year 2035 is simulated as a year with exceptional weather events resulting in a combination of fire, wind and biotic damages that occur across different regions across the EU (see Figure 97).

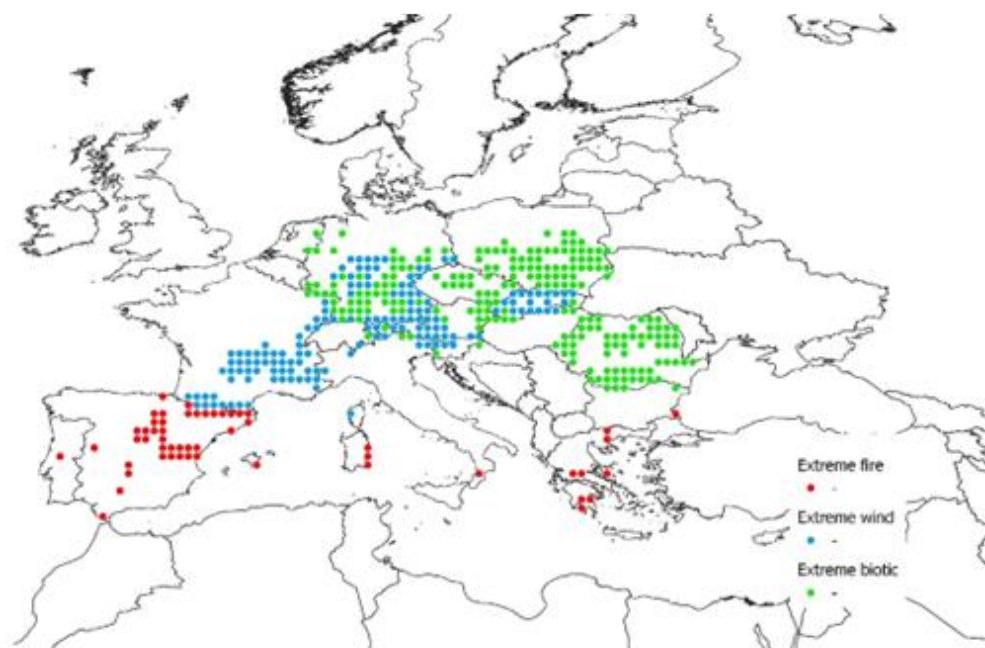
⁽²⁰⁰⁾ Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., ... & Reyer, C. P., 'Forest disturbances under climate change', *Nature climate change*, 7(6), 395-402, 2017.

⁽²⁰¹⁾ Asensio, D., Zuccarini, P., Ogaya, R., Marañón-Jiménez, S., Sardans, J., & Peñuelas, J., 'Simulated climate change and seasonal drought increase carbon and phosphorus demand in Mediterranean forest soils', *Soil biology and biochemistry*, 163, 108424, 2021.

⁽²⁰²⁾ Copernicus Climate Change Service, 'European State of the Climate Summary 2022', 2022.

⁽²⁰³⁾ corroborating with the results (Laurila et al. 2021)

Figure 97: Area coverage of simulated series of extreme events in 2035



Note: The graph shows the distribution of the different disturbance agents (extreme fire, extreme wind and extreme biotic disturbance) across the EU from the simulated extreme events.

Source: GLOBIOM

To model the damage on forests, historically the worst wind, fire, and biotic events over the period 1990–2020 for each disturbance agent were selected⁽²⁰⁴⁾. The approximate damage from these events⁽²⁰⁵⁾ is simulated to affect the most vulnerable forest stands across the EU (see Figure 97). In the simulation the Mediterranean region is strongly affected by extreme fires, while large parts of central Europe are affected by extreme wind and biotic events causing in total more than 300 000 000 m³ of forest damage. It is important to note, that the model assumes that salvage logging and replanting of the damaged trees occur the same year as the disturbance and that they predominantly affect more vulnerable older and larger trees, which are then salvage logged to the extent possible⁽²⁰⁶⁾. Consequently, a partial compensation of the disturbance-induced forest loss through reduced harvesting rates is assumed. Thus, the simulation entails the assumption of an ideal environment for the recovery of the carbon pool and the LULUCF

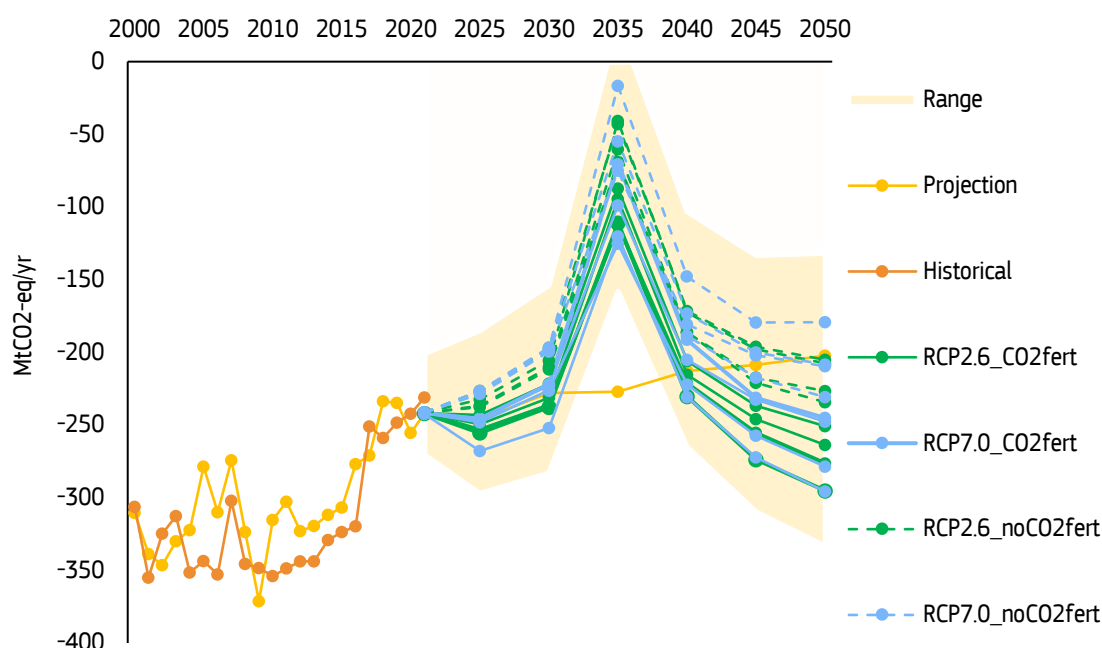
⁽²⁰⁴⁾ Patacca, M., Lindner, M., Lucas-Borja, M. E., Cordonnier, T., Fidej, G., Gardiner, B., Hauf, Y., Jasinevičius, G., Labonne, S., Linkevičius, E., Mahnken, M., Milanovic, S., Nabuurs, G.-J., Nagel, T. A., Nikinmaa, L., Panyatov, M., Bercak, R., Seidl, R., Ostrogović Sever, M. Z. ... Schelhaas, M.-J. 'Significant increase in natural disturbance impacts on European forests since 1950', *Global Change Biology*, 29, 1359–1376, 2023.

⁽²⁰⁵⁾ In total, 333,066,346 m³ of forest are damaged in the simulation, wind damages 228,520,374 m³, biotic agents 77,828,111m³, and fire 26,717,862 m³ of forest wood.

⁽²⁰⁶⁾ Disturbances usually damage older and larger trees, therefore, the extreme disturbance event eliminates a considerable amount of older trees, shifting the age structure of the damaged forest and enhancing forest regrowth. The model assumes that 86% of wood damaged by wind, 72% of wood damaged by biotic and 54% of wood damaged by fire, is harvested. The rest of the damaged wood is becoming deadwood and litter when disturbed by wind or biotic agents, while for wildfires about 10% of merchantable wood and 22% of litter and deadwood are burnt.

net removals. If these conditions are not met in a real event, the recovery of the LULUCF net removals might significantly be impeded. The extreme events will cascade not only to the European forest carbon pool, but also to wood processing industry and markets, via changes in wood supply and market shocks⁽²⁰⁷⁾.

Figure 98: Estimated climate change impacts and extreme events on LULUCF net removal



Note: The graph displays a model-based projection of the range of the LULUCF net removal under impacts from climate change and simulated extreme events. The 'historical' trajectory shows the inventory data based on UNFCCC 2023, the 'projection' shows the trajectory of the lower boundary of the LULUCF range (lower level net removal) without impacts from climate change and extreme events. The different 16 trajectories show RCP 2.6 vs. 7.0 (2) X different climate models (4) X CO₂ fertilisation vs. no fertilisation (2). The range illustrates the range of uncertainty due to climate change impacts across all trajectories including uncertainty due to soil carbon removals. In 2035 a series of extreme events is simulated to illustrate its impact on the LULUCF net removal.

Source: GLOBIOM, UNFCCC 2023

In Figure 98 the impacts of a series of possible extreme events in one year for the LULUCF net removal are depicted through an uncertainty range that takes climate change impacts into account. The net removal level of the LULUCF sector drops to a range between -160 and +30 MtCO₂-eq at the time of the disturbance but recovers relatively quickly in the next 5 years (-105 to -265 MtCO₂-eq). Over the next 15 years the simulation provides a slightly higher range for the LULUCF net removals in 2050 (-130 to -330 MtCO₂-eq) than a scenario without extreme events (-70 to -285 MtCO₂-eq; see previous section), because of the enhanced forest regrowth of younger trees and under the assumption of immediate reforestation.

⁽²⁰⁷⁾ Gardiner, B., Schuck, A. R. T., Schelhaas, M. J., Orazio, C., Blennow, K., & Nicoll, B. (Eds.). 'Living with storm damage to forests', Vol. 3, pp. 129-p, Joensuu: European Forest Institute, 2013.

However, it should be noted that the modelling of such extreme events is at an early stage of development and assumptions on the severity of events, the share of wood that can be harvested after the event and replace otherwise planned harvests, the speed of forest recovery (i.e., cleaning and replanting), is critical for the outcome. For example, salvage logging preparation for replanting and afforestation may take several years due to lack of capacity, which will delay the forest recovery and consequently its capacity as a carbon removal. Furthermore, the range of uncertainty illustrates, that even when taking properly the development of the LULUCF net removal and climate change impacts into account, disturbances can disrupt the net carbon removal levels for years.

1.9. Environmental and health impacts

In addition to reducing GHG emissions, the different policy options directly or indirectly affect other environmental indicators.

Air quality is impacted in particular by the evolution of the energy and transport sector as well as the agricultural sector. Changes in the LULUCF and agricultural sector influence biodiversity and ecosystems, food security and the sustainable use of natural resources such as water.

1.9.1. Air quality

Clean air is essential to human health and sustaining the environment. Air quality has improved in the EU over the past three decades as a result of joint efforts by the EU and national, regional and local authorities in the Member States to reduce the adverse impacts of air pollution. However, nowadays, around 300 000 premature deaths per year and a significant number of diseases such as asthma, cardiovascular problems and lung cancer, among others, are still attributable to air pollution (and especially to particulate matter, nitrogen dioxide and ozone) ⁽²⁰⁸⁾. There is also increasing evidence that low air quality may be associated with changes in the nervous system, cognitive decrements, and dementia ⁽²⁰⁹⁾.

Air pollution remains the most frequent environmental cause of early death in the EU, and it disproportionately affects vulnerable groups such as children, elderly people and persons with pre-existing conditions, as well as socioeconomically disadvantaged groups ⁽²¹⁰⁾. In addition, air pollution threatens the environment through acidification and eutrophication, causing damage to natural ecosystems and crops. Currently, eutrophication from deposition of nitrogen exceeds critical loads in two thirds of ecosystem areas across the EU, with significant impact on biodiversity ⁽²¹¹⁾. This has a direct impact on the health of ecosystems and can aggravate situations of nitrogen surplus via water pollution. Furthermore, high ground-level ozone concentrations negatively affect plant growth.

⁽²⁰⁸⁾ European Environment Agency (2021). Air Quality in Europe 2021.

⁽²⁰⁹⁾ United States Environmental Protection Agency (2022). Supplement to the 2019 Integrated Science Assessment for Particulate Matter.

⁽²¹⁰⁾ European Environment Agency (2018). Unequal exposure and unequal impacts: social vulnerability to air pollution, noise and extreme temperatures in Europe.

⁽²¹¹⁾ COM(2022) 673 final (The Third Clean Air Outlook).

Research to quantify the benefits of climate action associated with improved air quality highlights the significant magnitude of such co-benefits⁽²¹²⁾. In general, the economic, technological and societal transformations required to reduce GHG emissions in the EU have positive impacts on air quality because they lead to lower energy consumption and a shift to non-emitting renewable energy sources and to less polluting combustion fuels. Therefore, these developments lead to lower emissions of pollutants such as fine particulate matter with a diameter of 2.5 µm or less (PM2.5) and nitrogen oxides (NOx). In addition, climate action will contribute to mitigate the increasing negative effects that climate change itself has on air quality, due notably to heatwaves or wildfires⁽²¹³⁾.

The GAINS model has been used to produce projections of air pollutant emissions and their impacts on public health and ecosystems for the decarbonisation pathways analysed in this impact assessment⁽²¹⁴⁾. The combination of existing air pollution policies as well as ambitious climate policies result in strong reductions of air pollutants by 2040. As shown in Table 19, in scenarios S1, S2 and S3, primary PM2.5 emissions in the EU decrease by 62% by 2040 compared to 2015 levels. Moreover, primary SO2, NOx, NH3 and VOC emissions decrease by 77%, 71%, 16% and 29%, respectively, over the same period. Note, however, that the consumption of solid biomass, which still represents a large share of renewable energy consumption in Europe, emits large amount of particulate matter (PM2.5 and PM10), non-methane volatile organic compounds (NMVOCs) and polycyclic aromatic hydrocarbons (PAHs)⁽²¹⁵⁾. In 2021, in the EU, more than 60% of PM2.5 emissions were generated by the residential sector, showing the large share of domestic heating (and, particularly, bioenergy) in fine particulate matter emissions⁽²¹⁶⁾. Thanks to further electrification of heating needs and more energy efficient buildings, the consumption of solid biomass in the residential sector is much lower in 2040 than today in all analysed scenarios (see section 1.3.3 in this Annex). The small differences in particulate matter emissions between scenarios are mainly due to differences in solid biomass consumption.

Differences in air pollutant emissions between LIFE and the other scenarios stem from significant differences in agricultural activity levels (i.e., reduction in livestock numbers and fertiliser application in LIFE). The largest reduction is observed for NH3 emissions (from livestock, manure management and mineral fertiliser application), but there are also substantial reductions in NOx emissions (from the fertilisation of agricultural soils) and VOC emissions (from manure). More specifically, in LIFE, in 2040, NH3 emissions are 36% lower than in 2015 (i.e., the decrease is 20 percentage points higher than in the S1, S2 and S3 scenarios), NOx emissions are 74% lower than in 2015 (i.e., the decrease

⁽²¹²⁾ Vandyck, T. et al. (2018). Air quality co-benefits for human health and agriculture counterbalance costs to meet Paris Agreement pledges, *Nature Communications*, Vol. 9, No. 4939.

⁽²¹³⁾ World Meteorological Organization (2023). WMO Air Quality and Climate Bulletin, No 3, September 2023.

⁽²¹⁴⁾ Note that the methodology used in this impact assessment is similar to the one used in the Third Clean Air Outlook (COM(2022) 673).

⁽²¹⁵⁾ European Environment Agency (2019). Renewable energy in Europe: key for climate objectives, but air pollution needs attention.

⁽²¹⁶⁾ European Environment Agency. National air pollutant emissions data viewer 2005-2021 (online). [Retrieved in August 2023.]

is 3 pp higher than in the other scenarios) and VOC emissions are 33% lower than in 2015 (i.e., the decrease is 4 pp higher than in the other scenarios). A relatively small reduction in primary PM_{2.5} emissions is also observed, due to lower crushing of bedding material by livestock movements. The level of SO₂ emissions is similar to that of the other scenarios, since agriculture activities do not emit much SO₂.

Table 19 also shows the positive impact that reducing air pollutant emissions has on public health⁽²¹⁷⁾. In the S1, S2 and S3 scenarios, the number of premature deaths per year caused by PM_{2.5} and ozone exposure in the EU drops by 58% in 2040 compared to 2015. This means around 270 000 less premature deaths per year in total. Furthermore, the annual number of years of life lost due to PM_{2.5} and ozone⁽²¹⁸⁾ exposure decreases by 55% (i.e., around 3.3 million years of life lost per year less) between 2015 and 2040. In LIFE, the number of premature deaths per year goes down by 60% between 2015 and 2040 (which means 277 000 cases per year less), and the annual number of years of life lost decreases by 57% (i.e., 3.4 million years of life lost per year less) over the same period. This implies reductions in the annual number of premature deaths and years of life lost between 2015 and 2040 that are 2 percentage points greater than in the other scenarios.

The decrease in air pollutant emissions reduces the costs of air pollution control in the EU. Table 19 shows that in 2040 these costs are EUR 25-27 billion lower than in 2015 in the S1, S2, S3 scenarios, and EUR 27 billion lower than in 2015 in LIFE. There is a reduction in air pollution control costs for the agricultural sector in LIFE compared to the S2 scenario (EUR 1 billion less), since agricultural activity is lower. However, as the main part of the air pollution control costs are associated with sectors other than agriculture, the overall difference in control costs is relatively small.

Moreover, the reduction in mortality has been assessed economically using two methods: Value of Statistical Life (VSL) and Value of a Life Year (VOLY). In this impact assessment, the value of a statistical life is assumed to be EUR 4.36 million, and the value of a life year is assumed to be EUR 114 722⁽²¹⁹⁾. As shown in Table 19, in the S1, S2 and S3 scenarios, in 2040, the premature mortality costs are EUR 1 046 to 1 051 billion lower compared to 2015 (i.e., a 61% reduction) if the VSL method is used, and EUR 380 to 382 billion lower compared to 2015 (i.e., a 56% reduction) if the VOLY method is used⁽²²⁰⁾. In LIFE, the premature mortality costs are slightly lower because of the decrease in PM_{2.5} emissions: EUR 1 077 billion lower in 2040 compared to 2015 if

⁽²¹⁷⁾ The analysis considers the direct effects of PM_{2.5} (full exposure range) and ozone on human health, together with the indirect effects of NO_x as precursors of particulate matter and ozone. However, the direct effects of NO₂ are not considered to avoid the risk of double counting, since there is conflicting scientific evidence on the extent to which the health impacts of PM_{2.5} and NO₂ overlap.

⁽²¹⁸⁾ Like the Third Clean Air Outlook, this impact assessment assumes that on average one year of life is lost for each premature death caused by ozone exposure.

⁽²¹⁹⁾ In accordance with the premature mortality valuation methodology used in the Third Clean Air Outlook (COM(2022) 673). Note that in the Third Clean Air Outlook the value of a statistical life and the value of a life year are expressed in EUR 2015, whereas in this impact assessment these values are expressed in EUR 2023.

⁽²²⁰⁾ As indicated in the Third Clean Air Outlook (Annex to the Final Report, p. 122), premature mortality caused by ozone exposure is considered only in the VOLY method, but not in the VSL method.

the VSL method is used, and EUR 394 billion lower in 2040 relative to 2015 if the VOLY method is used.

Table 19: Air pollution emissions, impacts on public health and costs

		2015*	2040		Change 2015-2040	
			S1, S2 & S3	LIFE	S1, S2 & S3	LIFE
Primary emissions	Air pollutant emissions (kt)					
	SO ₂	2316	525 to 529	529	-1787 to -1791 (-77.1% to -77.3%)	-1787 (-77.1%)
	NO _x	7392	2114 to 2140	1913	-5252 to -5277 (-71.1% to -71.4%)	-5478 (-74.1%)
	PM _{2.5}	1380	521 to 524	517	-857 to -859 (-62.1% to -62.2%)	-863 (-62.5%)
	VOC	6362	4497 to 4503	4259	-1860 to -1865 (-29.2% to -29.3%)	-2103 (-33.1%)
	NH ₃	3690	3086 to 3091	2346	-599 to -604 (-16.2% to -16.4%)	-1345 (-36.4%)
Public health	Premature mortality caused by PM_{2.5} exposure					
	Expressed in 1000 cases/year	395	154 to 155	148	-240 to -241 (-60.7% to -61.0%)	-247 (-62.5%)
	Expressed in million life years lost/year	5.91	2.61 to 2.63	2.50	-3.28 to -3.30 (-55.6% to -55.8%)	-3.40 (-57.6%)
	Premature mortality caused by ozone exposure					
	Expressed in 1000 cases/year	71	42	40	-28 (-40.1% to -41.3%)	-30 (-42.8%)
	Expressed in million life years lost/year	0.07	0.04	0.04	-0.03 (-40.1% to -41.3%)	-0.03 (-42.8%)
Costs	Economic costs (EUR 2023 billion/year)					
	Air pollution control**	83	56 to 58	56	-25 to -27 (-30.3% to -32.6%)	-27 (-32.4%)
	Premature mortality (VSL)***	1724	673 to 677	646	-1046 to -1051 (-60.7% to -61.0%)	-1077 (-62.5%)
	Premature mortality (VOLY)****	686	304 to 306	292	-380 to -382 (-55.6% to -55.8%)	-394 (-57.4%)

*Note: *Historical values for 2015 are slightly different than the ones reported in the Third Clean Air Outlook because of a different emission scope as well as recent updates in the emission factors assumed by the GAINS model. **Air pollution control costs are the costs associated with the measures/technologies employed in the control strategies of each scenario. ***In accordance with the valuation methodology used in the Third Clean Air Outlook, the value of a statistical life is assumed to be EUR 4.36 million (in EUR 2023), and the premature mortality costs estimated using the VSL method do not consider premature deaths caused by ozone exposure. ****In accordance with the valuation methodology used in the Third Clean Air Outlook, the value of a life year is assumed to be EUR 114 722 (in EUR 2023), and the premature mortality costs estimated using the VOLY method consider premature deaths caused by ozone exposure.*

Source: GAINS.

Note that not all air pollution costs have been included in the quantitative analysis presented in this section and shown in Table 19. Besides reducing premature mortality, improving air quality also reduces morbidity (impact of diseases) caused by air pollution (e.g., asthma). Consequently, improved air quality can reduce healthcare costs (due to avoided hospital admissions, lower need for medication, etc.), as well as trigger economic growth (by reducing employee absenteeism and increasing work productivity). Furthermore, improved air quality increases crop yields and reduces damage to materials and sensitive ecosystems. These co-benefits have not been quantified in this impact

assessment. However, regarding the last point, Table 20 shows the total ecosystem area in the EU where acidification and eutrophication exceed critical loads harmful to these ecosystems. The total area where acidification exceeds critical loads decreases by around 126 000 km² between 2015 and 2040 in the S1, S2 and S3 scenarios (which means an 80% reduction). The largest part of this reduction involves forest areas. Note that acidification is caused by atmospheric deposition of SO₂, NO_x and NH₃. In addition, the total ecosystem area where eutrophication exceeds critical loads decreases by 272 000 to 274 000 km² between 2015 and 2040 in these scenarios (23.5% reduction). The reduction in eutrophication effects is lower than the reduction in acidification effects (in relative terms) because the primary source of eutrophication is NH₃ leakage from agricultural activities, and emissions of this air pollutant do not decrease as much as SO₂ and NO_x emissions, which are an important cause of acidification. In LIFE, the ecosystem area in the EU affected by severe acidification and/or eutrophication decreases more than in the other scenarios because of the lower NO_x and NH₃ emissions from agricultural activities: the total area where acidification and eutrophication exceed critical loads decreases by 88% (around 7 percentage points more than in the other scenarios) and 36% (around 13 pp more than in the other scenarios), respectively, between 2015 and 2040.

Table 20: Area affected by acidification and eutrophication per scenario

	2015	2040		Change 2015-2040	
		S1, S2 & S3	LIFE	S1, S2 & S3	LIFE
Acidification (1000 km ²)	157	30.6 to 30.7	19.3	-126 (-80.4%)	-137 (-87.7%)
Eutrophication (1000 km ²)	1164	890 to 892	742	-272 to -274 (-23.4% to -23.5%)	-422 (-36.3%)

Note: The table shows the affected ecosystem area within the EU (expressed in 1000 km²) where acidification or eutrophication exceed critical loads.

Source: GAINS.

1.9.2. Biodiversity and ecosystems

Climate change is expected to have significant influences on biodiversity including species-level reductions in range size and abundance⁽²²¹⁾ as it is one of the five main drivers of global biodiversity loss, with change of land and sea use, direct exploitation, pollution, and invasive alien species⁽²²²⁾. For example, fire-prone areas are expected to expand across Europe due to climate change threatening not only carbon sinks but also biodiversity through habitat loss and fragmentation⁽²²³⁾. At the same time, more biodiverse forests may deliver more ecosystem services necessary for climate mitigation and adaptation⁽²²⁴⁾. In other words, making forest ecosystems more biodiverse can help

⁽²²¹⁾ Warren, R., VanDerWal, J., Price, J. et al. Quantifying the benefit of early climate change mitigation in avoiding biodiversity loss. *Nature Clim Change* 3, 678–682 (2013)

⁽²²²⁾ IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Zenodo. Available at: <https://doi.org/10.5281/ZENODO.3831673>.

⁽²²³⁾ For more details on the complex interaction see IPCC AR6 WGII Chapter 13

to increase their resilience against forest fires. Forest management practices like monoculture plantations of fast-growing trees (eucalyptus, pines) are more prone to fires ⁽²²⁵⁾ than biodiverse forests such as primary or old-growth forests ⁽²²⁶⁾. However, the relationship goes both ways: an improved biodiversity and functioning ecosystems also positively impact both climate mitigation and adaptation ⁽²²⁷⁾.

On a general level, limiting the magnitude of climate change via GHG mitigation is necessary to preserve biodiversity and prevent further loss. More specifically, stringent GHG mitigation that includes nature-based mitigation efforts can deliver a net benefit to global biodiversity even if it comes at the cost of regional biodiversity loss in Europe. But, in view of these potential losses, policies in EU should be carefully designed to conserve local biodiversity and to minimize the conversion of natural habitats ⁽²²⁸⁾. It is therefore important to focus on the many nature-based removals for carbon removals, which entail positive side-effects for biodiversity as they can provide new habitats and ecosystems and to consider biodiversity impacts from nature-based removals that can alter the habitat available for wildlife.

Modelling results showed that across all scenarios, overall species and habitats co-benefit from nature-based removals, which proved to be the main driver of change while at the same time providing additional carbon removals. Additional nature-based removals, applied in S2 and S3, delivered clear benefits for the suitable habitat of species and therefore biodiversity. The main factors for the improvement are afforestation, an increase in deadwood in forests and intensification coupled with longer rotation time of managed forests, and additional rewetting of peatlands. The impact of a second driver for biodiversity, the increased biomass demand from lignocellulosic crops and forestry, had a minor impact on biodiversity, resulting in statistically non-significant differences between the scenarios.

On average the suitable habitat for European species increases by about 3% (S3) to 4% (S2) in 2040 compared to 2020. For S1 the average suitable habitat declined slightly by around 1% in 2040 compared to 2020 ⁽²²⁹⁾. The application of a carbon value to cover mitigation costs in the land sector of up to 50 €/tCO₂-eq in S2 and S3 results in small but positive biodiversity trends although it is worth noting the large variations around the

⁽²²⁴⁾ Pukkala, T. 2016. Which type of forest management provides most ecosystem services? *Forest Ecosystems* 3:9; <https://forestecosyst.springeropen.com/track/pdf/10.1186/s40663-016-0068-5>

⁽²²⁵⁾ Barquín, J., L. Concostrina-Zubiri, I. Pérez-Silos, G. Hernández-Romero, A. Vélez-Martín, and J. M. Álvarez-Martínez. "Monoculture plantations fuel fires amid heat waves." *Science* 377, no. 6614 (2022): 1498-1498.

⁽²²⁶⁾ Barredo, J.I., Mansuy, N. and Mubareka, S.B., Primary and old-growth forests are more resilient to natural disturbances – Perspective on wildfires, European Commission, 2023, JRC133970.

⁽²²⁷⁾ Pörtner, H.-O. et al. (2021) Scientific outcome of the IPBES-IPCC co-sponsored workshop on biodiversity and climate change. Zenodo. Available at: <https://doi.org/10.5281/ZENODO.5031995>

⁽²²⁸⁾ Ohashi, H., Hasegawa, T., Hirata, A. et al. Biodiversity can benefit from climate stabilization despite adverse side effects of land-based mitigation. *Nat Commun* 10, 5240 (2019)

⁽²²⁹⁾ Biodiversity impacts were calculated with GLOBIOM modelling framework. The biodiversity indicator provides the average suitable habitat change since 2020, by assessing the suitability of a habitat for each species. The indicator is based on a total set of 1033 species living across five land categories.

mean trend. In 2050, the average change in suitable habitat stays stable in S2 and S3 and returns to 2020 levels for S1.

In sum, the effects on biodiversity related to additional nature-based removals are positive but small. However, the results also confirm the need to align climate and environmental action in a co-beneficial way to obtain synergistic effects. Overall, on biodiversity and ecosystems, the effects on suitable habitats in Europe in S1 to S3 need to be complemented with the effects on acidification and eutrophication as shown in Table 20. The scenarios show a decline of affected area by 80% for acidification and 23.5% for eutrophication in 2040, which provides a significant positive impact for ecosystems.

LIFE evolves around a dietary change from consumers towards more healthy and sustainable food consumption, the implementation of the Farm to Fork Strategy, and food waste reduction (see Annex 6). Derived from the Farm to Fork Strategy and the Biodiversity Strategy for 2030, the scenario produced some relevant outputs ⁽²³⁰⁾ which have a beneficial impact on biodiversity as shown in Table 21.

Table 21: Overview of Farm to Fork objectives indicators in LIFE in 2040

	total	Change to 2020	Change to S1 - S3 in 2040
Nutrient surplus total [in 1000t]	5,504.794	-49%	-48%
Mineral fertilizer use	5,904	-41%	-44%
Chemical pesticide Use	7307	-39%	-50%
High-diversity landscape features (Set aside and fallow land) - Share of EU's agricultural land	14%		
Share of EU's agricultural land for organic agriculture	25%		

Source: CAPRI

Key factors in agriculture, such as the nutrient surplus, the amount of fertilizer and pesticides applied, and the intensity of farming practices impact ecosystems and biodiversity across different regions. Consequently, since LIFE has substantial impacts on agricultural land and farming practices (Table 21), the changes also affect ecosystems and biodiversity on these lands positively. Next to changes of farming practices, LIFE shows a decline in livestock from cattle and other animals, which also leads to a reduction in livestock density (Table 22). This reduction of livestock is due to the declining demand for meat and dairy products, the implementation of the objective to reduce nutrient losses by 50%, and to a limited extent to a reduction of food waste.

⁽²³⁰⁾ The exact steering towards the different objectives from the Farm to Fork and Biodiversity strategy, the dietary changes, as well as the targets for the food waste reduction in the modelling is technically difficult, which results in the overfullfillment of some targets and missing the threshold for others in the LIFE scenario.

Table 22: Overview of LIFE outputs related to biodiversity in 2040

	total	per ha	Change to S1 - S3
Beef meat activities [in 1000 LSU]	7,877		-49%
All Dairy [in 1000 LSU]	29,151		-18%
Pigs, poultry, sheep [in 1000 LSU]	42,875		-24%
All cattle activities [LSU/ha]		0.23	-29%
Other (non-cattle) animals [LSU/ha]		0.26	-26%

Note: LSU indicates livestock units, either as 'total' in 1000t or 'per ha' kg/ha.

Source: CAPRI

To assess biodiversity impacts on LIFE an indicator for biodiversity was necessary that can account for impacts on agricultural land. The biodiversity impacts of the LIFE setting uses the “BFP index” (Biodiversity-friendly farming practices), which assesses biodiversity friendly practices and reflects the likelihood to find agricultural areas with a high value for biodiversity and ecosystems in a region on NUTS 2 level ⁽²³¹⁾. The total index is an area weighted average of the partial indices for arable crops, permanent crops, grassland and set aside / fallow land. In LIFE, this index increases by 14% compared to the three scenarios, reaching on EU level up to about 71%. The estimated improvement in biodiversity is mostly driven by three factors. Biodiversity on areas with arable crops improves by about 20% due to the nutrient surplus reduction on the fields ⁽²³²⁾, supplemented with reduced pesticide use. Areas with permanent crops benefit (38%), mainly due to the reduction of pesticides, while lower nutrient surpluses are a secondary driver here. Also managed grassland improves to a limited extent (3%), because the stocking intensity of livestock units decreases, resulting in a substantial increase of extensive use of grassland (see Table 23), while the pesticide reduction is less influential on grassland.

Table 23: Agricultural area change in 2040 by scenarios.

Area use [in 1000 ha]	S1 - S3	LIFE	Change
Utilized agricultural area	160,108	161,763	1%
Fodder activities	65,922	54,185	-18%
- of which: Gras and grazings intensive	23,872	5,174	-78%
- of which: Gras and grazings extensive	23,867	36,595	53%
Total set aside or rewetted land*	7,084	22,360	216%

**This includes fallow land set aside and rewetted cropland or grassland. The additional area is partly mobilized by displacing agricultural crops and partly by converting other “unproductive” land.*

Source: CAPRI

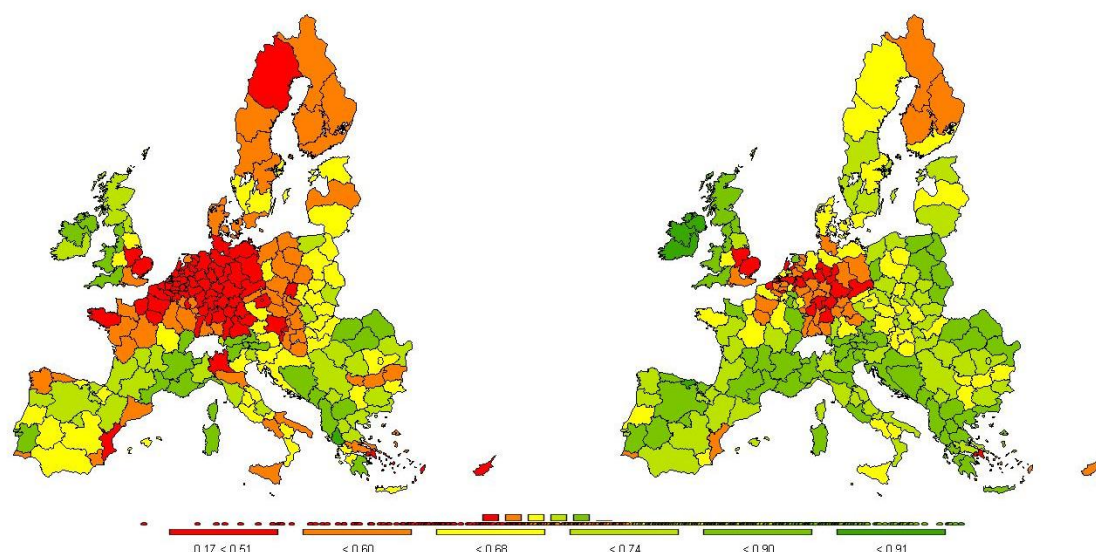
The third key driver for improved biodiversity friendliness would be the expansion of areas for landscape elements such as hedges, buffer strips etc. The share of this set aside

⁽²³¹⁾ Using the ‘Biodiversity Friendly Practices’ (BFP), a biodiversity indicator capturing the likelihood to find High Nature Value farmland in a region. Partial indices for different land use categories are weighted according to their proportion of the total utilized agricultural area.

⁽²³²⁾ The nutrient reduction through the farm to fork strategy aims to reduce nutrient losses by 50%. The areas for arable crops make up almost 60% of the total farmland, therefore this partial index plays a significant role.

or fallow land would more than double to about 14.5 Mha in total. Figure 99 Shows the regional biodiversity impacts through LIFE, indicating that the improvements are evenly distributed across the EU, shifting particularly southern and eastern European regions into a much more favourable state for biodiversity.

Figure 99: Biodiversity impacts from LIFE by region.



Note: Results on the total BFP index in LIFE (right) against the default setting of the scenarios S1, S2 and S3 (left) in 2040 on NUTS 2 level. The Biodiversity Friendly Practices (BFP) indicator depicts the likelihood to find High Nature Value farmland in a certain NUTS 2 region. The indicator ranges from red (17%-51%) to dark green (<100%).

Source: CAPRI

1.9.3. Food security, animal welfare and health

The food system itself is not only contributing to climate change but is also highly exposed to climate change itself, which jeopardises food security⁽²³³⁾. Foodborne diseases and an increase in extreme weather events are expected in the future under altered climatic conditions, such as draughts and heavy rainfall, impacting the food system and food safety. For Europe a combination of heats and droughts resulting from a 2°C to 3°C global warming level will lead to substantive agricultural production losses for most European areas which will not be offset by possible gains; an effect that will also affect the economic output from agriculture in the EU⁽²³⁴⁾.

Food security and sustainable and healthy diets are strongly interlinked⁽²³⁵⁾. A sustainable food system makes optimal use of natural resources. Dietary patterns with high meat consumption require more energy, water and land resources. One hectare of land may produce enough lamb or beef to feed one to two people, while the same hectare

⁽²³³⁾ IPCC AR6 SPM

⁽²³⁴⁾ IPCC AR6 WG II, 13

⁽²³⁵⁾ Capone, R., et al., 'Food System Sustainability and Food Security: Connecting the Dots.', *Journal of Food Security*, 2, 1, 13-22, 2014.

can produce rice or potatoes for 19 to 22 people per annum ⁽²³⁶⁾. Thus, because livestock farming demands extensive land use, a decrease of animal-based products in human diets would reduce demand for feed and make more land available for growing human food. Today, more than 50% of EU's use of cereals goes into animal feed ⁽²³⁷⁾. Reducing the demand of cereals for animal feed would contribute to strengthen strategic autonomy in the food sector and thereby enhance food security.

However, a closer look at the net production of agricultural products (see Table 24:) shows that LIFE with its shift towards healthier diets and a reduction of food waste not only decreases demand for food but also decreases livestock herds and agricultural area related to animal products (see Table 22; Table 23), but also net production of animal based and many other agricultural products. In part this is due to market adjustments due to declining demand but partly this is also reflecting the desired move to less intensive production systems with higher shares of organic agriculture, lower pesticide use, and nutrient surpluses and some additional agricultural area taken out of production in view of biodiversity targets. On a global perspective it is important to mention that only the combination of supply side measures through the Farm to Fork objectives, together with demand side measures (i.e., dietary shift and food waste reduction) result in a mutual decline of production and demand, which does not jeopardise global food security.

Table 24: Net production of agricultural outputs in 2040 by scenarios

Net production [in 1000 t]	S1, S2, S3	LIFE	Change
Feed energy input	704,146,368	563,934,976	-20%
Cereals	267,900	214,751	-20%
Vegetables and Permanent crops	126,013	122,510	-3%
Wheat	118,239	98,450	-17%
Meat	45,368	33,841	-25%
Other Animal products	168,985	151,862	-10%
Raw milk	161,303	145,473	-10%
Dairy products	64,444	57,295	-11%

Source: CAPRI

Compared to scenarios S1, S2 and S3, LIFE leads to a shift from intensive grazing to extensive grazing (Table 22) and to an overall reduction in livestock density per ha for cattle and dairy cows but also for pigs and poultry ⁽²³⁸⁾. This may also positively impact animal welfare and increase resilience against transboundary animal diseases in animal related food production ⁽²³⁹⁾.

⁽²³⁶⁾ Institution of Mechanical Engineers-UK, 'Global food, waste not, want not'. London. 2013. Available online at: [global-food---waste-not-want-not.pdf \(imeche.org\)](https://www.imeche.org/global-food-waste-not-want-not.pdf)

⁽²³⁷⁾ Based on the years 2020 to 2022; European Commission, DG Agriculture and Rural Development, 'EU agricultural outlook for markets, income and environment, 2022-2032', Brussels, 2022.

⁽²³⁸⁾ In LIFE the overall animal density [livestock units / ha] decrease by -27%; for all cattle activities by -29% and other animals -26%. See Table 22

⁽²³⁹⁾ Sundström, J.F., Albiñ, A., Boqvist, S. et al. ,Future threats to agricultural food production posed by environmental degradation, climate change, and animal and plant diseases – a risk analysis in three economic and climate settings', *Food Security*, 6, 201–215, 2014.

LIFE incorporates significant health benefits for its citizens. For Europe, research finds a greater consumption of red meat, eggs and dairy products than recommended consumption levels of healthy reference diets ⁽²⁴⁰⁾ ⁽²⁴¹⁾. Studies indicate that reducing meat consumption, while maintaining a broad and varied diet is beneficial for human health as it reduces the risk of cardiovascular diseases ⁽²⁴²⁾ ⁽²⁴³⁾, cancer ⁽²⁴⁴⁾, diabetes and obesity ⁽²⁴⁵⁾. This has also significant economic benefits on health costs. For example, adopting an energy-balanced, low-meat dietary pattern is associated with large reductions in premature mortality, both for a flexitarian (-19%) and a vegan (-22%) diet ⁽²⁴⁶⁾.

The reduction of meat consumption (i.e., shift to more plant-based diets) and fertiliser application in LIFE also generates significant co-benefits for air quality, since it reduces methane emissions, a short-lived climate forcer but also a precursor of ozone ⁽²⁴⁷⁾, and ammonia emissions. Hence, an increase in plant-based diets in the EU is improving human health both directly through more healthy diets and indirectly through cleaner air, which creates economic benefits from improved human health that would compensate some part of the economic losses in agricultural sector ⁽²⁴⁸⁾.

⁽²⁴⁰⁾ Willet et al., 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems', Lancet, 2019.

⁽²⁴¹⁾ WHO/FAO (2003) Diet, nutrition and the prevention of chronic diseases: report of a joint WHO/FAO expert consultation. World Health Organization, Geneva.

⁽²⁴²⁾ Koch et al. (2023) Vegetarian or vegan diets and blood lipids: a meta-analysis of randomized trials. European Heart Journal

⁽²⁴³⁾ Westhoek, Henk, Jan Peter Lesschen, Trudy Rood, Susanne Wagner, Alessandra De Marco, Donal Murphy-Bokern, Adrian Leip, Hans van Grinsven, Mark A. Sutton, and Oene Oenema. 'Food choices, health and environment: Effects of cutting Europe's meat and dairy intake.' *Global Environmental Change*, 26, 196-205, 2014.

⁽²⁴⁴⁾ Chan, Doris SM, Rosa Lau, Dagfinn Aune, Rui Vieira, Darren C. Greenwood, Ellen Kampman, and Teresa Norat. "Red and processed meat and colorectal cancer incidence: meta-analysis of prospective studies." *PloS one* 6, no. 6 (2011): e20456.

⁽²⁴⁵⁾ Tukker et al. (2011) Environmental impacts of changes to healthier diets in Europe. *Ecological Economics*

⁽²⁴⁶⁾ Springmann et al. 'Health and nutritional aspects of sustainable diet strategies and their association with environmental impacts: a global modelling analysis with country-level detail', *Lancet Planet Health*, 2018.

⁽²⁴⁷⁾ COM(2022) 673 final

⁽²⁴⁸⁾ A shift to flexitarian diets could reduce ammonia emissions by 33% in the EU. Through avoided premature mortality rates, economic losses in the agricultural sector from dietary shifts could be mitigated by 39% in the EU in such a scenario. See Himics et al. 'Co-benefits of a flexitarian diet for air quality and human health in Europe', 2022

1.9.4. Raw materials

The demand for raw material is expected to grow considerably by 2050 ⁽²⁴⁹⁾, and this growth in raw materials use is likely to increase the pressure on the planet resources.

The material growth is expected to be driven only partially by the climate transition, with the rest is distributed among the electronic sector, the automotive and building sector and production of alloys for different applications. The share of the raw material increase attributed to climate actions depends strongly on the material. BNEF calculates that the share of manganese, and silver needed for clean energy use are responsible for less than 25% of the total demand increase by 2050 ⁽²⁵⁰⁾, while the IEA indicates that the share of nickel, cobalt and copper needed by the energy transition will represent per each of these materials less than 40% of total demand in 2040 ⁽²⁵¹⁾. The IEA estimates that clean energy technologies and infrastructure account for 2-3% of cement and steel demand today, and this value will increase to only about 2% (for cement) and 7% (for steel) in 2050 ⁽²⁵²⁾.

Furthermore, climate policy, together with increase material efficiency, circular economy actions and possible sufficiency measures can create synergies to reduce the need of primary raw materials and pressure on planet resources to produce them ⁽²⁵³⁾.

The IEA estimates that most of the growth in the total global material demand associated to clean technologies and infrastructure in the NZE scenario will occur between 2021 and 2030, while after 2030, growth in demand is much more modest, despite the continuously increasing of the in-use stocks of these materials ⁽²⁵⁴⁾. This is attributed to several factors often associated to direct climate policy or related measures. Technology innovation accelerates quickly with economy of scale ⁽²⁵⁵⁾, leading for example to more energy-dense batteries (requiring lower material needs) in a world with higher share of electric vehicles, or faster development of innovative catalysts reducing the need for platinum group metals in electrolyzers in a decarbonised energy system requiring hydrogen. Material substitution with low-carbon technologies can also play a role in limiting the increase in material demand the pressure on resources. In efforts to reduce demand for nickel, Tesla is producing Evs with a lithium iron phosphate (LFP) battery that contains no nickel and have suggested that a large share of the future EV battery market will contain iron-based cells rather than nickel based ⁽²⁵⁶⁾. Likewise, efforts to eliminate

⁽²⁴⁹⁾ World Bank (2020), Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.

⁽²⁵⁰⁾ BNEF (2023b), Transition Metals Outlook 2023.

⁽²⁵¹⁾ As per the STEPS scenario of the IEA, described in The Role of Critical Minerals in Clean Energy Transitions, Revised Version in May 2022.

⁽²⁵²⁾ IEA (2023) Energy Technology Perspectives.

⁽²⁵³⁾ Desing et al., Resource pressure – A circular design method, Resources, Conservation and Recycling, Volume 164, 2021, 105179, ISSN 0921-3449.

⁽²⁵⁴⁾ IEA (2023) Energy Technology Perspectives.

⁽²⁵⁵⁾ See for instance Moore's law and Swanson' law

⁽²⁵⁶⁾ [Tesla to use iron-based batteries in Semi electric trucks and affordable electric car | Reuters](#)

lithium from batteries have seen battery manufacture CATL announce a sodium-ion EV battery ⁽²⁵⁷⁾. Material efficiency measure associated to less energy-intensive production methods reducing resource intensity of products, while providing the same service. Some metals have high potential for recycling in the future. Cobalt and copper are supplied almost completely by primary supply today but has the potential to have over 80% for cobalt and approximately 60% for copper being supplied from recycled metals in 2050 ⁽²⁵⁸⁾. Circularity actions, and more in general sufficiency-driven behavioural change can decrease primary demand of critical materials in favour of products with longer life, repair or products manufactured from secondary raw materials that stay longer in the market.

2. SOCIO-ECONOMIC IMPACTS

The options under consideration for the 2040 target in this impact assessment take the legally defined ambition for 2030 and 2050 as a given. The impact assessment for the 2030 Climate Target Plan ⁽²⁵⁹⁾ made a detailed analysis of the socio-economic impacts of the achievement of the net GHG reduction 55% target for 2030. It assessed these impacts in relation to a baseline defined by the Reference 2020 scenario, which reflects the first national energy and climate plans as submitted by Member States and the EU legislation prior to the adoption of the Fit-for-55 proposals. The impact assessment covered a wide range of issues, from the impacts on GDP and employment to sectoral transformations, competitiveness and distributional effects. Issues relating to impacts on households or competitiveness, among others, were further assessed in the impact assessments that accompanied the legislative proposals of the Fit-for-55 package.

Overall, the impact assessment for the 2030 Climate Target Plan concluded that the 55% objective was expected to have only limited impacts on broad macro-economic aggregates, including GDP and total employment. It nevertheless stressed that the impacts of the transition are projected to be significant in terms of sectoral output and employment, investment and relative prices. Transformations across sectors and within sectors, including as they related to skills needs, and in consumption patterns will be major and would need to be managed carefully in order to ensure a fair and orderly transition process that preserves the competitiveness of the EU economy and leaves no one behind. Similar conclusions were derived from the in-depth analysis in support of the EU long-term strategy, which underpinned the endorsement of the climate neutrality objective by the European Council in December 2019 and its subsequent adoption in the EU Climate law.

This impact assessment therefore does not seek to revisit the expected impacts of the 2030 targets or assess the economic pathways to climate neutrality in relation to a baseline that would significantly deviate from that objective. Instead, the macro-economic models use S2 as the point of comparison for the other scenarios. To some extent, deviations from the macro-economic benchmark are therefore less relevant for the

⁽²⁵⁷⁾<https://www.bloomberg.com/news/articles/2021-07-29/catl-debuts-sodium-ion-batteries-amid-raw-material-cost-spike#xj4y7vzkg>

⁽²⁵⁸⁾ BNEF (2023). Transition material outlook.

⁽²⁵⁹⁾ [SWD\(2020\) 176 final](#).

analysis than under previous impact assessments. An increased focus is therefore placed in the following sections on the transformation requirements over time across pathways to climate neutrality, with specific attention placed on investment needs, competitiveness, and social and regional impacts. The co-benefits of the transition are also assessed.

The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

2.1. Macro-economic impacts ⁽²⁶⁰⁾

2.1.1. GDP and employment

As indicated in previous impact assessments, the transition to climate neutrality is unlikely to be a major driver of GDP growth and employment levels in and of its own. The transition will nevertheless imply transformations in production and consumption patterns. These are assessed in more details in the sections below.

At aggregate level, the models consistently show that a higher level of mitigation in 2040 is associated with a somewhat larger negative impact on GDP, at least on a transitory fashion. With the highest level of climate ambition (S3) in 2040, GDP is projected to be at best unchanged and at worst 0.8% lower than under S2 (Table 25). A lower level of ambition by 2040 (S1) translates at best into a slightly higher level (+0.6%) of GDP. By 2050, however, GDP is projected to return broadly to the same level under all three scenarios. As projected by the JRC-GEM-E3, the impact of the transition on GDP is also somewhat more negative under a “global action” scenario (where the rest of the world implements policies aligned with the 1.5°C objective under the Paris agreement) than under a “fragmented action” scenario (where the rest of the world implements NDCs). This is driven by the fact that higher climate ambition in the rest of the world is associated with higher negative impacts on global GDP, which reduces external demand for EU producers.

The negative impact is therefore mainly a transition effect, with no lasting impact, and it remains small across models and scenarios. As total employment is mostly driven by trends in aggregate output, the impact of a higher level of ambition is also only marginally negative in 2040, before converging across scenarios by 2050.

⁽²⁶⁰⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudge the future design of the post-2030 policy framework.

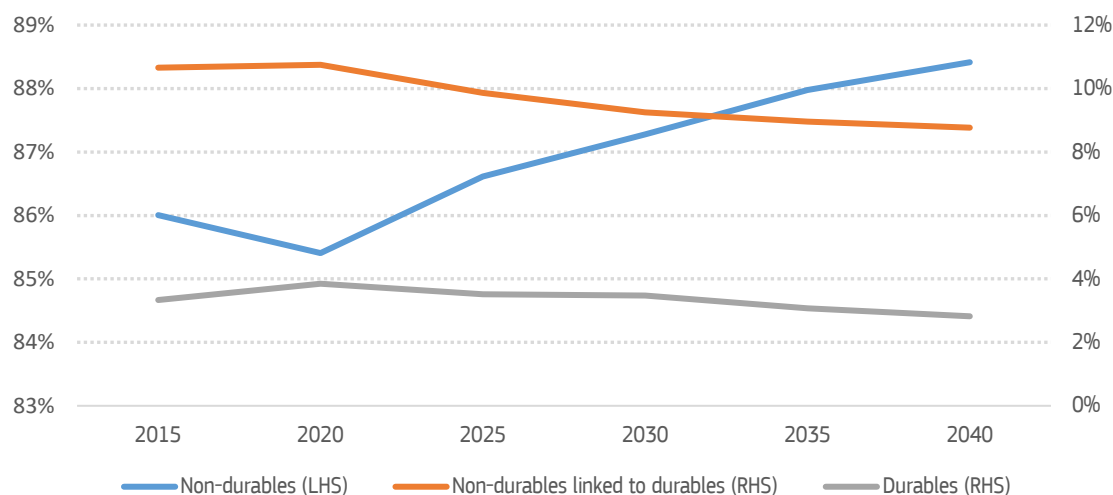
Table 25: Macro-economic impacts (% change compared to S2)

	S1 fragmented		S1 global		S3 fragmented		S3 global	
	2040	2050	2040	2050	2040	2050	2040	2050
JRC-GEM-E3								
GDP	0.5%	0.1%	0.6%	0.2%	-0.2%	-0.1%	-0.2%	-0.1%
Private consumption	0.7%	0.1%	1.8%	2.1%	-0.5%	-0.1%	-0.5%	-0.1%
Investment	-0.1%	0.3%	-0.5%	-0.5%	1.1%	-0.1%	1.1%	-0.1%
Exports	1.2%	0.1%	-0.1%	-2.6%	-0.8%	-0.1%	-0.7%	0.0%
Imports	0.3%	0.1%	1.6%	1.5%	0.1%	-0.1%	0.1%	0.1%
Employment	0.3%	0.1%	0.3%	0.1%	-0.1%	0.0%	-0.1%	-0.1%
E3ME								
GDP	0.00%	0.04%	0.01%	0.04%	0.04%	-0.02%	0.00%	-0.04%
Private consumption	0.3%	0.0%	0.4%	0.0%	-0.2%	0.0%	-0.3%	0.0%
Investment	-0.9%	0.1%	-0.9%	0.1%	0.7%	-0.2%	0.7%	-0.2%
Exports	-0.2%	0.0%	-0.2%	0.0%	0.1%	0.0%	0.1%	0.0%
Imports	-0.03%	0.02%	-0.03%	0.02%	0.02%	0.00%	0.01%	0.00%
Employment	0.03%	0.00%	0.03%	0.01%	-0.01%	0.00%	-0.02%	-0.01%
E-QUEST								
GDP	0.4%	-0.02%	n.a.	n.a.	-0.8%	0.01%	n.a.	n.a.
Private consumption	0.3%	0.03%	n.a.	n.a.	-0.5%	-0.01%	n.a.	n.a.
Investment	0.3%	0.03%	n.a.	n.a.	-0.5%	-0.03%	n.a.	n.a.
Employment	0.02%	0.00%	n.a.	n.a.	-0.03%	0.00%	n.a.	n.a.

Source: JRC-GEM-E3, E3ME and E-QUEST.

The macro-economic models also indicate that a higher level of ambition for GHG mitigation in 2040 is associated with a more significant shift in the composition of GDP from consumption towards investment, at least on a transitory basis. The negative impact on private consumption is nevertheless small across models and levels of ambition. Further, the JRC-GEM-E3 model projects that while private consumption is likely to be negatively impacted, the composition of consumption should also evolve, with a gradual decrease in the share of consumption of non-durables linked to the use of durable goods (i.e. mainly energy consumption) and a corresponding increase in the share of other non-durables (Figure 100). This shift in composition would be positive from a welfare perspective, as energy-related services would not be negatively affected by lower consumption of energy itself (e.g., a better insulated house provides the same – or likely better – level of comfort than a poorly insulated one, with lower energy consumption).

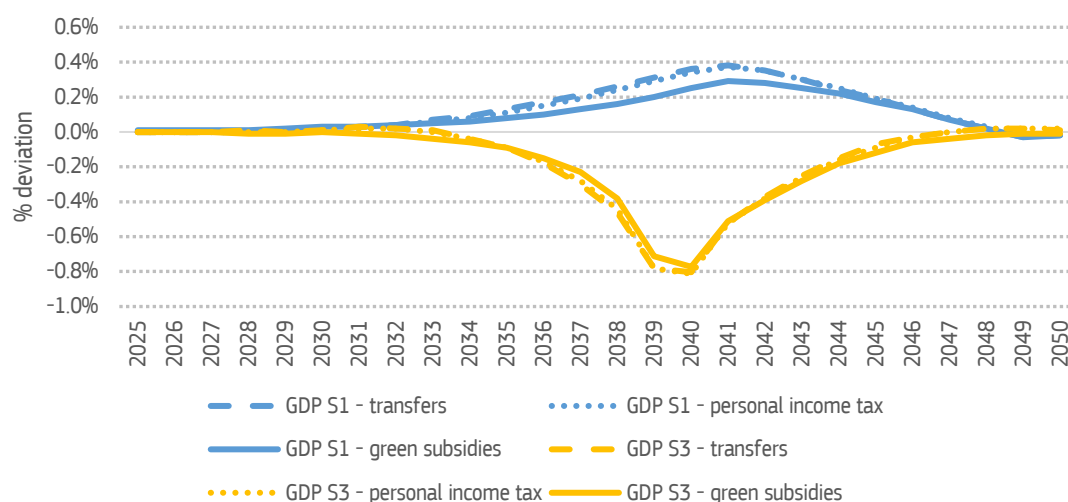
Figure 100: Composition of private consumption (% of total, S3)



Source: JRC-GEM-E3.

DG ECFIN's E-QUEST model shows that S3 generates some cumulative impacts in terms of output loss over the whole transition period (2025 to 2050) compared to S2, even if output levels converge by 2050 (Figure 101). In contrast, S1 generates very modest cumulative output gains compared to S2, with the GDP level converging across scenarios by 2050. Further, it indicates that using the economy-wide carbon revenues to subsidise green investment is more efficient in terms of output than lump sum transfers to households or the recycling of revenues to reduce personal income taxation on low-skilled workers. This is strictly an efficiency gains in terms of output, and it abstracts from distributional and equity considerations, which are discussed below.

Figure 101: Real GDP, deviation from S2



Source: E-QUEST.

2.1.2. The impact of frictions in the economic transition

Macro-economic models typically assume that frictions in the reallocation of capital and labour across sectors are limited. Capital is reallocated sectorally over time mostly via new investment and the depreciation of existing assets. In turn, the labour force is assumed to be mobile and responsive to evolving demand across sectors of the economy. While frictional unemployment is modelled and labour matching functions can operate

more or less efficiently, workers are assumed to be in a position to take new jobs as they arise in any sector of the economy.

Such assumptions are simplifications used for modelling purposes, which are reasonable in particular when assessing impacts under a long-term perspective. However, the faster the transition, the more the simplifications diverge from the reality of the sectoral transformations. Model-based simulations were therefore used to provide an assessment of frictions in capital markets and investment decisions, and frictions in the reallocation of the labour force across sectors.

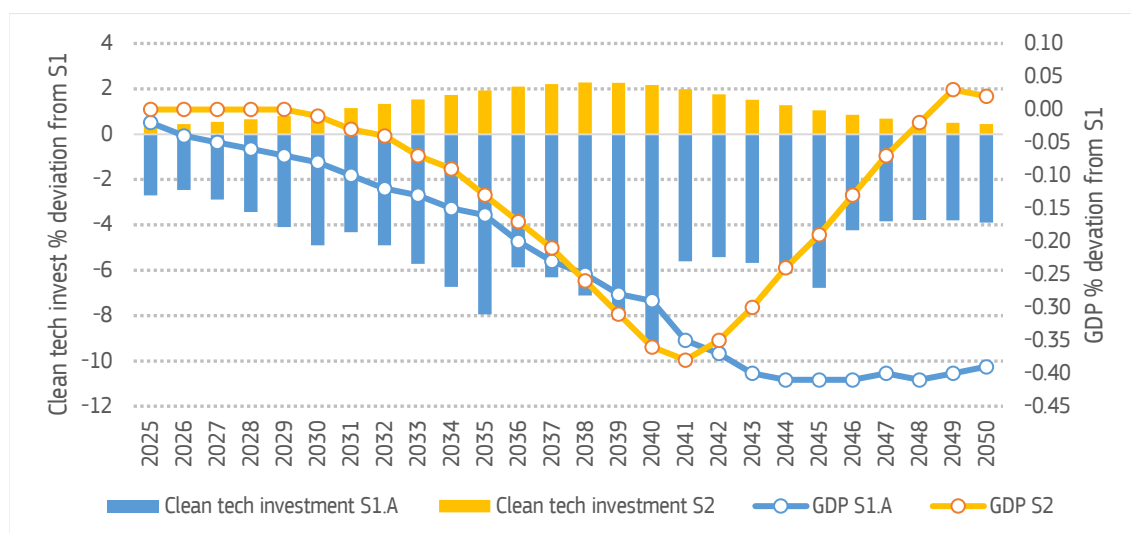
DG ECFIN's E-QUEST model is a dynamic stochastic general equilibrium model with fully forward-looking agents, which enables the assessment of the impacts of fully credible, partly credible or non-anticipated policies. While the main scenarios modelled in this impact assessment assume that the pathways under consideration are fully anticipated by economic agents (i.e., fully credible), a variant was used to assess the impact of potentially "erroneous" investment decisions on the economy, modelled via partial anticipations (or partly credible pathways). In essence, this aims to capture investment decisions that are not aligned at all times with the targeted GHG pathway. In this modelling variant, economic agents fail to recognise that additional policies (introduced as carbon values in the model) will be put in place to achieve the climate neutrality pathway and they base their expectations on the continuation of existing policies. Expectations are sequentially updated every five years to correct for erroneous predictions and align with the actual pathway, which is consistent with climate neutrality.

As economic agents do not act fully in accordance with the climate neutrality pathway, they miss the opportunity to take early action by increasing their investment in decarbonised technologies and the value of the capital invested in fossil fuel intensive technologies or sectors is negatively affected, i.e., the economy suffers from stranded assets. The other types of investment represented in the model are not affected⁽²⁶¹⁾, as they are not contingent upon the level of mitigation ambition. These investments represent the majority of aggregate investment in the model.

Such a sequential, 5-yearly adjustment of expectations leads to negative outcomes on all key macro-economic variables compared to the scenarios where expectations, and hence the investment decisions of economic agents, are aligned with the climate neutrality pathway. The sequential adjustment in investment on a 5-year basis leads to a type of "catching up" process in investment in decarbonised technologies. To illustrate the impact of this type of frictions, the sequential scenario was modelled based on the level of climate ambition of scenario 1, and impacts are measured in relation to S1 as a baseline. While all scenarios achieve the same level of ambition in 2050, the sequential scenario (S1.A) leads to a gradually larger loss of output over time, with GDP about 0.4 percentage point lower than under S1 in 2050. In contrast, the higher level of ambition under S2 entails only a transitional cost in terms of lower output compared to S1, with GDP marginally higher in 2050. Over the whole transition period, the sequential scenario therefore entails a significant cost in terms of lost output relative to the S2 (Figure 102).

⁽²⁶¹⁾ E-QUEST includes a representation of 3 types of investment: (1) electricity intensive (clean technologies); (2) fuel-intensive technologies; and (3) all other types of investments.

Figure 102: Impact of frictions in investment decisions



Source: E-QUEST.

A recent analysis by the European Central Bank ⁽²⁶²⁾ also shows that an accelerated transition would provide significant benefits for firms, households and the financial system compared with a late-push scenario, which achieves the same level of ambition by a given year than under earlier action but postpones climate-related investment. Although the ECB's analysis is set with a 2030 horizon and is based on scenarios that are not aligned with those considered in this impact assessment, the conclusions concur with those above in that delaying action (or misreading policy signals and making errors in expectations as in the modelling exercise above) is costly. The ECB analysis concludes that credit risk would increase during the transition under all scenarios, but that it would be particularly so in case of a "late-push" configuration that would require very high levels of investment under a shorted period. They conclude that while early action would lead to greater costs for households and firms in the short-term, it would lower financial risks in the medium term because of a decrease in energy-related expenses and that the earlier the transition happens, the smaller the financial risks and potential costs in terms of policy support. Finally, they indicate that their analysis does not find financial stability concerns of the euro area, even if the transition would increase banks' expected losses and provisioning needs.

Cambridge Econometrics's E3ME model was further used to assess the potential impact of increased investment costs (captured in modelling terms as a lower return on investment) due to decisions that are not fully aligned with the transition and GHG mitigation requirements. Assets in selected sectors (mining, manufacturing, electricity supply, land transport and real estate) are assumed to generate lower returns or to operate for a shorter lifetime than projected under the investment decision, which means that investors incur an additional cost to either scrap and replace assets earlier than planned, or to refurbish them to extend their lifetime. The assumed increase in costs range from 1% in the real estate sector to about 4% in manufacturing and 3% in electricity supply. Higher investment costs driven by misaligned investment decisions lead to an increase in

⁽²⁶²⁾ [Occasional Paper Series N°328](#). The Road to Paris: stress testing the transition towards a net-zero economy. The energy transition through the lens of the second ECB economy-wide stress test.

consumer prices over the transition period as well as a negative impact on private consumption (-0.7%), investment (-0.2%) and GDP (-0.5%) by 2040, compared to the baseline without misallocations in investment decisions. Higher production costs also negatively impact total exports (-0.5%) and aggregate employment (-0.1%).

Cambridge Econometrics' E3ME model was also used to assess the impact of frictions and costs in the reallocation of the labour force across sectors of the economy. Transformations within sectors and across sectors constitute one of the main challenges of the transition to climate neutrality. Regardless of the scale of impacts on aggregate output, sectors will need to transform to adjust to the adoption of new production technologies and/or the production of new or different types of goods and services. On top of the capital investment needs that this will entail, the transformation will have significant impacts on the labour market, whether in terms of absolute and relative demand within and between sectors, occupations and skills requirements. It will also impact the investment needs in terms of labour force training, reskilling or upskilling.

Two types of effects were therefore modelled to assess potential macro-economic impacts. First, the risks and impacts related to the reallocation of the labour force across occupations and sectors is modelled by assuming that the economy faces retraining/reskilling costs that would not occur otherwise. It is assumed that on average 10% of the workforce receives training specifically to adapt to the climate and energy transition every year (up to 2050). The training costs are assumed to amount to EUR 10 000 per worker in mining and extraction (i.e., to transition them to other sectors as such jobs gradually disappear), EUR 1 500 per worker in manufacturing and agriculture, and EUR 500 in other sectors, where the skills implications of the green transition are likely to be much less significant⁽²⁶³⁾. In addition, basic training at a cost of EUR 1 100 per annum for around 300 000 new workers in low carbon jobs is projected up to 2030⁽²⁶⁴⁾. It is further assumed that the costs are fully borne by the employers, which therefore translates into a small increase in labour costs.

Modelling results suggest that such training costs have negligible impacts at macro-economic levels. The larger training/re-skilling costs for workers in mining and extraction apply to a marginal segment of the labour force and even the skilling costs in manufacturing are relatively small in comparison to the total labour force and labour costs. While the model suggests a small increase in aggregate labour costs to employers, the negative impact on GDP or private consumption by 2040 amounts to less than 0.1 percentage point relative to the no-skilling costs baseline.

Higher assumptions regarding training/re-skilling costs amplify the impacts to some extent, though they remain limited. Using the same assumption as above on the training cost per worker in mining and extraction but doubling the percentage of the workforce receiving training to 20%, doubling the costs of training for workers in manufacturing (to EUR 3 000) and other sectors (to EUR 1 000), introducing a cost of training of EUR 5 000 per worker in construction and of EUR 10 000 per worker in energy intensive

⁽²⁶³⁾ These figures draw on [European Economy Discussion Paper 176, December 2022: The Possible Implications of the Green Transition for the EU Labour Market](#).

⁽²⁶⁴⁾ This assumptions builds on [SWD\(2023\) 68 final](#) and [Employment and Social Developments in Europe 2023 \(Box 2.4\)](#)

industries and increasing the number of new workers receiving training in low-carbon clean technology sectors to 568 000 generates a negative impact of about 0.25% and 0.35% of GDP in 2040 for GDP and private consumption, respectively. It is important to note, however, that these results do not simulate the potential impact of skills/qualified labour not being sufficiently available for the deployment of green technologies. The latter remains a critical factor in the transition process, and it is assumed here that investing in training ensures that skills are indeed available as needed.

Second, there is firm-level evidence that on-the-job training leads to productivity and wage gains ⁽²⁶⁵⁾. An economy-wide effort to train the work force in the context of the climate transition could therefore lead to productivity gains overall. The joint effect of such productivity gains and the small increase in labour costs due to training costs is assessed with the E3ME model by assuming that training positively impacts labour productivity of the affected labour force and that workers consequently benefit from a 1% increase in average wages from 2035, by when a full round of training is completed (assuming again that 10% of the labour force benefits from training each year). Higher wages feed into an increase of about 1.4% and 0.8% in private consumption and GDP, respectively, in 2040, with an associated small increase in consumer prices.

2.2. The investment agenda ⁽²⁶⁶⁾

2.2.1. Aggregate investment needs

The transition to climate neutrality requires that the EU's energy system be decarbonised rapidly and comprehensively. All policy options envisaged in this impact assessment imply an intensification in efforts to replace fossil fuels with renewable and carbon-free sources of energy, achieving significant energy savings and the deployment of innovative processes in industry. Existing capital assets (e.g., fossil-based power plants, heating and cooling systems or industrial processes) will be replaced with renewables, carbon-free or electricity-based assets, whose capital intensity may be larger than fossil-based assets. Therefore, the transformations of the energy system will require a general substitution of fossil fuels inputs with capital.

As the technologies to decarbonise the energy system are mostly identified, if in certain cases still in need of deployment at scale and at lower costs, the transition of the energy system is to a large extent an investment challenge, associated to questions on deployment capacity, including in terms of availability of raw materials and skilled labour force or acceptability. The impact assessments for the 2030 Climate Target Plan ⁽²⁶⁷⁾ and the legislative proposals under the Fit-for-55 package ⁽²⁶⁸⁾ already assessed the scale of the investment requirements up to 2030 and stressed the need for a significant increase in energy system investment compared to the decade 2011-2020. The

⁽²⁶⁵⁾ See for example [Konings J. and Vanormelingen S. The impact of training on productivity and wages: firm-level evidence.](#)

⁽²⁶⁶⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

⁽²⁶⁷⁾ [SWD\(2020\) 176 final](#)

⁽²⁶⁸⁾ See for example [SWD\(2021\) 621 final](#)

REPowerEU plan further identified additional investment needs in order to reduce the EU's dependence on Russian fossil fuels ⁽²⁶⁹⁾.

The scenarios assessed under this impact assessment generate differentiated requirements in terms of aggregate investment over the entire transition period from 2031 to 2050, as well as in terms of the sectoral composition of these investment requirements and their timing during the post-2030 period. What is most salient across all scenarios, however, are the commonalities and the need for a significant investment effort over a prolonged period, as carbon-intensive systems and processes are substituted with capital intensive, carbon-free solutions on the supply and demand side (Table 26). What this indicates as well is the necessity to ensure that the conditions be in place to facilitate this level of investment and avoid investment decisions that are not compatible with the transition, including in terms of the clarity of signals sent to investors and in terms of access to finance, for businesses and households alike.

⁽²⁶⁹⁾ [SWD\(2022\) 230 final](#)

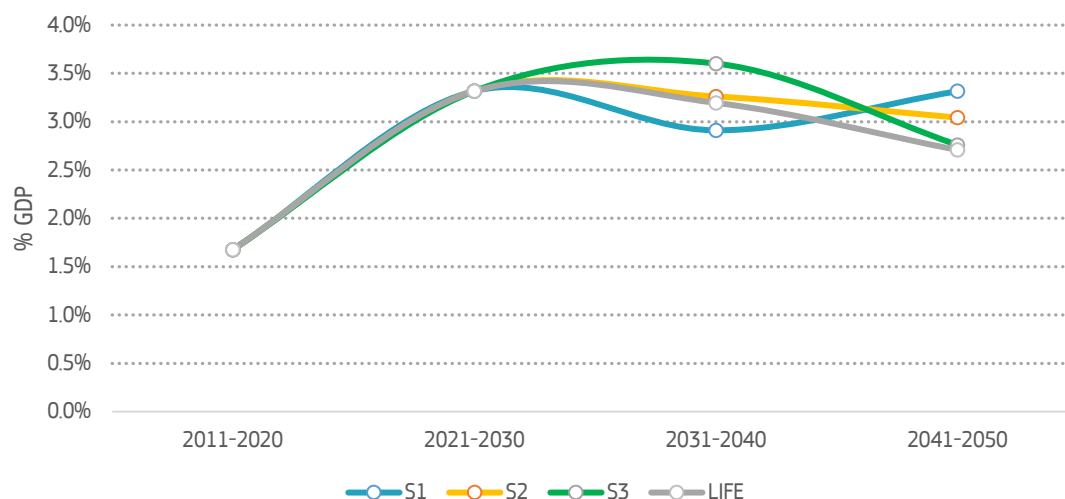
Table 26: Average annual energy system investment needs (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050
<u>Supply</u>	<u>236</u>	<u>377</u>	<u>306</u>	<u>289</u>	<u>328</u>	<u>308</u>	<u>341</u>	<u>281</u>	<u>311</u>	<u>282</u>	<u>268</u>	<u>275</u>
Power grid	79	88	84	88	81	85	96	75	85	80	73	76
Power plants	97	187	142	128	157	142	151	133	142	123	128	125
Other	59	102	81	72	90	81	94	73	83	79	67	73
<u>Demand excluding transport</u>	<u>332</u>	<u>377</u>	<u>354</u>	<u>355</u>	<u>357</u>	<u>356</u>	<u>372</u>	<u>338</u>	<u>355</u>	<u>349</u>	<u>339</u>	<u>344</u>
Industry	38	31	35	46	24	35	48	22	35	40	19	30
Residential	225	250	237	237	242	239	248	230	239	236	234	235
Services	49	78	63	53	73	63	57	67	62	53	68	60
Agriculture	19	19	19	19	19	19	20	18	19	19	19	19
<u>Transport</u>	<u>866</u>	<u>875</u>	<u>870</u>	<u>861</u>	<u>885</u>	<u>873</u>	<u>856</u>	<u>882</u>	<u>869</u>	<u>777</u>	<u>798</u>	<u>787</u>
<u>Total</u>	<u>1433</u>	<u>1629</u>	<u>1531</u>	<u>1505</u>	<u>1570</u>	<u>1537</u>	<u>1570</u>	<u>1501</u>	<u>1535</u>	<u>1407</u>	<u>1405</u>	<u>1406</u>
Total excluding transport	567	754	661	644	685	664	713	619	666	631	607	619
<u>Memo:</u>												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

Overall, the scenarios and associated pathways imply annual energy system investment needs (excluding transport) at or above 3% of GDP for the two decades from 2031 to 2050 (Figure 103). This amounts to an additional 1.5 to 2 percentage points of GDP compared to the average in 2011-2020. A higher level of ambition in 2040 is, as expected, associated with higher annual investment needs in 2031-2040 than lower levels of ambition in 2040, but also with comparatively lower investment requirements in 2041-2050 due to the early push on decarbonisation projects.

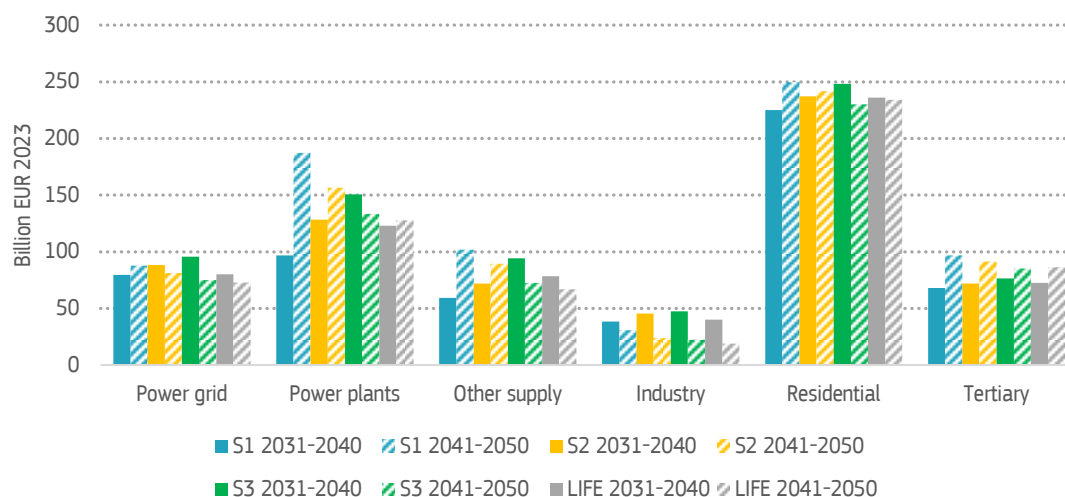
Figure 103: Average annual energy system investment needs, excluding transport



Source: PRIMES.

Cumulatively over the two decades (2031-2050), S3 implies a somewhat higher level of investment as well, partly because technologies need to be deployed faster, which reduces the gains from the projected decrease in the cost of decarbonisation technologies over time through learning-by-doing. S2 yields a smoother investment profile over the entire period 2031-2050 and avoids either anticipating or delaying investments. In turn, behavioural changes (LIFE), including in terms of mobility, consumption and energy use in the residential sector, enable a reduction in investment needs across the entire period (Figure 104). Excluding transport, average annual investment needs in 2031-2050 can be reduced by about EUR 47 billion (7%) compared to S3 over 2031-2050. The lowering of investment needs is evident across the board as reduced energy demand enables a reduction in average annual investment of about EUR 36 billion (12%) on the supply side in 2031-2050 while circularity enables a drop in annual investment needs of about EUR 5 billion (15%) in industry. As far as transport is concerned, lifestyle changes towards more active and public transport modes lead to a drop of around EUR 80 billion (9%) in annual investment needs in 2031-2050.

Figure 104: Average annual energy system investment needs by sector

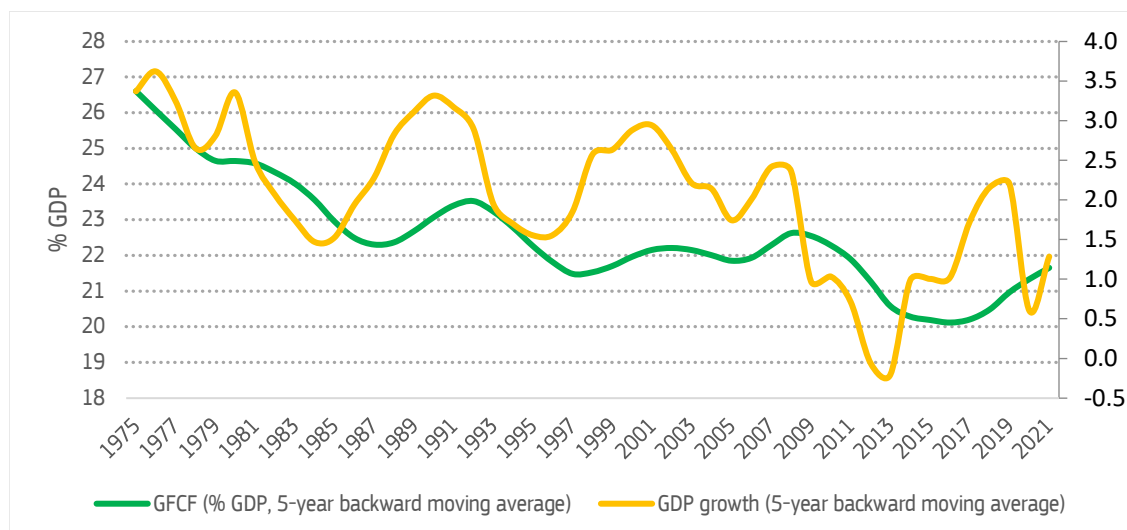


Source: PRIMES.

The projected increase in the investment to GDP ratio is significant, but not exceptional in historical terms. More mature economies typically have lower gross fixed capital formation (GFCF) to GDP ratios, as the need to invest in core infrastructure is lower than in less-developed economies. In the EU, the GFCF/GDP ratio was on a declining trend between the mid-1970s to the mid-1990s, before stabilising at around 21-22% (Figure 105). There has always been a fair bit of volatility in the ratio, however, with a marked low point in the mid-2010s followed by a return in more recent years towards the average of the first decade of the 2000s. Changes in the ratio of 1-2 percentage points of GDP within a relatively short period have not been uncommon in the past. The key difference in the current context is that an increase in the GFCF/GDP ratio would need to be sustained for an extended period, and that higher investment for decarbonisation purposes would need to be combined with higher investment on climate adaptation and higher investment to secure the EU's ability to benefit from the growth and employment opportunities in green technologies and its strategic security, as discussed in section 2.2.7⁽²⁷⁰⁾. The latter would indeed require that the EU be in a position to manufacture a significant share of the green technologies necessary for the climate transition domestically.

⁽²⁷⁰⁾ [SWD \(2023\) 68 final](#) estimates investment needs for 2023-2030 associated with boosting EU manufacturing capacity for a part of strategic net-zero technologies, focusing on wind, solar photovoltaic, heat pumps, batteries and electrolyzers, as part of the Net Zero Industry Act proposal.

Figure 105: Ratio of gross fixed capital formation to GDP and GDP growth (5-year backward moving average)



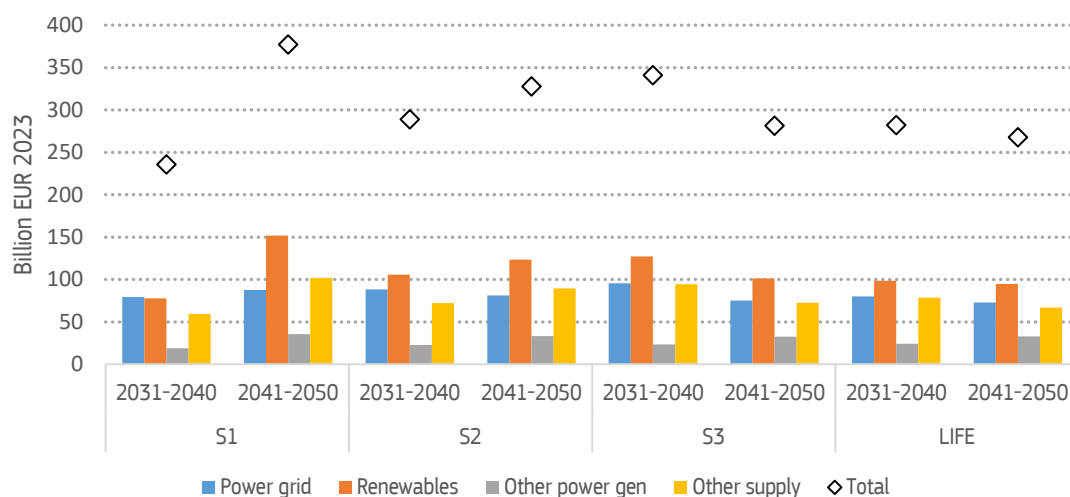
Source: World Bank.

2.2.2. Supply-side investment needs

The continued large-scale deployment of renewable and carbon-free sources of energy, in particular electricity, is a necessity across all scenarios and the shares of renewable electricity and energy reach very similar levels by 2050. However, the levels of primary and final energy demand vary somewhat across scenarios, and the speed at which renewable and carbon free energy sources are deployed differ, together with the composition of energy sources (section 1.2).

Over 2031-2050, average investment needs in power plants is projected at around EUR 140 billion per annum across scenarios (Table 26), more than 80% of which would be in renewables, mainly wind and solar. S3 entails a much faster deployment of renewable and other carbon-free power generation, with average annual investment of around EUR 135 billion in 2031-2040, while S1 entails a significant delay in such investments, with very high deployment levels in 2041-2050 (Figure 106). S2 entails a smoother investment profile overall, with lower investment needs in 2031-2040 compensated by higher investment needs in 2041-2050 compared to S3. In turn, LIFE enables a reduction of about EUR 17 billion (12%) in annual investment in power plants in 2031-2050 compared to S3. It also translates into a significant reduction in power grid investment needs of close to EUR 10 billion (10%) per annum.

Figure 106: Average annual investment in power supply



Source: PRIMES.

Given the similar high reliance on variable sources of renewable electricity, all scenarios require significant investment in electricity storage, starting this decade already and extending to 2050, at about EUR 8 billion annually in 2031-2050. Similarly, integrating a very high share of variable and geographically dispersed renewable electricity sources into the electricity network will require the upscaling and upgrading of the transmission and distribution networks. Average annual investment needs in the power grid are comparable across scenarios at about EUR 85 billion per annum, with an early push in investment under S3, a delayed deployment under S1, a more even profile under S2 and a reduction in investment needs under LIFE. Infrastructure investment in carbon storage is projected at around EUR 5 billion per annum on average in 2031-2050 and is similar across scenarios. The faster development of carbon capture and storage under S3 and S2 means that investment in carbon storage infrastructure is anticipated compared to S1, with average annual investment of EUR 9 billion in 2031-2040 under S3, compared to EUR 6 billion under S2 and EUR 1 billion under S1.

The bulk of investment needs on the supply side of the energy system will originate from power utilities and by the regulated operators of the transmission and distribution systems, many of which in the EU are fully or partly publicly owned corporations. Industrial companies also invest to some extent in their own (decarbonised) energy supply infrastructure, as illustrated by recent developments in investments in the generation of green hydrogen from electrolysis by large players in the steel industry. So far, the deployment of renewable electricity has mainly taken place with public support via a range of State aid schemes providing operating aid for generation ⁽²⁷¹⁾. EU funding

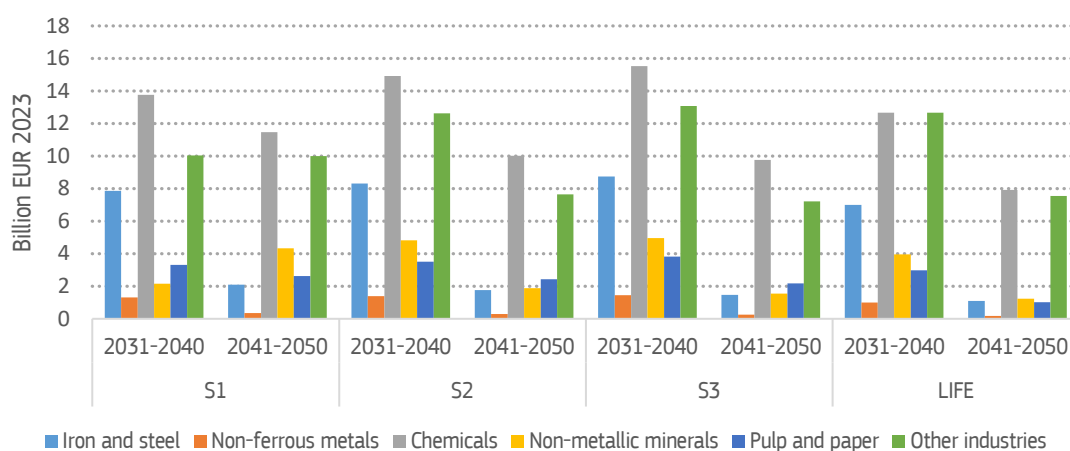
⁽²⁷¹⁾ The Guidelines for Energy and Environmental Aid (EEAG) facilitated the provision of State aid for the deployment of renewable electricity and promoted the competitiveness of aid mechanisms by promoting competition auction mechanisms for the allocation of aid and requiring aid to be granted as a premium over market prices. The Guidelines on State aid for climate, environmental protection and energy (CEEAG), as adopted in 2022, further improved the framework for the allocation of aid for renewable electricity generation. Finally, the Temporary Crisis and Transition Framework further facilitates the granting of aid to accelerate the rollout of renewable energy and energy storage relevant for REPowerEU.

has also facilitated the deployment of renewables in the power sector, including via the Modernisation Fund. To some extent, households are also involved as investors on the supply side via the installation of rooftop solar panels and or/via energy communities, which have risen in importance in recent years. Investment costs for the deployment of renewable electricity have fallen sharply in the last decades, and renewable electricity is set to become cost-competitive on a market basis in a broad range of market situations encountered in Europe by 2030 ⁽²⁷²⁾. The need for public support should therefore decrease in future and it is expected that deployment should be increasingly driven under market conditions.

2.2.3. Demand-side investment needs, industry, services and agriculture

The shift towards electricity as the principal energy carrier on the demand side, the decarbonisation of industrial processes and improvements in energy efficiency will require significant investment over the coming decades. Investment needs to decarbonise industrial output will be most significant in energy-intensive industries, which tend to be dominated by large privately owned corporations. The estimated investment needs in iron and steel, non-ferrous metals, chemicals, non-metallic minerals and pulp and paper account for about 70% of investment needs in industry in 2031-2050 and the amounts vary little across scenarios (Figure 107). However, LIFE shows clear benefits from higher levels of circularity in industry, with investment needs reduced by 15% compared to S3 (Table 28). This is particularly noticeable in sectors where circularity offers most potential, including pulp and paper (-33%), non-ferrous metals (-31%), iron and steel (-21%) and chemicals (-19%).

Figure 107: Average annual energy system investment needs in industrial sectors



Source: PRIMES.

In the decade 2031-2040, annual energy-system investment needs in energy-intensive industries are projected at around EUR 28-34 billion in S1-S2-S3 (with a reduction of about EUR 7 billion under LIFE compared to S3). These estimates do not capture the full investment costs of new or refurbished production facilities, but only the part that relates

⁽²⁷²⁾ Sebastian Busch, Ruben Kasdorp, Derck Koolen, Arnaud Mercier, Magdalena Spooner: The Development of Renewable Energy in the Electricity Market. Directorate-General for Economic and Financial Affairs. [Discussion Paper 187. June 2023](#).

to decarbonisation, e.g., the additional cost of a hydrogen-based steel plant relative to a baseline fossil-fuel based plant or investment in carbon capture. In turn, the investment needs related to hydrogen production are captured in supply-side investments (section 2.2.2). The estimates also do not capture possible investment in R&D itself. The faster deployment of industrial carbon capture under S3 and S2 means that investment is anticipated compared to S1, with average annual investment in carbon capture for industry as a whole of EUR 4 billion in 2031-2040 under S3 and S2, compared to less than EUR 1 billion under S1. On average over 2031-2050, however, industrial investment in carbon capture is almost the same across scenarios at about EUR 2 billion per annum.

Investment needs in other industrial sectors are more diffuse, both in terms of sectors concerned and in terms of size of enterprises. While there are no estimates of investment needs by size of enterprises, most SMEs active in manufacturing fall under these “other” sectors. SMEs active in manufacturing account for about 9% of total SMEs, and the vast majority are involved in non-energy intensive manufacturing activities (Table 27). While manufacturing-oriented SMEs account for a large share of total SME gross value added and employment in the economy with a share of 20%, the majority of that is again in SMEs involved in non-energy intensive manufacturing. SMEs are therefore most likely to decarbonise their production processes mainly via electrification and improvements in energy efficiency. The scenarios differ little in terms of investment needs for non-energy-intensive sectors in 2031-2050 at an average of around EUR 10 billion per annum, but S3 and S2 imply a fair degree of early push compared to S1.

Table 27: Indicators of SME activity by sector (2019)

	SME shares in the economy (% of total)		Sectoral split of SMEs (% of economy-wide SMEs)		
	Share in GVA	Share in employment	Number of companies	GVA	Employment
Fossil fuels	7.0%	6.6%	0.0%	0.1%	0.0%
Other mining and extraction	53.1%	59.2%	0.1%	0.3%	0.2%
Energy intensive industries	29.1%	34.4%	0.6%	2.9%	2.0%
Manuf. transport equipment (incl. parts and accessories)	7.9%	14.1%	0.1%	0.6%	0.6%
Manuf. electrical equipment and other machinery	32.0%	35.4%	0.5%	3.1%	2.0%
Other manufacturing	44.4%	65.0%	7.5%	14.3%	15.9%
Electricity, gas, steam and air conditioning supply	22.3%	29.0%	0.7%	1.4%	0.5%
Construction and architecture services	77.8%	89.1%	19.0%	16.4%	17.5%
Transport and storage	49.0%	43.6%	5.4%	5.2%	4.9%
Services	62.7%	69.5%	65.7%	54.3%	55.5%
Water, treatment and waste	46.7%	45.3%	0.3%	1.3%	0.9%
Total	52.9%	64.4%	100.0%	100.0%	100.0%
Memo:			Million	Billion	Million
All sectors above	52.9%	64.4%	23.1	EUR 3332	76.3
Agriculture	66.7%	95.6%	8.7	128	8.3

Source: Eurostat ⁽²⁷³⁾.

⁽²⁷³⁾ The data is calculated from the Structural Business Statistics (SBS), except for agriculture, which is not included in the dataset. For SBS sectors, the table is based on an aggregation of sectors by size class for special aggregates of activities (NACE 2). Fossil fuel sectors (B05, B06, C19); other mining and extraction activities (B07, B08, B09); energy intensive industries (C17, C20, C21, C23, C24);

Table 28: Average annual energy-related side investment needs in industry, services and agriculture (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050
<u>Industry</u>	<u>38</u>	<u>31</u>	<u>35</u>	<u>46</u>	<u>24</u>	<u>35</u>	<u>48</u>	<u>22</u>	<u>35</u>	<u>40</u>	<u>19</u>	<u>30</u>
Iron and steel	8	2	5	8	2	5	9	1	5	7	1	4
Non-ferrous metals	1.3	0.4	0.8	1.4	0.3	0.8	1.4	0.2	0.8	1.0	0.2	0.6
Chemicals	14	11	13	15	10	12	16	10	13	13	8	10
Non-metallic minerals	2.1	4.3	3.2	4.8	1.9	3.3	4.9	1.5	3.2	4.0	1.2	2.6
Pulp and paper	3.3	2.6	3.0	3.5	2.4	3.0	3.8	2.2	3.0	3.0	1.0	2.0
Other	10	10	10	13	8	10	13	7	10	13	8	10
<u>Services</u>	<u>49</u>	<u>78</u>	<u>63</u>	<u>53</u>	<u>73</u>	<u>63</u>	<u>57</u>	<u>67</u>	<u>62</u>	<u>53</u>	<u>68</u>	<u>60</u>
Renovations	6	15	10	11	9	10	16	3	10	14	6	10
New constructions	3	3	3	3	3	3	3	3	3	3	3	3
Energy equipment	40	60	50	39	61	50	38	60	49	36	58	47
Heating	21	40	30	21	40	30	20	40	30	18	38	28
Cooling and others	6	7	7	6	7	6	6	7	6	6	7	6
Electrical appliances and lighting	13	13	13	13	13	13	13	13	13	13	13	13
<u>Agriculture</u>	<u>19</u>	<u>19</u>	<u>19</u>	<u>19</u>	<u>19</u>	<u>19</u>	<u>20</u>	<u>18</u>	<u>19</u>	<u>19</u>	<u>19</u>	<u>19</u>
<u>Memo:</u>												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

It is also to be noted that the assessment of investments needs, including on the supply side, relate to the investment by the user/investor in asset, e.g., the investment costs related to the installation of windmills, solar panels, a hydrogen-based plant or a heat pump. While the installation costs of these technologies are fully accounted for, the assessment is silent on the sourcing of the equipment, which can be produced domestically or imported, without impact on the figures reported in these sections.

The sourcing of the technologies required for the decarbonisation of the economy, including manufacturing capacities, raw material supply chain and deployment of clean innovative processes, is nevertheless anything but neutral in terms of impacts on the economy, including GDP, investment, sectoral output and employment or skills needs and in terms of geo-strategic implications. The Commission recently conducted an evaluation of investment needs in key net-zero technologies for the period up to 2030 for key sectors in green technologies ⁽²⁷⁴⁾. It estimated that achieving a situation of no dependency on imports in wind, solar photovoltaic, heat pumps, batteries, and electrolyzers would require a cumulative investment of about EUR 120 billion (in constant euros of 2022) until 2030. These investments, together with those to decarbonise the different industrial sector, typically require support and market creation to cover the capital and operational expenditure. Maintaining a strategic autonomy in key decarbonisation technologies post 2030 would further add to the economy's overall investment needs. Section 2.2.7 elaborates on investment needs in key net-zero technologies for the period 2031-2040.

As for investments on the supply side, the bulk of investment in industry should originate from private investors. Member States have nevertheless actively supported the decarbonisation of industry in recent years via State aid mechanisms in favour of R&D&I or in favour of the deployment at scale of innovative, low-carbon processes ⁽²⁷⁵⁾. Similarly, EU funding has been established to support innovation for decarbonisation, including the Innovation Fund and the Horizon Europe programme.

While the deployment at scale of innovative production processes will be an important factor driving investment needs in industry on the path to climate neutrality, investment needs in tertiary sectors involve essentially the deployment of well-established technologies and a renovation drive. To the extent that investments in energy efficiency and the substitution of fossil fuels-based technologies with carbon-free ones generate a positive economic return over their lifetime, the potential barriers to deployment would therefore mainly relate to awareness, access to (long-term) finance at moderate costs and

⁽²⁷⁴⁾ [SWD \(2023\) 68 final](#)

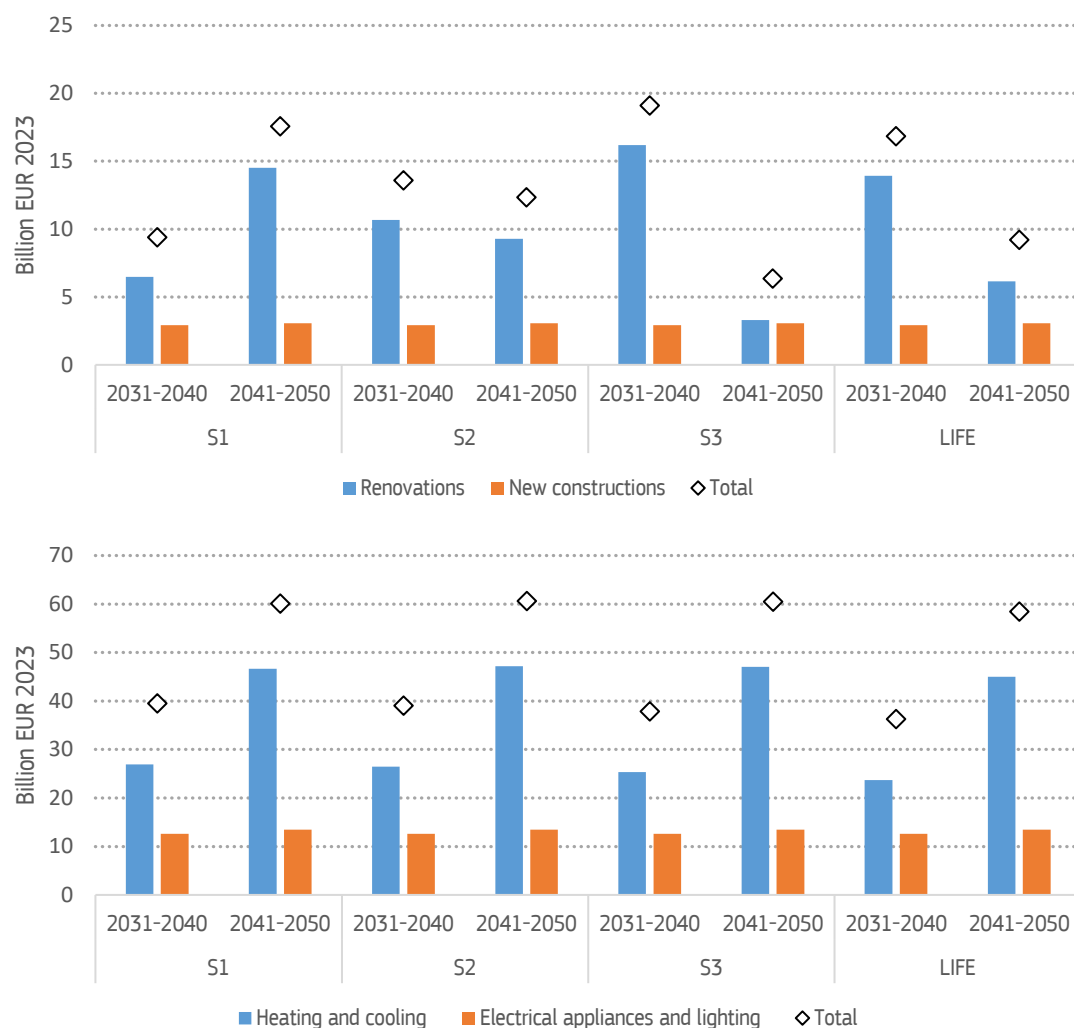
⁽²⁷⁵⁾ For example, the Commission approved the granting of EUR 1 billion of State aid by Gemarny to Salzgitter to green its steel manufacturing processes, and over EUR 130 million of aid to BASF to replace natural gas-based hydrogen with renewable hydrogen at its chemical production facilities. Recently as well, the Commission approved two schemes notified by Slovakia, with a total budget of over EUR 1.1 billion from the RRF and the Modernisation Fund, aiming at reducing CO₂ emissions in industrial production processes as well as to implement energy efficiency measures in industrial installations. The measures supported under the schemes range from electrification projects to the installation of industrial waste heat recovery technologies. The projects will be selected through an open competitive bidding process and will be ranked on the basis of two criteria: (i) the lowest amount of aid requested per ton of CO₂ emissions avoided, and (ii) the highest contribution to the achievement of the CO₂ emission reduction objective.

access to skills, rather than a matter of innovation and new production processes. These potential barriers would likely be more significant for SMEs than for large players in the tertiary sectors.

The investment needs will also be much more diffuse among sectors and players than in industry, as they will involve a very wide range of services sectors, from retailers, hospitality or finance to energy-intensive data centres and encompass a wide mix of large, medium, small and even micro enterprises. SMEs are likely to account for a significant share of investment needs in the tertiary sector, given that a high proportion of them are active in services sectors and that they represent a large share of economy-wide gross value added and employment. In 2019, SMEs accounted for about 63% of economy-wide gross value added and close to 70% of overall employment in services. Within SMEs, about 65% of companies are involved in the services sector (Table 27). Public sector investment will also be an important source of investment in the tertiary sector, given the scale of its buildings portfolio in central, regional and local administration, schools, hospitals or judiciary system.

On the buildings themselves, the main driver for investment will consist in the renovation of existing assets with the view to improve overall energy efficiency via insulation. The higher ambition in 2040 under S3 implies a significant early push in the renovation drive compared to S2 and S1, although cumulative investments over the full period 2031-2050 would be similar. Investment in new construction is projected to be relatively small in the three pathways, as the estimates capture only the additional investment in the building's energy performance relative to a baseline, which already entails high energy performances given the existing stringent standards for new constructions at national and EU level (Figure 108).

Figure 108: Average annual energy system investment needs in services



Source: PRIMES.

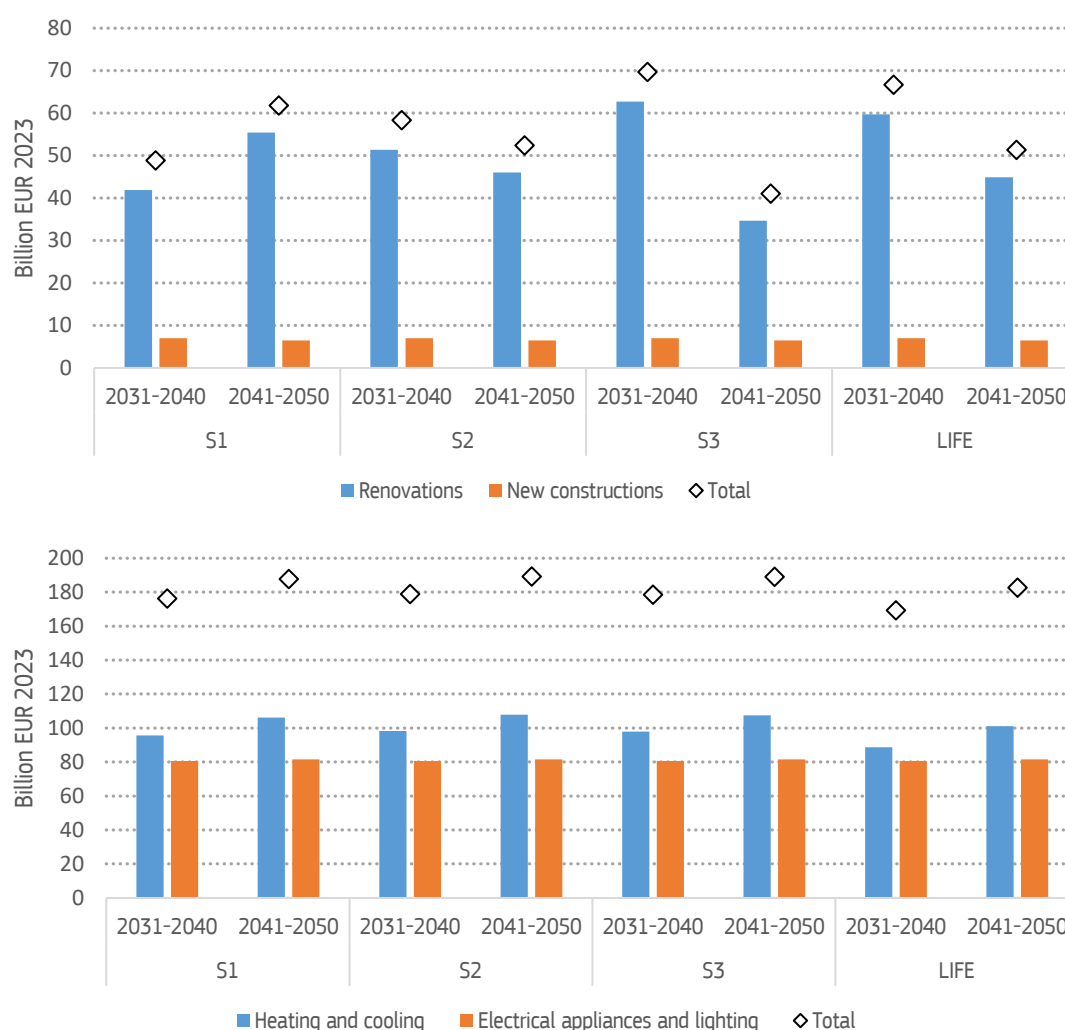
The bulk of the investment needs in tertiary sectors is projected to take place via the acquisition of energy equipment for heating, cooling, appliances and lighting. The full acquisition cost of such equipment is captured in the numbers as reported in Table 28, contrary to investments in on the building structure. The deployment of heat pumps is projected to start at a large scale during this decade already and to continue into the 2031-2050 period as the technology almost entirely replaces conventional technologies for heating. Investment in heat pumps in tertiary sectors is projected at around EUR 23 billion per annum in 2031-2050 under all main scenarios, with a comparable time profile. LIFE, however, enables a slightly lower investment level in tertiary sector heating and cooling systems.

2.2.4. Demand-side investment needs, households

Investments needs for the decarbonisation of the residential sector will be similar in nature to those in the tertiary sectors, focusing on improvements in the energy efficiency of buildings and the substitution of fossil fuels-based technologies for heating and cooling with carbon-free options. However, the scale of the residential building stock and current energy efficiency levels are such that investment needs will be a multiple of those in the tertiary sectors.

As in the tertiary sector, the higher level of ambition in 2040 under S3 would require an early push in renovation rates compared to S2 and S1. The latter would see higher renovation rates in 2041-2050, however, which means that average investment levels over the full period 2031-2050 would be very similar across scenarios, with differences mainly in terms of timing (Figure 109). On average in 2031-2050, renovation investment in the residential sector amounts to around EUR 50 billion per annum across scenarios (Table 29). This represents a significant increase compared to historical investment levels (2011-2020) in renovation and is about 5 times as much as the investment level required in renovation for tertiary sectors. As far as new constructions are concerned, the investment needs are relatively limited and do not vary across scenarios, as the estimates capture only the additional investment in the building's energy performance relative to a baseline.

Figure 109: Average annual energy system investment needs in residential sector



Source: PRIMES.

As in the tertiary sectors, the second big component of investment needs in the residential sector relates to heating and cooling equipment, and electrical appliances and lighting. The full acquisition cost of such equipment is again captured in these numbers (Table 29), which implies that households would incur a non-negligible share of such expenses under any circumstances. The estimated annual investment needs in 2031-2050 in energy equipment amount to around EUR 185 billion across scenarios, about twice the level in

2011-2020. The increase in energy equipment is most significant in heating and cooling systems (+240%) and less so in appliances and lighting (+56%).

The deployment of heat pumps is projected to start at a large scale in this decade and to continue in the following two decades. Average annual investment in heat pumps in 2031-2050 is projected at almost EUR 60 billion across scenarios and the timing of investment over the two decades is very similar, with slightly higher investment levels in 2041-2050 than in 2031-2040. The switch to heat pumps is a constant across the main scenarios, but the LIFE setting enables a reduction in investment in heating systems overall of about EUR 7 billion (10%) per annum in 2031-2050.

As for heating and cooling systems, investment needs for electrical appliances and lighting are estimated at full acquisition costs, which again implies that households would incur a significant share of such expenses under any circumstances. The estimated investment needs in appliances and lighting nevertheless represent about a third of estimated total investment needs in the residential sector, at around EUR 80 billion per annum in 2031-2050 across scenarios.

Investments in the residential sector will fall upon a range of players. While the costs of appliances will be borne mostly by households themselves, the situation is more contrasted for other types of investment needs. Homeowners will bear the full costs of improvements in energy efficiency and shifting to carbon-free heating and cooling systems. They will also reap the full benefits in terms of reduced utility bills and comfort levels.

In contrast, funding the necessary investment in energy efficiency and heating and cooling system for rented accommodation will fall upon a range of actors, from landlords owning a single asset to large property owners/developers and public housing entities. While access to affordable finance could be better for such players than for many home-owning households, the incentives to renovate and upgrade heating and cooling systems might not be as strong, as the benefits of lower utility bills and higher comfort levels arise to tenants. Finally, where distributed heating is well developed, households will also not directly face the need to provide up-front finance for investment, though the capital cost of modernising the centralised heating system will be reflected in their utility bills. Overall, the funding of investment needs in the residential sector will therefore involve a multiplicity of actors, who will need to be provided the appropriate incentives or financial support to act in accordance with the needs to decarbonise the sector.

Table 29: Average annual demand side investment, residential sector (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050
<u>Total</u>	<u>225</u>	<u>250</u>	<u>237</u>	<u>237</u>	<u>242</u>	<u>239</u>	<u>248</u>	<u>230</u>	<u>239</u>	<u>236</u>	<u>234</u>	<u>235</u>
Renovations	42	55	49	51	46	49	63	35	49	60	45	52
New constructions	7	6	7	7	6	7	7	6	7	7	6	7
Energy equipment	176	188	182	179	189	184	179	189	184	169	183	176
Heating	66	74	70	68	75	72	67	75	71	59	69	64
Cooling and others	30	32	31	30	33	31	31	33	32	30	33	31
Electrical appliances and lighting	81	82	81	81	82	81	81	82	81	81	82	81
<u>Memo:</u>												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

2.2.5. Demand-side investment needs, transport

Estimated average annual investment needs in transport in 2031-2050 are similar across the main scenarios at about EUR 870 billion ⁽²⁷⁶⁾. LIFE nevertheless enables a significant lowering of investment needs of about EUR 80 billion (9%) per annum in 2031-2050 compared to S3. While investment in public road transport and rail is 4% and 6% higher under the LIFE setting, the modal shift enables a decrease in the purchase of private cars of nearly EUR 70 billion (13%) per annum in 2031-2050. Similarly, changes in behavioural patterns under LIFE could reduce investment needs in aviation by about EUR 14 billion (23%) annually compared to S3 (Table 30).

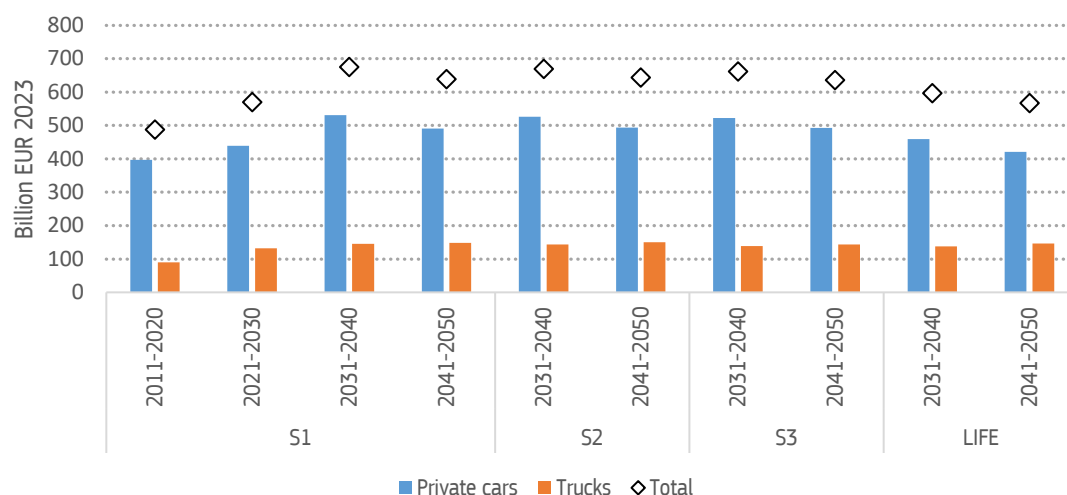
The acquisition of private cars represents the bulk of the investment needs in transport, accounting for around 60% of the total over 2031-2050. This is also the case in historical terms, as the share was 65% in 2011-2020. Average annual investment in the acquisition of private cars in 2031-2050 amounts to about EUR 510 billion across scenarios, which is almost 30% higher than on average in 2011-2020 (Figure 110).

This increase reflects two factors. An increase of around 18% in the number of new private cars purchased annually is projected between 2011-2020 and 2031-2050 under the three main scenarios. LIFE enables this increase to be limited to only 2%. As electric vehicles are deployed, it is also projected that the average purchasing cost of vehicles will increase during the transition. The increase is expected to take place mainly during 2031-2040, before tapering off in the last decade to 2050 as the cost of electric vehicles decreases. Over the entire 2031-2050 period, the average purchasing cost of vehicles is expected to be only around 10% higher than in 2011-2020. In addition, it must be noted that the maintenance and operating costs of electric vehicles, which will become dominant under all pathways, is significantly lower than internal combustion engine cars, which would generate net benefits to users, i.e., mainly households ⁽²⁷⁷⁾.

⁽²⁷⁶⁾ These figures represent the full acquisition cost of new vehicles, not only the incremental cost related to the decarbonisation of transport. In addition, it should be noted that investments in transport reflect here the expenditures on vehicles, rolling stock, aircraft and vessels plus recharging and refuelling infrastructure. They do not cover investments in infrastructure to support multimodal mobility and sustainable urban transport.

⁽²⁷⁷⁾ [SWD\(2021\) 613 final](#).

Figure 110: Average annual investment needs in transport



Source: PRIMES.

While timely investment in recharging and refuelling infrastructure is critical for the transition to vehicles with zero tailpipe emissions, total investment in alternative fuelling infrastructure is relatively small from the perspective of overall investment needs. The needs are virtually the same across scenarios, with an average annual investment of around EUR 15 billion (1.7% of total investment needs in transport) in 2031-2050, and in terms of timing. The phasing in of zero tailpipe emission vehicles and the EU-wide ban on the sale of other types of light-duty vehicles as of 2035 implies a peak in annual investment in recharging and refuelling infrastructure of around EUR 20 billion in 2036-2040 before tapering off somewhat.

The second large component of investment in road transport relates to trucks, for which average annual investment is projected to increase by around 60% compared to the average in 2011-2020 (Table 30). Investment needs are broadly similar across scenarios. As far as public road transport is concerned the investment needs are relatively small and do not vary much across scenarios, with the exception of the LIFE setting and its associated modal shift towards public transport entails an increase in investment in the sector.

The 3 main scenarios differ little in terms of investment needs for rail, aviation and navigation. As a share of total transport annual average investments over 2031-2050, rail transport represents 5%, aviation represents 7%, and domestic navigation and international maritime transport represent 5-6% of the total. However, they do typically represent a significant increase relative to investment levels in 2011-2020. In contrast, S3 and S2 entail somewhat higher investment levels in international maritime transport than S1. As indicated above also, LIFE also implies a moderately higher level of investment in rail, and a decrease in average annual investment in aviation of EUR 14 billion (23%) in 2031-2050 compared to S3.

Table 30: Average annual demand side investment needs, transport (billion EUR 2023)

	S1			S2			S3			LIFE		
EU27	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050	2031- 2040	2041- 2050	2031- 2050
<u>Total</u>	<u>866</u>	<u>875</u>	<u>870</u>	<u>861</u>	<u>885</u>	<u>873</u>	<u>856</u>	<u>882</u>	<u>869</u>	<u>777</u>	<u>798</u>	<u>787</u>
Road	718	688	703	712	693	702	704	686	695	640	617	629
Public transport	24	29	26	23	30	27	24	30	27	25	31	28
Private cars	531	491	511	526	494	510	523	493	508	459	421	440
Two-wheelers	18	19	19	18	20	19	18	20	19	18	20	19
Trucks	145	149	147	143	150	147	139	144	142	137	147	142
Rail	41	51	46	42	51	47	43	52	47	46	54	50
Aviation	51	70	60	51	70	61	52	70	61	36	58	47
Domestic navigation	13	12	13	13	13	13	12	13	13	13	13	13
International maritime	26	41	33	27	42	35	31	47	39	27	42	35
Alternative fuel infrastructure	16	14	15	16	15	16	16	15	15	14	13	14
<u>Memo:</u>												
Real GDP (period average)	19444	22369	20906	19444	22369	20906	19444	22369	20906	19444	22369	20906

Source: PRIMES.

2.2.6. Sensitivity of investment needs to technology costs assumptions

Cost assumptions for the deployment of mitigation technologies are exogenous to the modelling exercise and constant across all scenarios. They are discussed in more details in annex 6, and summarised in Table 31 for a few technologies on the supply side and for heat pumps, based on averages in each case (average of sizes of installations for solar, wind and heat pumps and average of centralised and decentralised technology for hydrogen).

Over the past decades, the cost of solar, wind or heat pumps has decreased sharply as a result of technological progress and learning by doing fostered by the rising scale of deployment in the EU and globally. However, as demand for renewables and electrification – and the associated raw materials needed for the production of such technologies – is set to increase globally, the sector could potentially be subject to price shocks or sustained price pressures, depending on the capacity of global markets to respond to rising demand, on the ability of circular economy policies to create a resource base for “secondary” materials production in the EU and on the capacity of the EU to create a domestic value chain for primary materials.

Table 31: Technology investment costs assumptions (EUR 2015 per kW)

	2020	2030	2040	2050
Solar, residential	1399	1067	878	841
Solar, commercial	941	711	580	561
Solar, utility	511	394	322	284
Wind onshore	1347	1021	941	920
Wind offshore, shallow	2673	2067	1708	1619
Wind offshore, floating	5107	3212	2531	2478
Hydrogen, low temperature electrolysis – PEM	1586	833	683	529
Hydrogen, low temperature electrolysis – alkaline	1423	675	572	518
Hydrogen, high temperature electrolysis – SOEC (centralised)	2250	1050	792	580
Heat pumps, air to air *	468	551	445	424
Heat pumps, air to water *	1172	1243	1107	1068

Note: * residential sector only.

Source: PRIMES.

Understanding how investment needs could be affected by potential increases in technology costs is important. A sensitivity analysis on what a stylised price shock on the cost of renewable technologies would mean in the different scenarios is therefore presented in Table 32. It assumes that supply-side technologies are subject to a 20% increase in costs relative to the standard assumptions used across scenarios. Supply side technologies are most susceptible to be subject to price shocks as they rely on critical raw materials. The shock is tested for the 2031-2040 as it is more likely that demand could outpace supply for such technologies during that time, as the rest of the world also steps up investment to deploy renewables and as EU and worldwide manufacturing facilities take time to be established in response to the likely increase in global demand. It is

simulated for solar, wind, new fuels and heat pumps, i.e., green technologies at the core of the Commission proposal on a Net Zero Industry Act that will be critical as enablers of the EU's decarbonisation objectives ⁽²⁷⁸⁾.

Given the scale of the investment needs, wind and heat pumps are the technologies that would be most susceptible to trigger an increase in energy system investment requirements. A 20% price shock on wind would add between EUR 9 billion (S1) to EUR 17 billion (S3) to annual investment needs in 2031-2040, while the same shock on heat pumps would add between EUR 11 billion (S3) to EUR 14 billion (S2) annually. A shock on all four technologies considered in this sensitivity analysis would increase annual energy system investment needs (excluding transport) in 2031-2040 by 5.5%, 6.1% and 6.3%, respectively under S1, S2 and S3. As expected, S3 is most affected as it anticipates investment in renewable technologies (Table 32).

It is important to note that the increase in total investment needs from such a shock nevertheless remains relatively small, with a cumulative impact of EUR 44 billion annually under S3, which is equivalent to 0.2% of average GDP over the period. Further, the impact on energy system costs should be smaller still, as capital costs represent only a share of total costs and as the shock would only affect new capacity installed during the period and not the entire capital stock. In this regard, a price shock on renewables technologies (or raw materials needed for their production) is therefore fundamentally different from a price shock on fossil fuels.

Table 32: Sensitivity of average annual energy system investment needs (excluding transport) to a price shock

	Deviation vs. default (bn EUR 2023)			% change over default		
	S1	S2	S3	S1	S2	S3
EU27						
Energy system invest. (default costs)	566	634	700			
Impact of 20 % cost increase vs. default::						
Solar	5	6	7	0.9%	1.0%	1.0%
Wind	9	14	17	1.7%	2.1%	2.4%
New fuels	3	5	9	0.6%	0.8%	1.2%
Heat pumps	13	14	11	2.4%	2.2%	1.6%
Cumulative increase on all of the above	31	38	44	5.5%	6.1%	6.3%

Source: PRIMES.

2.2.7. Investment needs for net-zero technology manufacturing capacity

The resilience of future energy systems will be measured notably by a secure access to the technologies that will power those systems: wind turbines, solar PV, electrolyzers, batteries, heat pumps and others. In this context, the Net-Zero Industry Act is part of the actions announced in the Green Deal Industrial Plan of February 2023, aiming at simplifying the regulatory framework and improving the investment environment for the Union's manufacturing capacity of technologies that are key to meet the Union's climate neutrality goals and energy targets.

⁽²⁷⁸⁾ Given that there is very little difference across scenarios regarding the deployment of electric vehicles, no shock is simulated on the transport side.

Net-zero technologies are at the centre of strong geostrategic interests and at the core of the global technological race, as exemplified by the United States' Inflation Reduction Act and China's dominance in manufacturing of some cleantech. Fostering a competitive and resilient European net-zero industry can play a significant role in reducing high import dependence for key net-zero technologies, while guaranteeing affordable, reliable and sustainable clean energy to EU citizens and businesses.

This section estimates the investments needed to build an EU-based manufacturing capacity for five key net-zero technologies: wind, solar PV, batteries, heat pumps and electrolyzers. The analysis focuses on the investment needs for the decade 2031-2040 ⁽²⁷⁹⁾.

Table 33: Manufacturing capacity and investment needs per technology (2031-2040)

Technology	Max annual technology deployment in 2030-2040	Installed EU manufacturing capacity in 2030	Market share of EU production	EU manufacturing capacity in 2040	New manufacturing capacity needed post-2030	Factory CAPEX (M€22/unit/year)	Manufacturing capacity investment needs (bn EUR)
Wind	62	33	85%	53	20	260	5.2
Solar PV	55	23	45%	25	2	340	0.7
Heat Pump	53	31	60%	32	1	333	0.5
Battery cell	729	549	90%	656	107	144	15.4
Electrolysers	49	25	100%	49	24	60	1.4
Total							23.3

Note: manufacturing capacity needed and investment needs per technology. Capacity is expressed in GWh/year for batteries and GW/year for the other technologies (GW of electricity for electrolysers, GWAC for solar PV)

Source: Commission own calculations based on PRIMES ⁽²⁸⁰⁾

In a scenario where the EU achieves the market shares indicated in the Net-Zero Industry Act proposal ⁽²⁸¹⁾, total investment needs reach a cumulative EUR 23 billion over 2031-2040. Two thirds of those investments are for battery manufacturing, one fifth to one quarter are for manufacturing of wind technologies, and electrolysers, solar PV and heat pumps represent each between 2 and 6% of the total. This level of investment needs takes into account that investments in manufacturing capacity already take place by 2030, so the EU has already a manufacturing base in place in 2030. Manufacturing investment needs would be lower in scenarios S1 and S2, as in 2040, net installed renewable power capacity is lower by 7% in S2 and by 16% in S1 compared with S3.

2.2.8. Technical feasibility

The cost-efficient decarbonisation relies on the deployment of net-zero technologies with varying but sufficient degree of maturity to be used on a large scale. The maturity of

⁽²⁷⁹⁾ Investment needs until 2030 have been assessed in the Commission [Staff Working Document Investment needs assessment and funding availabilities to strengthen EU's Net-Zero technology manufacturing capacity \(SWD\(2023\) 68 final\)](#).

⁽²⁸⁰⁾ See Annex 8 of SWD(2023) 68 final.

⁽²⁸¹⁾ Objectives of global market shares of 85% for wind, 45% for solar PV, 60% for heat pumps, 90% for battery cells and 100% for electrolysers.

technologies is an important driver of the projected portfolio of net-zero technologies. In recent years, pressing innovation gaps have been addressed which resulted in significant improvements of the technology readiness.⁽²⁸²⁾ For the bulk of net-zero technologies needed to reach the 2040 targets, the Technology Readiness Level (TRL) already amounts to at least 8 (out of 9) which means that they are in an advanced deployment stage.⁽²⁸³⁾

DAC is at the lower end of the deployment stage having a TRL of 7. Bioenergy with carbon capture and storage (BECCS) is the only technology that has a TRL of 5-6 (“Technology demonstrated in relevant environment”) indicating that it is not fully established. However, there are already a variety of BECCS demonstration projects in Japan, Norway, Sweden and the United Kingdom.

Due to their relatively low maturity, DAC and BECCS come into play only between 2030 and 2040 allowing the technology to be further developed over the coming years. In 2040, DAC and BECCS is projected to capture 16 MtCO₂ (S1) to 155 MtCO₂ (S3) making up around 0.3% (S1) to 3.3% (S3) of 1990 total GHG emissions. The S3 scenario anticipates decarbonisation via DAC up to 2040.

2.2.9. Other related investment needs

The needs analysed above concern mainly the investment required to decarbonise the energy system, and to some extent the investment required to increase the domestic production of the clean technologies that will be essential to decarbonisation efforts. Beyond the energy system, additional climate-related investments will be necessary in the coming decades, in two main areas: LULUCF sectors and agriculture, and climate adaptation.

Investment in the land sector. The Bioeconomy Strategy Progress Report 2022⁽²⁸⁴⁾ finds that although at least EUR 2.7 billion of private investment have been unlocked to develop new technologies for sustainable and circular bio-based value chains more is needed to transfer knowledge into innovations due to the lack of financing. These investments are needed for example to tap the biomass potential, new biorefineries and plant lignocellulosic crops on EU cropland as feedstock for bioenergy.

The LULUCF sector plays already a very important role with its net removal, and it will become even more important in the future. Importantly investments into the sector are needed to maintain and enhance its capacity as a carbon sink, particularly considering the recent decline of the LULUCF net removals. Nature-based removals in the LULUCF and agricultural sector provide many options for implementation at large scale, but they require significant additional investments. Examples for such nature-based removals are afforestation and reforestation, peatland restoration activities, as well as the reduction of

⁽²⁸²⁾ IEA (2023). “Net Zero Roadmap. A Global Pathway to Keep the 1.5°C Goal in Reach”

⁽²⁸³⁾ The TRL evaluation is based on the EU’s Clean Energy Technology Observatory (CETO).

⁽²⁸⁴⁾ European Commission, Directorate-General for Research and Innovation, European bioeconomy policy – Stocktaking and future developments – Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Publications Office of the European Union, 2022, <https://data.europa.eu/doi/10.2777/997651>

emissions from agricultural soil (e.g., through practices such as agroforestry or paludiculture). More generally, nature-based solutions currently receive only a small proportion of the existing financing on climate-mitigation, if one considers their potential⁽²⁸⁵⁾. Globally, they can provide about one-third of the cost-effective climate mitigation needed until 2030 to stabilize warming to below 2°C⁽²⁸⁶⁾. Notably, offsets on the voluntary market are of variable quality, which is why investments should be directed towards nature-based solutions that are ecologically sound, socially equitable and designed for the medium and long-term⁽²⁸⁷⁾. According to GLOBIOM modelling, within the EU about 85% of available nature-based solutions with costs up to 200 €/tCO₂-eq are available for up to 100 €/tCO₂-eq in 2040 and about 65% for up to 50 €/tCO₂-eq (see Annex 8).

Investments in adaptation. The European Climate Law requires the Union institutions and Member States to ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change. As part of this, the Commission adopted a new EU strategy on adaptation to climate change in 2021⁽²⁸⁸⁾. The strategy sets out how the European Union can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. It builds on four principal objectives: smarter adaptation, faster adaptation, more systemic adaptation and stepped-up international action on adaptation.

While the need for increased investment in climate adaptation and resilience is obvious, there is a big knowledge gap regarding the scale of the investment needs, in part because of methodological complexities. Existing estimates of adaptation investment needs at Member State level vary significantly depending on the methods used, the underlying assumptions (e.g., about the frequency and scale of hazards in future, or the time horizon chosen), the hazards taken into consideration, or the level of adaptation/resilience sought. The fact that the returns to investment are frequently reaped at the societal level rather than at the individual level and insufficient knowledge about adaptation investments also means that private agents do not sufficiently assess their own needs.

At EU level, there is currently no consolidated and coherent estimate of climate adaptation investment needs. The Commission is nevertheless addressing this knowledge gap via a number of initiatives, including the ongoing European Climate Risk Assessment⁽²⁸⁹⁾ exercise and a tender⁽²⁹⁰⁾ that will lead to a comprehensive assessment of adaptation investment needs at the EU level.

⁽²⁸⁵⁾ Girardin, C. A., Jenkins, S., Seddon, N., Allen, M., Lewis, S. L., Wheeler, C. E., ... & Malhi, Y. (2021). Nature-based solutions can help cool the planet—if we act now. *Nature*, 593(7858), 191-194.

⁽²⁸⁶⁾ Griscom, Bronson W., Justin Adams, Peter W. Ellis, Richard A. Houghton, Guy Lomax, Daniela A. Miteva, William H. Schlesinger et al. "Natural climate solutions." *Proceedings of the National Academy of Sciences* 114, no. 44 (2017): 11645-11650.

⁽²⁸⁷⁾ Girardin, C. A., Jenkins, S., Seddon, N., Allen, M., Lewis, S. L., Wheeler, C. E., ... & Malhi, Y. (2021). Nature-based solutions can help cool the planet—if we act now. *Nature*, 593(7858), 191-194.

⁽²⁸⁸⁾ [COM\(2021\) 82 final](#) and accompanying impact assessment [SWD\(2021\) 25 final](#).

⁽²⁸⁹⁾ [European Climate Risk Assessment](#).

⁽²⁹⁰⁾ [CINEA/2023/OP/0013](#).

2.2.10. The role of the public sector and carbon pricing revenues

As pointed at above, direct public sector investment is likely to be important but contained to a relatively limited number of sectors. The key investment requirement on the public sector will relate to the renovation of buildings and the shift to decarbonised heating and cooling systems and transport modes across all levels of public administration and public services.

Indirectly, however, the public sector is likely to play a much more significant role in fostering the necessary levels of investment, as has been the case in the past. In past decades, public funding at the level of the EU and Member States has played a critical role in enabling the deployment of renewable electricity and the sharp reduction in the costs of solar, wind or other renewable sources of energy. Similarly, Member States have long provided support for the renovation of the residential housing stock. While such expenditures are accounted as current expenditure in government accounts, in essence they positive impact the capital stock of the economy as a whole.

Looking forward, public support will remain critical for the successful research, development and deployment at scale of the technologies that will underpin the necessary transformation of the EU economy. The need to ensure a fair transition will likely require continued targeted support from the public sector for the renovation of the residential building stock and the transition to carbon-free sources of heating and cooling. Similarly, support might be needed in transport in order to address concerns about transport poverty (section 2.4.1).

Similarly, direct public support will be essential for the decarbonisation of industry, the deployment of renewable hydrogen at scale and the development of carbon capture and storage/use. Finally, as evidenced recently with the adoption of the Inflation Reduction Act in the United States, the Temporary Crisis and Transition Framework for State aid in the EU, and the Commission proposal for the Net Zero Industry Act and Green Deal Industrial Plan, public support will be essential for the EU to build or strengthen its position in strategically and economically critical manufacturing sectors and their associated value chains, including wind and solar energy technologies, electrolyzers and fuel cells, batteries and electricity storage, heat pumps and carbon capture and storage. It is necessary to collectively address those challenges and coordinate national measures to avoid any risk of distorting competition and fragmenting the single market.

The extent to which public finances could be affected by the transition itself and by the policy options reviewed in this impact assessment will depend on a multiplicity of factors, many of which will be determined at the level of Member States. On the revenue side, there should be a base erosion for environmental taxes as the EU progresses towards climate neutrality. In 2021, environmental taxes represented about 2.2% of GDP or 5.5% of total government revenue from taxes and social contributions ⁽²⁹¹⁾, the bulk of which is linked to energy taxes linked to fossil fuels.

While no model-based assessment of direct and indirect public investment needs or impacts on total government revenues has been carried out, the pathways considered in

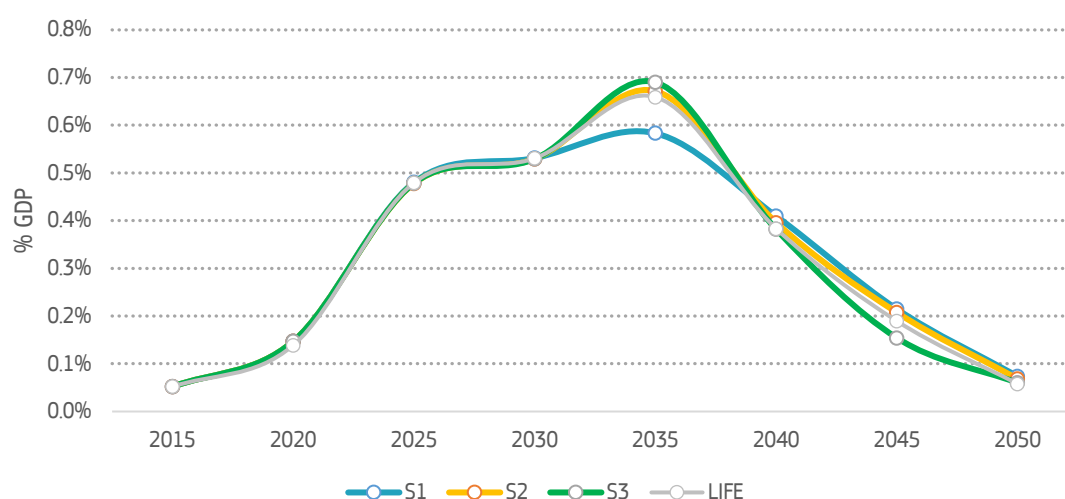
⁽²⁹¹⁾ [Environmental tax statistics](#)

this impact assessment provide an indication of the level of resources that the public sector could obtain from carbon pricing. While the use of these revenues will face competing demands, including to ensure a fair transition, they should be sizeable enough to also fund public support for investment.

Revenues from carbon pricing are very difficult to predict. While the emissions pathways for the sectors subject to the ETS (which will cover nearly the entire scope of domestic CO₂ emissions by 2030) are well defined in the scenarios, the price of ETS allowances is not a variable that the Commission predicts as such. The revenues from carbon pricing are nevertheless assessed on the basis of the carbon values that underpin the mitigation scenarios in the PRIMES model. These are not predictions of ETS carbon prices per se, but rather model-based carbon values necessary to achieve given levels of mitigation under the policy and techno-economic assumptions made in each scenario. Using such carbon values and based on the profile of CO₂ emissions over the transition period, carbon revenues are projected to peak around 2035. While carbon values are projected to increase beyond that time, the fall in CO₂ emissions will quickly erode the revenue base itself.

At their peak, revenues from carbon pricing could amount to close to 0.7% of GDP, which is significant in relation to the total energy investment needs for the transition to climate neutrality, and the contribution that may be required from the public sector (Figure 111). Between 2031 and 2050, total revenues from carbon pricing, based on the carbon values from the PRIMES model, would amount to about EUR 1 500 billion. This compares with cumulative energy system investment needs (excluding transport) of about EUR 13 100 billion, i.e., close to 11% of the total. Such projections are obviously very sensitive to assumptions regarding carbon values.

Figure 111: Carbon pricing payments



2.3. Competitiveness

2.3.1. Total energy system costs

Total energy system costs ⁽²⁹²⁾ include capital costs (for energy installations such as power plants and energy infrastructure, end-use equipment, appliances and energy related costs of transport), energy purchase costs (fuels, electricity and heat) and direct efficiency investment costs, the latter being also expenditures of capital nature. Capital costs (also for the equipment that is scrapped prematurely, *i.e.*, reflecting the costs of stranded assets) are expressed in annuity payments, calculated on the basis of sector-specific discount rates. For transport, only the additional capital costs for energy purposes (additional capital costs for improving energy efficiency or for using alternative fuels) are covered, but not other costs including the significant transport related infrastructure costs *e.g.*, related to rail to accommodate the increased rail capacity. Direct efficiency investment costs include additional costs for house insulation, double/triple glazing, control systems, energy management and for efficiency enhancing changes in production processes not accounted for under energy capital and fuel/electricity purchase costs. Unless specified, energy system costs do not include any disutility costs associated with changed behaviour, nor the cost related to the auctioning of allowances that leads to corresponding revenues that can be used in *e.g.*, in the social climate fund. Energy system costs are calculated *ex-post* after the model is solved ⁽²⁹³⁾.

⁽²⁹²⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

⁽²⁹³⁾ The calculated cost is influenced by the discount rate used. The discount rate of 10% is used to reflect in the perspective of the private investor faced with real world investment constraints. It is also applied *ex-post* to calculate system costs. The value of 10% is kept constant between modelling scenarios, to ensure comparability across scenarios. For planning investments, the model uses slightly different discount rates that are representative of investors' hurdle rates in the sector. A detailed explanation of this methodology is provided in the annex of the 2016 reference projection: https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en.

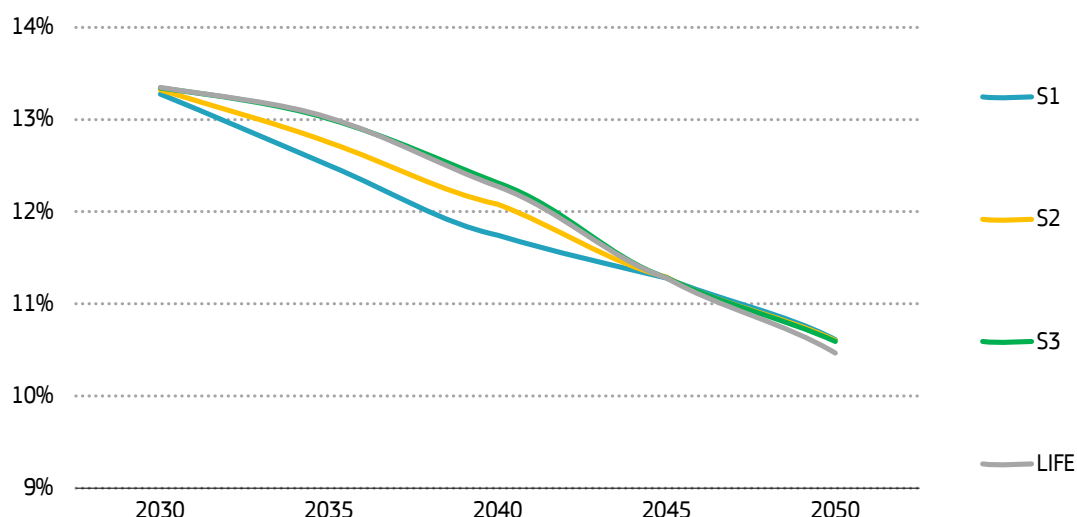
Table 34: Sectoral disaggregation of energy system costs (% difference vs. S2)

	2031-2040			2041-2050		
	S1 vs. S2	S3 vs. S2	LIFE vs. S3	S1 vs. S2	S3 vs. S2	LIFE vs. S3
EU27						
Total energy system costs	-2.1%	1.5%	-2.6%	-0.8%	0.1%	-4.6%
Industry	-3.4%	2.3%	-3.8%	-1.1%	0.6%	-8.7%
Tertiary	-0.5%	0.5%	-1.1%	0.2%	-0.3%	-2.7%
Residential	-1.4%	1.0%	-1.4%	-0.6%	0.2%	-2.0%
Transport	-3.1%	2.0%	-4.0%	-1.4%	-0.1%	-6.0%
Capital and direct efficiency investment costs	-1.8%	1.7%	-2.4%	-1.3%	1.2%	-3.4%
Industry	-3.2%	1.6%	-3.5%	-2.0%	0.8%	-8.1%
Tertiary	-2.1%	2.4%	-1.9%	-0.7%	1.0%	-1.9%
Residential	-1.9%	1.6%	-1.6%	-1.0%	0.9%	-0.4%
Transport	-1.1%	1.6%	-4.0%	-2.0%	2.0%	-7.5%
Energy purchases	-2.3%	1.3%	-2.7%	-0.4%	-0.7%	-5.5%
Industry	-3.4%	2.5%	-3.8%	-0.8%	0.5%	-8.9%
Tertiary	0.3%	-0.5%	-0.6%	0.8%	-1.0%	-3.1%
Residential	-0.7%	0.3%	-1.1%	0.0%	-0.8%	-4.3%
Transport	-3.9%	2.1%	-4.0%	-1.0%	-1.3%	-5.1%

Source: PRIMES.

Total energy system costs are relatively close across scenarios. In 2031-2040 they are 2.1% lower in the S1 scenario and 1.5% higher in S3 compared with the S2 scenario. In the residential sector, system costs are lower by 1.4% in S1 and higher by 1% in S3 compared with S2. While for the tertiary sector system costs are relatively similar across scenarios, they are 3.1% lower in S1 and 2% higher in S3 compared with S2 in 2031-2040. Capital costs and direct efficiency investment costs are increasing from S1 to S2 and S3 (-1.8% for S1 and +1.3% for S3 compared with S2 in 2031-2040), as higher ambition requires investments. For the tertiary sector, higher ambition and investments are also associated with lower energy purchases. This is illustrated by the fact that energy purchases are higher by 0.3% in S1 vs S2 and lower by 0.5% in S3 vs S1 for this sector in 2031-2040. For the following decade, the difference is even +0.8% and -1% respectively for S1 and S3 vs S2. As regards LIFE, energy system costs are lower than for the other scenarios in 2041-2050, as the increase in capital costs and direct efficiency investment costs is more than compensated by the 5.5% decrease in energy purchases compared with S3.

Figure 112: Total energy system costs as a percentage of GDP



Source: Commission based on the PRIMES model.

As a percentage of GDP, energy system costs decrease between 2030 and 2040 as GDP growth offsets the slight increase in system costs. As a result, the percentage of system costs over GDP decreases from 13.3% in 2030 to 11.7%-12.3% in 2040 and to 10.6% in 2050 for S1, S2 and S3 (10.4% for LIFE), as illustrated by Figure 112. In 2040, energy system costs represent a lower share of GDP in S1 (11.7%) than in S2 (12.1%) and S3 and LIFE (12.2-12.3%). Decreasing energy purchases are the main reason for the decrease in the share of energy system costs as a percentage of GDP.

Importantly, energy system modelling captures well the energy system costs but the costs associated with the transition are much broader and the challenge to address them much bigger. Rapid structural change will lead to the devaluation of equipment and other assets of several industries notably in fossil fuels extraction and processing. It will also force consumers to replace durable consumer goods and renovate houses more quickly. Workers with sector specific knowledge might lose part of their investment in training and education. These phenomena will have to be addressed by active labour market policies with greater demand on public expenditures.

2.3.2. Energy system costs and prices for industry

Table 35 shows energy costs for industry in relative terms compared to S1. Necessary implementation of low-carbon processes and energy efficiency improvements lead to stronger differentiation of capital-related costs across scenarios for energy-intensive industries in 2031-2040, with a difference of -3.4% for S1 and +1.7% for S3 compared with S2 (respectively -2.6% and +1.4% for non-energy intensive industries). Energy purchases increases across scenarios by 2040, with e-fuels driving the variation from S1 to S2 (-3.4% for S1 vs S2) and to S3 (+2.5% vs S2), in line with the level of decarbonisation and their role to substitute remaining fossil fuels. The part of the energy purchases that are linked to carbon revenues could also be channelled back toward industry through funding mechanisms encouraging the transition.

Table 35: Energy system costs for industry (% difference vs. S2)

EU27	2031-2040			2041-2050		
	S1 vs. S2	S3 vs. S2	LIFE vs. S3	S1 vs. S2	S3 vs. S2	LIFE vs. S3
<u>Total energy system costs</u>	-3.4%	2.3%	-3.8%	-1.1%	0.6%	-8.7%
Energy intensive industries	-4.4%	2.9%	-5.0%	-1.3%	0.3%	-11.5%
Non-energy intensive industries	-1.1%	0.9%	-0.9%	-0.3%	1.3%	-1.7%
<u>Capital and direct efficiency investment costs</u>	-3.2%	1.6%	-3.5%	-2.0%	0.8%	-8.1%
Energy intensive industries	-3.4%	1.7%	-4.5%	-1.8%	0.4%	-10.3%
Non-energy intensive industries	-2.6%	1.4%	-0.6%	-2.3%	1.9%	-1.9%
<u>Energy purchases</u>	-3.4%	2.5%	-3.8%	-0.8%	0.5%	-8.9%
Energy intensive industries	-4.7%	3.3%	-5.1%	-1.2%	0.3%	-11.9%
Non-energy intensive industries	-0.8%	0.8%	-1.0%	0.3%	1.1%	-1.7%

Note: Energy purchases include carbon revenues.

Source: PRIMES.

Table 36 shows the evolution of the average electricity prices for industry in 2040 and 2050. They remain fairly stable on the long run and are similar across all scenarios, reflecting the evolution of the electricity production system costs that evolve towards lower operating costs and higher capital-related costs. Low-carbon capacities substitute CO₂-emitting assets progressively driving the system to a more capital-based structure less exposed to fossil fuels prices.

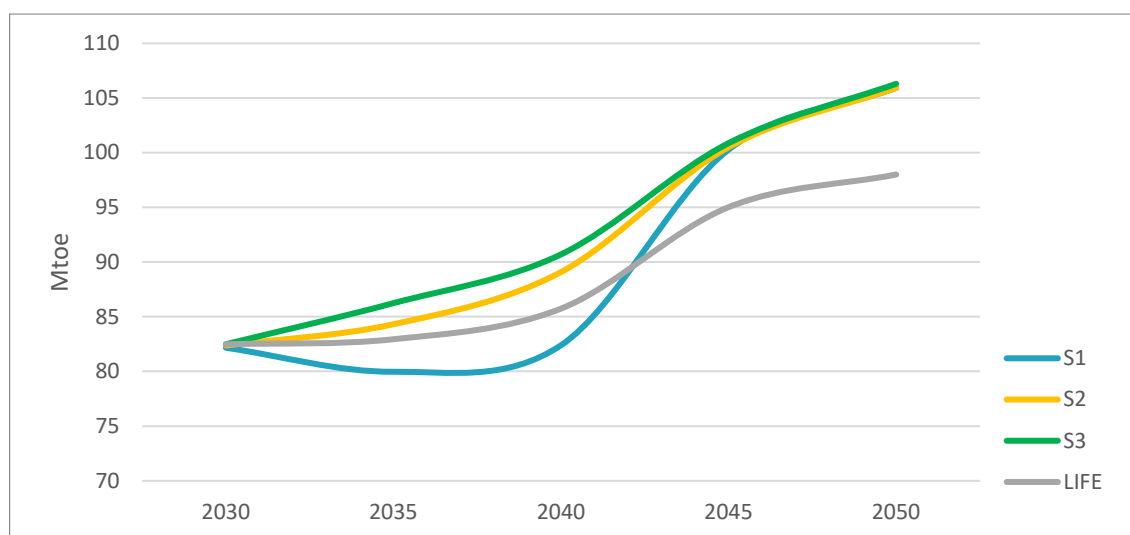
Table 36: Average final price of electricity for industry

EUR23/MWh	2030	2040	2050
	S1, S2, S3, LIFE	S1, S2, S3, LIFE	(S2)
Industry	133	130-131	131

Note: The electricity prices shown here reflects the evolution of the average electricity production costs to supply industry (i.e., considering their load profile) as well as the taxes applied to the sector.

Source: PRIMES.

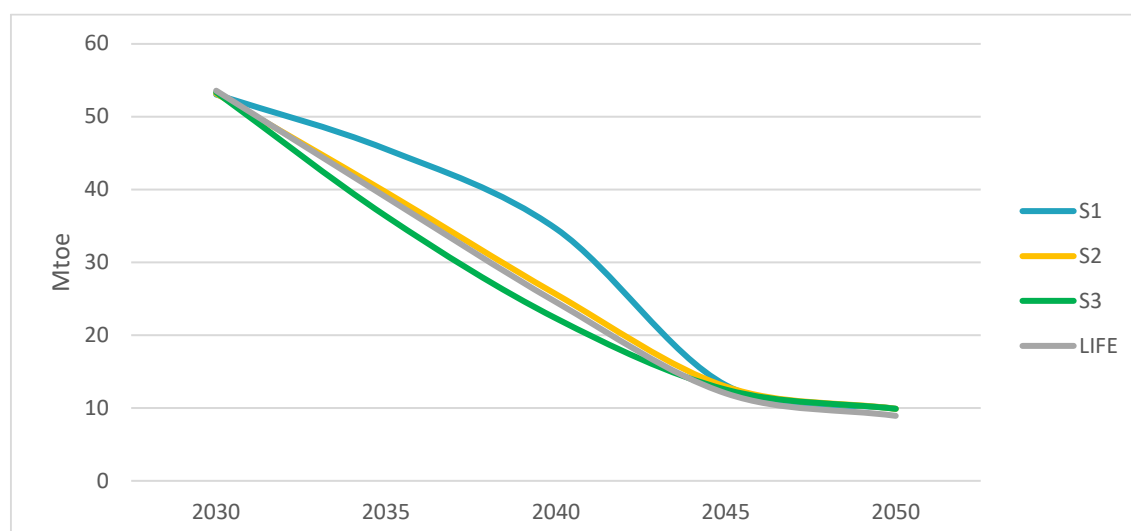
Figure 113: Consumption of electricity by industry



Source: PRIMES.

Figure 113 Shows also that electrification is delayed in the scenario S1 and has to accelerate significantly in 2040-2045 to catch up with the needed level by 2050. In scenario S1, the necessary increase of almost 20 Mtoe of electricity consumption by industry in only 5 years between 2040 and 2045 will put the system under pressure and will make it vulnerable to any possible delay in the deployment of some technologies such as renewables or storage.

Figure 114: Consumption of gas by industry



Source: PRIMES.

Figure 114 Shows that the increase in electricity consumption is concomitant with a swift decrease of gas consumption in industry. This is possible thanks to the investments made by industry in energy equipment, both in energy efficiency and in switching from fossil fuels to electricity. The phase-out of gas is slower in S1 compared with the other scenarios due to the lower investments made in energy equipment but catches up with the other scenarios by 2045. In all scenarios, gas consumption is reduced to around 10 Mtoe for all EU industry in 2050.

2.3.3. Energy system costs and prices for services

For services, total energy system costs are 0.5% lower in S1 and 0.5% higher respectively in S1 and S3 vs S2 for the decade 2031-2040 (Table 34). On the contrary, for the following decade 2041-2050, energy system costs are slightly higher in S1 (+0.2%) and lower in S3 (-0.3%) compared with S2. This illustrates that more ambitious scenarios lead to lower system costs for services. LIFE shows even lower cost, 2.7% less than in the S3 scenario in 2041-2050.

Increases in the capital-related cost in 2031-2040 are mostly related to investments to renovate buildings, with stronger energy efficiency related renovation effort in S3 (up to 2.4% more) than in S2, and which results in lower energy purchases expenses. Indeed, energy purchases are 0.5% lower in S3 compared with S2 in 2031-2040.

Table 37 shows the evolution of the average electricity prices for services in 2040 and 2050, which follow a similar trend as the prices for industry, remaining fairly stable on the long run and similar across all scenarios.

Table 37: Average final price of electricity for services

EUR23/MWh	2030	2040	2050
	S1, S2, S3, LIFE	S1, S2, S3, LIFE	(S2)
Services	255	249	255

Note: The electricity prices shown here reflects the evolution of the average electricity production costs to supply the services sector (i.e., considering its load profile) as well as the taxes applied to the sector.

Source: PRIMES.

2.3.4. Energy system costs and prices for transport

For transport too, total energy system costs are lower in S1 and higher in S3 compared to S2, respectively 3-3.1% and +2% for the decade 2031-2040 (see Table 34). LIFE leads to even lower system costs in 2041-2050, 6% lower than S3 in 2041-2050.

For LIFE, an increase in car occupancy due to higher use of shared mobility, as well as a stronger modal shift from passenger cars to public transport and rail explain the lower capital related costs in both decades in S2 and S3 compared with S1. Higher capital-related costs in S3 in 2031-2040 translate in lower energy purchases for this scenario in the following decade (-1.3% in S3 vs S2).

Table 38 shows the evolution of prices of electricity and gasoline for private transport in 2040 and 2050, which remaining stable on the long run.

Table 38: Energy prices for private transport in S2

EUR23/MWh	2030	2040	2050
Electricity*	226	222	225
Gasoline	215	279	280

*Note: *Average final price of electricity. The electricity prices shown here reflects the evolution of the average electricity production costs to supply the sector of private transport (i.e., considering its load profile) as well as the taxes applied to the sector.*

Source: PRIMES.

2.3.5. Costs related to mitigation of GHG emissions in the LULUCF sector and non-CO2 GHG emissions

2.3.5.1. Sectoral mitigation costs

Table 39 provides an overview of the average annual costs in the LULUCF sector and for non-CO2 emissions in the different scenarios. The costs are related to the implementation of abatement technologies or nature-based removal solutions. The technical available potential for nature-based removals and mitigation measures differs between the two decades, leading to varying annual costs across decades, as the entire potential up to the respective maximum carbon value is implemented.

Table 39: Costs related to GHG emissions mitigation in LULUCF and non-CO2

Average annual costs [EUR 2023 billion/year]	2031-2040			2041-2050			2031-2050		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
Mitigation of LULUCF GHG emissions	1.1	2.5	2.5	1.6	2.8	2.8	1.3	2.7	2.7
Mitigation of non-CO2 GHG emissions	0.0	0.7	3.4	3.9	4.1	5.0	2.0	2.4	4.2
- of which in the agriculture sector	0.0	0.4	3.2	3.8	3.9	4.8	1.9	2.2	4.0

Note: All costs are expressed in EUR2023.

Source: GLOBIOM, GAINS.

S1 does not assume specific LULUCF and non-CO2 policies in 2040, showing smaller mitigation costs for the 2031-2040 period. Both sectors have to contribute to meeting climate neutrality in 2050 also in that scenario, which entails some mitigation action and associated costs in the last decade 2041-2050.

For LULUCF, additional nature-based removals such as improved forest management, afforestation or rewetting are applied in S2 and S3 by 2040. The associated average annual cost in these scenarios amount to EUR 2.5 billion in 2031-2040 and EUR 2.8 billion in 2041-2050.

The average annual costs associated to mitigation of non-CO2 emissions over the 2031-2040 period are around EUR 0.7 billion per year in S2 and around EUR 3.4 billion per year in S3. Over the 2041-2050 period, the average annual costs are higher than in the previous decade: EUR 3.9 billion in S1, EUR 4.1 billion in S2, and EUR 5 billion in S3. Most of the annual mitigation costs take place in the agriculture sector, which represents the bulk of the unabated non-CO2 GHG emissions after 2030. The mitigation costs of the sector are reflected in the macro-economic analysis presented in section 2.3.6.

2.3.5.2. The LIFE variant

The LIFE variant shows limited impacts on the agricultural sector. An analysis with the CAPRI model shows a decrease in 2040 by -5.4% ⁽²⁹⁴⁾ of the total revenues, most pronounced in meat production (-12% to -20%), while other activities such as vegetables and permanent crops benefit (+12%).

The LIFE variant demonstrates that freed up land from fodder production could be used for additional forest management land, which may counterbalance the overall decrease with additional income opportunities for example through other agricultural products, carbon farming, payment for ecosystem services (PES), and other activities.

⁽²⁹⁴⁾ Consumer prices for products from organic agriculture are conservatively assumed to be similar to conventional agricultural products. However lower outputs of products or higher quality of products may lead to higher producer prices, partly buffering the losses. Also, consumers' budgetary savings for food, which result from changing diets, which may be reinvested into food products with higher quality are not considered.

2.3.6. Sectoral output and international trade

As highlighted in section 2.4.3, the impacts of the climate and energy transition and the 2040 target need to be assessed while bearing in mind a general context that is affected by a multiplicity of factors, including the increased share of services in mature EU economies, digitalisation, the projected gradual decline in the EU population and the falling share of the EU in global GDP. Abstracting from such changes, the level of ambition in 2040 does nevertheless impact sectoral output in somewhat contrasted manners.

As expected, a higher level of ambition is associated with a bigger decline in the output of fossil fuel industries by 2040. Output under S3 is about 6% lower compared to S2 in 2040 (fragmented action scenario), which already entails a sharp drop in the sector's activity relative to current levels (Table 40). The sector's output is higher under S1 than S2, but only temporarily as the levels converge by 2050. The output of energy intensive industries is also projected to be affected by a higher level of ambition. The impact under S3 is small at -0.2% (relative to S2) in 2040 and 2050 under the fragmented action scenario. The lower level of ambition under S1 only generates a small positive impact of +1.4% in 2040 and +0.2% in 2050, relative to S2 (fragmented action). It must be noted also that the output of energy intensive industries is projected to continue growing across all scenarios in future decades. The growth rate between 2015 and 2040 is projected to range between 25.5% and 27.6%.

It must be noted also that under the global action scenario, the output of energy intensive industries is higher than under the lower ambition S1 scenario both for S2 and S3, with S3 yielding only a marginally lower output level than S2. This is driven by the early adoption of decarbonised technologies in EU industry relative to the rest of the world, which increases its competitiveness in a setting where the rest of the world also needs to invest in low-carbon processes. In addition, the decarbonisation of production processes in energy-intensive industries and the associated fall in fossil fuel inputs are susceptible to shelter EU industry from potential shocks on fossil fuel prices. They would indeed be impacted by such shocks to a lower extent than competitors elsewhere and less advanced in their decarbonisation process.

Table 40: Sectoral output, deviation vs. S2 (%)

	S1 fragmented		S1 global		S3 fragmented		S3 global	
	2040	2050	2040	2050	2040	2050	2040	2050
Fossil fuel industries	10.2%	-0.3%	15.0%	6.4%	-5.6%	-0.7%	-5.2%	-1.0%
Energy intensive industries	1.4%	0.2%	-0.3%	-2.3%	-0.2%	-0.2%	-0.2%	-0.3%
Transport equipment	0.7%	0.2%	0.6%	-0.5%	-0.5%	-0.1%	-0.4%	-0.1%
Other equipment goods	0.5%	0.2%	-1.3%	-4.9%	0.2%	-0.1%	0.3%	-0.1%
Consumer goods industries	0.7%	0.1%	-0.8%	-3.6%	-0.6%	0.0%	-0.8%	-0.1%
Transport	2.0%	0.1%	1.0%	-3.1%	-1.0%	-0.2%	-1.1%	-0.1%
Construction	0.0%	0.2%	0.0%	0.3%	0.5%	-0.1%	0.6%	-0.1%
Market services	0.5%	0.1%	1.1%	1.5%	-0.2%	0.0%	-0.2%	0.0%
Non-market services	0.2%	0.0%	0.4%	0.3%	-0.2%	0.0%	-0.2%	0.0%
Agriculture	2.0%	0.1%	1.0%	-3.1%	-1.0%	-0.2%	-1.1%	-0.1%
Forestry	-10.9%	-1.0%	-13.1%	-6.8%	-0.5%	-2.2%	-1.4%	-2.3%
Memo:								
GDP	0.5%	0.1%	0.6%	0.2%	-0.2%	-0.1%	-0.2%	-0.1%

Source: JRC-GEM-E3.

Other sectors that are likely to be affected by a higher level of ambition include transport (road, maritime and air), equipment goods and consumer goods industries, which would be impacted by the overall decline in GDP and private consumption. Under a global action setting, these sectors could actually be better off with a higher level of climate ambition as global demand for equipment goods linked to decarbonisation increases and as the EU gains competitiveness and export market shares, thereby also driving up transport activity (S2 and S3 both have a higher level of output under a global action setting than S1 in 2050, with S3 only marginally lower than S2). Agriculture is mildly affected by higher levels of ambition, with output only 2% higher under S1 than under S3 in 2040, and 1% lower under S3 than under S2. In contrast, output in the forestry sector in 2040 is significantly higher under the higher ambition scenarios than under S1 as a result of the increased demand for biomass. By 2050, the differences are much less significant as biomass uses tend to converge across scenarios.

In terms of output shares, it is assumed that the past trend towards a more services-oriented economy continues in the coming decades. Output in key industrial sectors, including energy intensive industries, is projected to grow significantly between 2015 and 2040 or 2050, and the growth rates across sectors is affected by the level of climate ambition for 2040 only to a very limited extent, with output levels in 2040 and 2050 broadly unchanged across the three scenarios (Table 41).

Table 41: Sectoral output, % change vs. 2015

	S1			S2		S3	
	2030	2040	2050	2040	2050	2040	2050
Fossil fuel industries	-32.9%	-59.4%	-73.0%	-63.1%	-72.9%	-65.2%	-73.1%
Energy intensive industries	17.6%	27.6%	39.7%	25.8%	39.4%	25.5%	39.1%
Transport equipment	15.3%	30.8%	43.3%	30.0%	43.1%	29.4%	43.0%
Other equipment goods	21.5%	38.7%	58.6%	38.0%	58.3%	38.3%	58.1%
Consumer goods industries	12.6%	21.3%	31.4%	20.4%	31.3%	19.7%	31.2%
Transport	25.7%	44.5%	68.1%	41.7%	67.9%	40.2%	67.6%
Construction	27.9%	47.9%	70.7%	47.9%	70.3%	48.7%	70.2%
Market services	22.6%	40.5%	62.6%	39.9%	62.4%	39.5%	62.4%
Non-market services	21.3%	38.3%	59.7%	38.0%	59.7%	37.8%	59.7%
Agriculture and forestry	9.7%	33.6%	47.8%	36.6%	47.4%	36.3%	46.3%
Memo: GDP	22.8%	40.6%	62.1%	39.9%	61.9%	39.5%	61.8%

Source: JRC-GEM-E3.

The secular trend towards a relatively higher growth rate in services than in industry nevertheless implies that the share of energy intensive industries, consumer goods industries and transport equipment is projected to decline across scenarios over the coming decades, with a corresponding increase in the share of market services. The share of fossil fuel industries in total sectoral output would become negligible by 2040 already across scenarios, at about 0.5% of the total (Table 42).

Table 42: Sectoral output, share of total (%)

	S1				S2		S3	
	2020	2030	2040	2050	2040	2050	2040	2050
Fossil fuel industries	1.6%	1.1%	0.6%	0.3%	0.5%	0.3%	0.5%	0.3%
Energy intensive industries	10.4%	9.7%	9.3%	8.9%	9.2%	8.9%	9.2%	8.9%
Transport equipment	3.8%	3.5%	3.5%	3.4%	3.5%	3.4%	3.5%	3.4%
Other equipment goods	6.3%	6.2%	6.3%	6.2%	6.3%	6.2%	6.3%	6.2%
Consumer goods industries	6.0%	5.7%	5.4%	5.1%	5.4%	5.1%	5.4%	5.1%
Transport	4.6%	5.1%	5.2%	5.3%	5.1%	5.3%	5.1%	5.3%
Construction	7.3%	7.2%	7.3%	7.3%	7.3%	7.3%	7.4%	7.3%
Market services	38.3%	39.3%	39.6%	39.9%	39.6%	39.9%	39.6%	39.9%
Non-market services	14.7%	15.0%	15.0%	15.1%	15.1%	15.1%	15.1%	15.1%
Agriculture and forestry	1.8%	1.7%	1.8%	1.7%	1.8%	1.7%	1.8%	1.7%
Other	5.2%	5.5%	6.0%	6.7%	6.1%	6.7%	6.1%	6.7%

Source: JRC-GEM-E3.

The extent to which SMEs are affected by the trends described above is in good part determined by the sectors of activity in which SMEs are most prominent. As indicated in Table 27 (section 2.2.3), around 66% of SMEs are active in services sectors and close to 55% of their total gross value added and employment are generated in services. Another 20% of SMEs and 16-18% of gross value added and employment are accounted for by the construction sector. Overall, SMEs therefore seem to be well positioned to gain from the projected continued rise in the share of market services in the economy and from a very resilient construction sector. In contrast, a very small proportion of SMEs are involved in fossil fuel industries, mining and extraction or energy intensive industries, and they account for a very small share of the gross value added and employment of the SME sector.

The impact of the scenarios on EU businesses, particularly on competitiveness, can also be viewed through the lens of their impact on the EU's export market shares across a range of sectors. The EU is not only the world's largest economy, but also the largest trading block, with a share of around 17% of global exports currently (Table 43). Export market shares are somewhat larger than this overall figure for energy intensive industries and significantly larger for transport equipment and market services. Given that the EU economy is projected to grow slower than most other large economies in the world, mainly as a result of contrasted population trends and the maturity of its economy, the share in global exports is set to decline in the coming decades. This pattern is unlikely to be much affected by the degree of climate ambition by 2040 and the three main scenarios show very similar patterns for all key sectors of the economy.

A more relevant factor concerning export market shares lies in the degree to which the rest of the world is projected to step up efforts to mitigate greenhouse gas emissions. A higher degree of ambition outside the EU (global action) is projected to increase the EU's export market shares across the board compared to a scenario with lower ambition (fragmented action). The benefits of a "first-mover" advantage for EU exporters is significant for most sectors, with the exception of market services, where decarbonisation is a less relevant factor.

Table 43: EU shares in global exports (% of total)

	Fragmented					Global		
	2015	2020	2030	2040	2050	2030	2040	2050
Scenario 3								
All exports	17.8%	17.2%	16.8%	16.1%	15.9%	17.6%	16.6%	16.8%
Energy intensive industries	19.1%	19.7%	18.3%	17.1%	16.8%	19.8%	17.6%	17.5%
Transport equipment	28.7%	28.4%	26.4%	25.0%	24.1%	26.9%	25.0%	24.3%
Other equipment goods	22.1%	21.1%	19.2%	17.1%	16.7%	21.1%	17.8%	18.7%
Consumer goods industries	15.0%	14.1%	13.4%	12.3%	12.0%	14.1%	13.0%	13.6%
Market services	25.2%	23.9%	23.7%	22.7%	21.5%	21.4%	21.7%	19.1%
Agriculture and forestry	8.2%	7.6%	7.8%	6.7%	6.0%	9.2%	7.1%	6.3%

Source: JRC-GEM-E3.

Besides affecting domestic businesses, the level of ambition for 2040 is susceptible to affect partner countries via trade channels, as the EU is also a major importer, with a share in world imports similar to its share in world exports of close to 18%. As is the case on the export side, this share is set to decline in the coming decades with higher economic growth rates elsewhere, but the EU will remain a major global trading partner, also on account of its openness and number of free trade agreements. As is again the case on the export side, there is very little differentiation across scenarios (level of ambition) in terms of the absolute amounts of EU imports or their share in global imports. The changing nature of the EU economy, however, implies that the share of the EU's imports in global imports could decline faster for some sectors than for others. In particular, the EU's share of imports of goods from energy intensive industries in world trade could decline significantly, while its share in global imports of consumer goods and market services could remain broadly stable. In turn, the EU's place as an importer of agriculture and forestry products is projected to increase in relative terms (Table 44).

As is the case on the export side, a bigger impact is projected to arise depending on whether the rest of the world implements a higher degree of climate ambition (global action) or not (fragmented action). Under a global action scenario, the EU's share in world imports is projected to be slightly higher than under a fragmented action scenario overall, with a most significant positive impact in terms of market services. As far as

more carbon-intensive products are concerned (e.g., energy intensive industries, transport equipment or consumer goods), the EU would account for a smaller share of global imports under a global action scenario than under a fragmented action scenario. This is the converse of the “first mover advantage” highlighted above, as trading partners would be in a situation of “second mover” under a global action scenario, which would reduce imports by the EU as domestic producers gain in terms of competitiveness.

Table 44: EU shares in global imports (% of total)

	Fragmented					Global		
	2015	2020	2030	2040	2050	2030	2040	2050
Scenario 3								
All imports	17.6%	17.3%	16.4%	15.7%	15.4%	16.4%	15.8%	15.7%
Energy intensive industries	14.8%	14.4%	12.8%	12.0%	11.2%	12.2%	11.8%	11.0%
Transport equipment	11.2%	11.6%	10.7%	10.6%	10.1%	10.7%	10.7%	10.3%
Other equipment goods	13.4%	13.1%	12.3%	11.8%	10.9%	11.7%	11.5%	10.4%
Consumer goods industries	18.7%	18.9%	18.6%	18.5%	18.4%	18.2%	18.1%	17.3%
Market services	29.6%	31.0%	30.1%	29.6%	29.9%	31.8%	30.1%	31.4%
Agriculture and forestry	17.6%	17.3%	16.3%	18.5%	19.7%	15.5%	17.3%	17.4%

Source: JRC-GEM-E3.

The extent to which the EU’s trade partners may be affected by the transition and the level of ambition for 2040 also depend to a significant extent on the type of goods that the EU imports, and how this may change over time and across scenarios. Table 45 provides further detail on the projected structure of EU imports. Fossil fuels (coal, crude oil, oil and gas) currently represent an important share of the EU’s total imports. The share and absolute value of such imports are projected to decline sharply as the EU decarbonises its energy system (Section 2.6.1) across all scenarios. A higher level of ambition (S3) is associated with an even faster drop than a lower level of ambition (S1 and S2), but the trend is clear and inevitable with fossil fuel imports projected to account for no more than 3% of the EU’s total imports by 2050 (Table 45). Although trade in the raw materials critical for the climate and energy transition is not captured explicitly in the JRC-GEM-E3 macro-economic model, the EU is likely to import a higher level of such goods as the transition progresses (Section 1.9.4).

The share of imports of goods from energy intensive industries and transport equipment in total EU imports is projected to decline across scenarios, but this is likely mostly due to factors unrelated to the climate transition and the level of ambition for 2040, such as the maturity of the economy and the gradual decline in the EU population in the long term. In contrast, the share of imports of consumer goods, equipment goods, market services and agriculture and forestry in total EU imports could increase over the coming decades. The share of market services, in particular, could rise sharply as it offsets the falling share of fossil fuel imports. Finally, the contrast between trends under fragmented action vs. global action scenarios are confirmed by figures regarding sectoral shares in EU total imports.

Table 45: Structure of EU imports (% of total)

	Fragmented					Global		
	2015	2020	2030	2040	2050	2030	2040	2050
Scenario 3								
Coal	0.5%	0.3%	0.2%	0.0%	0.0%	0.1%	0.0%	0.0%
Crude oil	10.5%	8.7%	6.0%	2.9%	1.6%	6.7%	2.8%	1.5%
Oil	2.4%	2.5%	2.4%	1.2%	0.9%	2.0%	1.1%	0.8%
Gas	2.2%	2.6%	1.3%	0.7%	0.4%	1.4%	0.7%	0.4%
Energy intensive industries	17.5%	17.5%	16.1%	15.6%	14.5%	15.5%	15.4%	14.2%
Transport equipment	4.8%	4.9%	4.6%	4.5%	4.1%	4.6%	4.6%	4.1%
Other equipment goods	8.3%	9.1%	10.0%	11.2%	11.5%	9.5%	11.0%	11.0%
Consumer good industries	10.3%	10.5%	11.0%	11.6%	11.8%	10.7%	11.3%	10.9%
Electric goods	11.1%	11.5%	11.5%	11.6%	11.0%	11.3%	11.5%	10.9%
Market services	18.2%	19.9%	22.1%	24.0%	26.3%	23.8%	25.0%	28.5%
Agriculture and forestry	2.9%	2.8%	3.0%	3.7%	4.0%	2.8%	3.7%	4.1%
Other	11.2%	9.7%	11.8%	13.0%	13.9%	11.6%	12.9%	13.6%

Source: JRC-GEM-E3.

How such trends in the composition of EU imports and in the size of the EU in global imports could affect trading partners will depend on the composition of their own exports and the extent to which they depend on the EU as a market for their goods and services. The JRC-GEM-E3 model cannot be the basis for a detailed assessment of how individual countries and trade in specific commodities could be affected by the transition to climate neutrality and the level of ambition for the 2040 target as it lacks the level of granularity required to do so. It nevertheless provides useful indications of what could be the impact of the transition in terms of broad trade aggregates and possible trends.

The sharp decline in fossil fuel imports over the course of the transition will affect the Middle East most negatively, together with other major exporters of fossil fuels elsewhere. The share of imports from the Middle East in total EU imports could fall by as much as 2 percentage points between 2015 and 2050 under all scenarios (Table 46). This trend could potentially be reduced if trade in RFNBOs were to pick up, though the modelling does not suggest that the latter could compensate for the fall in exports of fossil fuels ⁽²⁹⁵⁾.

In contrast, the modelling indicates that Africa could benefit from an increase in the share it represents as the place of origin for total EU imports. The increase in the continent's share as the origin of EU imports could be significant for primary goods, namely crops, livestock and forestry, but the modelling shows a positive evolution for other sectors, including energy intensive goods and market services. Overall, the rising share of Africa in EU imports and the increase in imports over time could lead total EU imports from Africa to more than double between 2020 and 2050.

The difference across scenarios is minimal, as the trends are driven by the overall climate and energy transition and wider economic considerations. Similarly, the geographic origin of EU imports does not change much between the fragmented and global action scenarios, at least as far as total imports are concerned. This is likely linked to the fact that

⁽²⁹⁵⁾ This was analysed in more details in the Joint Research Centre's [Global Energy and Climate Outlook 2022: Energy trade in a decarbonised world](#).

all EU partners are required to significantly step up mitigation efforts under the global action scenario, which means they are all similarly affected. One can notice, however, that the share of imports from the OECD slightly increases between the fragmented and global action scenarios, which is likely linked to their lower initial carbon intensity than other regions, including as far as energy intensive industries are concerned.

Table 46: Origin of EU imports by main trading partners (% of total EU imports, S3)

	Fragmented					Global		
	2015	2020	2030	2040	2050	2030	2040	2050
<u>Total imports</u>								
Africa	6.9%	6.8%	7.5%	8.7%	10.2%	7.8%	8.7%	10.3%
China	15.2%	16.2%	17.5%	17.5%	16.4%	16.8%	17.1%	16.1%
India	3.0%	3.2%	4.3%	5.0%	5.6%	4.4%	5.0%	5.5%
Latin America	4.7%	4.4%	4.6%	4.8%	4.9%	4.7%	4.8%	4.8%
Middle East	5.4%	5.2%	4.4%	4.3%	4.3%	4.5%	4.5%	4.9%
OECD	44.2%	43.5%	42.6%	41.7%	40.6%	43.0%	42.2%	41.4%
Other Asia	9.3%	9.4%	10.4%	11.5%	12.3%	10.6%	11.6%	11.7%
Rest of Euro-Asia	11.3%	11.3%	8.6%	6.6%	5.7%	8.2%	6.1%	5.4%
<u>Crops, livestock and forestry</u>								
Africa	18.7%	19.8%	22.1%	26.7%	30.9%	24.0%	29.9%	38.5%
China	4.4%	4.7%	5.1%	4.7%	4.3%	4.8%	4.6%	7.2%
India	2.6%	2.7%	3.5%	3.9%	4.5%	3.5%	3.1%	3.4%
Latin America	23.6%	22.7%	21.4%	19.4%	18.0%	23.4%	20.1%	17.9%
Middle East	3.3%	3.5%	3.3%	3.6%	3.5%	3.5%	4.3%	4.3%
OECD	29.6%	28.7%	28.1%	25.3%	23.4%	23.6%	22.3%	17.1%
Other Asia	6.4%	6.5%	7.0%	6.9%	6.8%	7.8%	5.7%	2.4%
Rest of Euro-Asia	11.3%	11.3%	9.6%	9.6%	8.6%	9.3%	10.0%	9.2%
<u>Energy intensive goods</u>								
Africa	6.1%	6.5%	7.4%	8.4%	8.1%	8.2%	8.8%	8.1%
China	9.3%	9.8%	10.6%	10.6%	10.6%	9.6%	10.5%	10.3%
India	2.3%	2.4%	2.7%	2.9%	2.9%	2.5%	2.8%	2.7%
Latin America	5.5%	4.9%	5.2%	5.3%	5.5%	5.7%	5.4%	5.5%
Middle East	4.7%	4.4%	3.9%	4.0%	4.0%	3.7%	4.1%	4.1%
OECD	56.0%	55.8%	54.7%	53.2%	53.0%	59.1%	55.0%	56.1%
Other Asia	4.7%	5.1%	6.0%	7.1%	8.5%	6.5%	7.4%	8.7%
Rest of Euro-Asia	11.4%	11.2%	9.4%	8.5%	7.4%	4.7%	6.0%	4.6%
<u>Market services</u>								
Africa	2.3%	2.5%	2.9%	3.7%	4.5%	2.5%	3.5%	4.2%
China	11.5%	12.4%	13.5%	13.2%	12.4%	14.2%	12.4%	10.6%
India	6.9%	7.0%	9.0%	9.9%	10.9%	10.6%	10.0%	11.9%
Latin America	4.2%	4.0%	4.1%	4.2%	4.2%	3.6%	4.1%	4.1%
Middle East	5.8%	5.8%	4.6%	5.0%	5.1%	6.7%	7.6%	9.1%
OECD	53.8%	52.2%	50.2%	48.0%	46.5%	46.6%	46.7%	42.6%
Other Asia	11.6%	11.8%	12.4%	12.9%	13.4%	11.1%	12.4%	14.6%
Rest of Euro-Asia	4.0%	4.3%	3.2%	3.1%	3.0%	4.8%	3.3%	2.9%

Source: JRC-GEM-E3.

The cost-efficient decarbonisation relies on the deployment of net-zero technologies with varying but sufficient degree of maturity to be used on a large scale. The maturity of technologies is an important driver of the projected portfolio of net-zero technologies. In

recent years, pressing innovation gaps have been addressed which resulted in significant improvements of the technology readiness ⁽²⁹⁶⁾. For the bulk of net-zero technologies needed to reach the 2040 targets, the Technology Readiness Level (TRL) already amounts to at least 8 (out of 9) which means that they are in an advanced deployment stage. ⁽²⁹⁷⁾

DAC is at the lower end of the deployment stage having a TRL of 7. Bioenergy with carbon capture and storage (BECCS) is the only technology that has a TRL of 5-6 (“Technology demonstrated in relevant environment”) indicating that is not fully established. However, there are already a variety of BECCS demonstration projects in Japan, Norway, Sweden and the United Kingdom.

Due to their relatively low maturity, DAC and BECCS come into play only between 2030 and 2040 allowing the technology to be further developed over the coming years. In 2040, DAC and BECCS is projected to capture 16 MtCO₂ (S1) to 155 MtCO₂ (S3) making up around 0.3% (S1) to 3.3% (S3) of 1990 total GHG emissions. The S3 scenario anticipates decarbonisation via DAC up to 2040.

2.4. Social impacts and just transition

2.4.1. Fuel expenses, energy and transport poverty, distributional impacts

Energy-related expenses ⁽²⁹⁸⁾ represent a high share of total expenditure for a large proportion of EU households, in particular middle- and low-income households. The recent increase in energy prices has generated major negative social impacts and increased the rates of energy (and transport) poverty. Assessing the implications of the energy transition and the 2040 policy options on energy system costs for households is therefore of critical importance.

The following assessment is based on model results, reflecting the current legislation and understanding of the possible evolution of technologies and costs. This assessment will feed into the development of the future policy framework and support measures in the coming years to meet the 2040 target and will determine the actual costs and how they impact individuals, regions and society.

The cost structure is characterised by an increase of capital-related costs in purchasing more efficient appliances and investment in enhancing the energy insulation of dwellings. This increase allows savings on energy purchases despite the assumed increasing fossil fuels international prices over time and the impact of ETS revenues and diffusion of new low carbon fuels.

The relative importance of energy-related cost for households in private consumption is projected to decline in 2041-2050 compared to 2031-2040, due to the decreasing importance of fuel purchases in all scenarios. For instance, the share of private

⁽²⁹⁶⁾ IEA (2023): “Net Zero Roadmap. A Global Pathway to Keep the 1.5°C Goal in Reach”

⁽²⁹⁷⁾ The TRL evaluation is based on the EU’s Clean Energy Technology Observatory (CETO).

⁽²⁹⁸⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

consumption dedicated to energy-related expenditures decreases from 8.1%-8.2% to 7.1% between the decades 2031-2040 and 2041-2050. Anticipated action in S3, driven by a larger direct efficiency investments (see section 2.2), also translates in a slightly higher share of energy-related expenses in S3 in 2031-2040, where it represents 8.2% of private consumption as opposed to 8% in S1 and 8.1% in S2. Electricity prices are projected to be very similar across both periods in real terms.

Table 47: Average annual energy system costs as % of private consumption and average final price of electricity for households in the residential sector

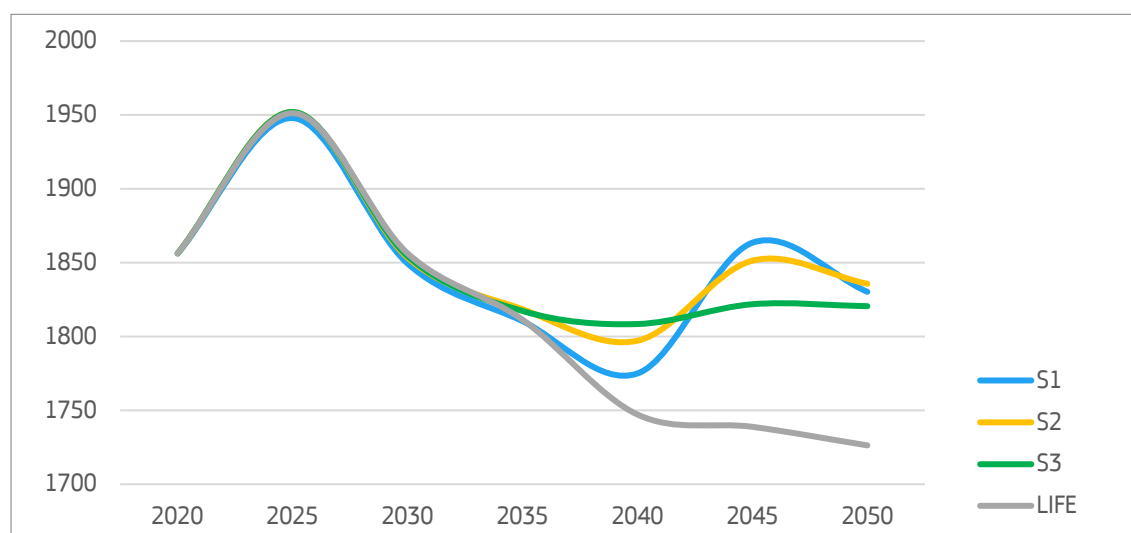
Average across all income categories	2031-2040				2041-2050			
	S1	S2	S3	LIFE	S1	S2	S3	LIFE
Total (% of private consumption)	8.0%	8.1%	8.2%	8.1%	7.1%	7.1%	7.1%	7.0%
Capital related costs*	4.5%	4.6%	4.7%	4.6%	4.1%	4.1%	4.1%	4.1%
Energy purchases**	3.4%	3.5%	3.5%	3.4%	3.0%	3.0%	3.0%	2.8%
Low Income Categories	S1	S2	S3	LIFE	S1	S2	S3	LIFE
Total (% of private consumption)	<u>14.0%</u>	<u>14.3%</u>	<u>14.4%</u>	<u>14.2%</u>	<u>12.0%</u>	<u>12.0%</u>	<u>12.1%</u>	<u>11.8%</u>
Capital related costs	7.8%	7.9%	8.1%	7.9%	6.5%	6.5%	6.6%	6.6%
Energy purchases	6.3%	6.3%	6.3%	6.3%	5.5%	5.5%	5.4%	5.2%
Electricity price (EUR/MWh)***								
Residential	288	288	288	288	289	290	290	290

Note: * includes purchase of appliances and cost of renovation. ** It does not include carbon revenues.

*** Average final price of electricity. The electricity price shown here reflects the evolution of the average electricity production cost to supply the sector (i.e. considering its load profile) as well as the taxes applied to the sector.

Source: PRIMES.

Figure 115: Annual fuel purchasing expenses in buildings per low-income household

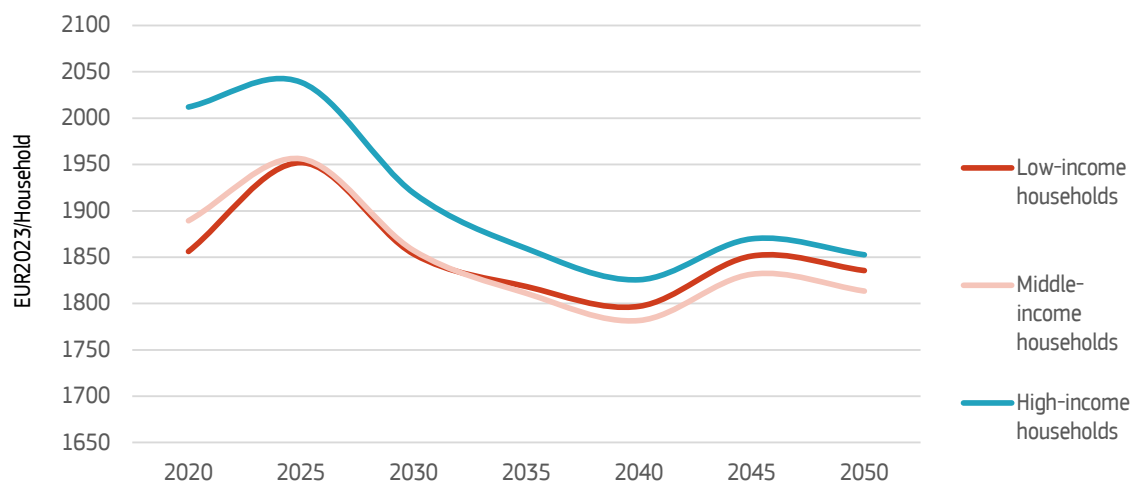


Source: PRIMES model.

Figure 116 illustrates that improved insulation leads to a decrease in annual fuel purchasing expenses, in particular for high-income households. As a result, the gap between expenses of different types of households closes and the level of expenses is closer for all categories in 2040 than in 2020. Low-income households have higher annual fuel expenses than middle-income households as of 2030, due to their dwellings

not being as well insulated, despite significant efforts in renovation. For all households, fuel expenses are on a downward trend as of 2025 (despite a temporary increase in 2045), illustrating that investments in renovation of buildings pay off.

Figure 116: Annual fuel purchasing expenses in buildings in S2

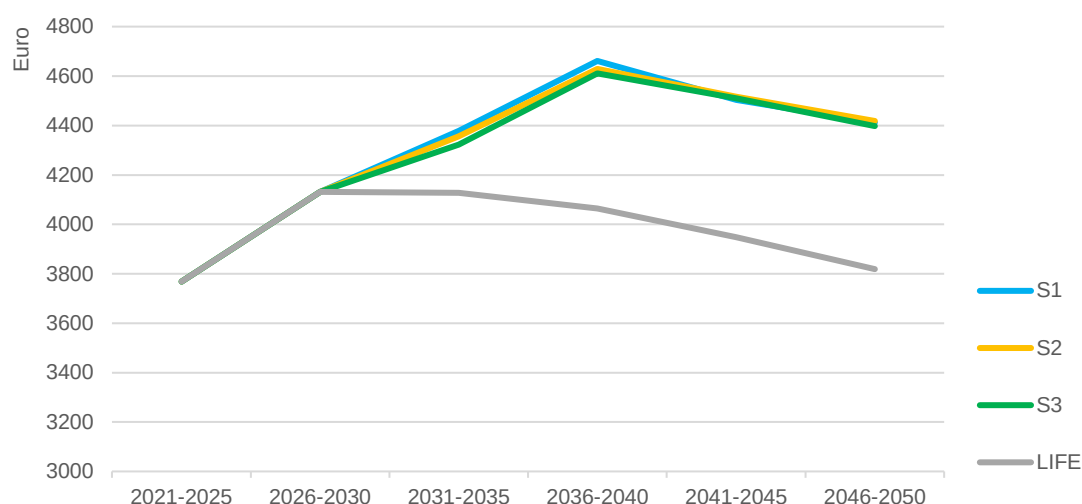


Source: PRIMES model.

Following the post-COVID recovery, annual expenditures for private vehicles⁽²⁹⁹⁾ are projected to increase in all scenarios by 2040, from around EUR 3770 per year per household during 2021-2025 to around EUR 4610-4660 per year per household in the S1, S2 and S3 scenarios and around EUR 4065 in LIFE during 2036-2040 (see Figure 117). These changes are driven by the increase in the capital expenditures for the replacement of the vehicle fleet, including for meeting the CO2 standards regulation. Post-2040, households' expenditures for private vehicles are projected to remain stable or slightly go down. In LIFE, the annual expenditures for private vehicles are lower, mostly because of lower activity by passenger car (expressed in passenger-km) due to modal shift to active modes and collective transport, and because of higher use of shared mobility. Expressed as share of private consumption, annual expenditures for private vehicles are however projected to be stable over time until 2040 and decrease after 2040, from around 7.5-8.5% during 2021-2025 and 2036-2040 to 6-7% during 2046-2050. This is mainly due to the sustained increase in the private consumption over time following the post-COVID recovery.

⁽²⁹⁹⁾ The annual expenditures for private vehicles cover the total expenditures to purchase vehicles as well as the fixed operation costs (excluding taxes).

Figure 117: Annual expenditures for private vehicles per household

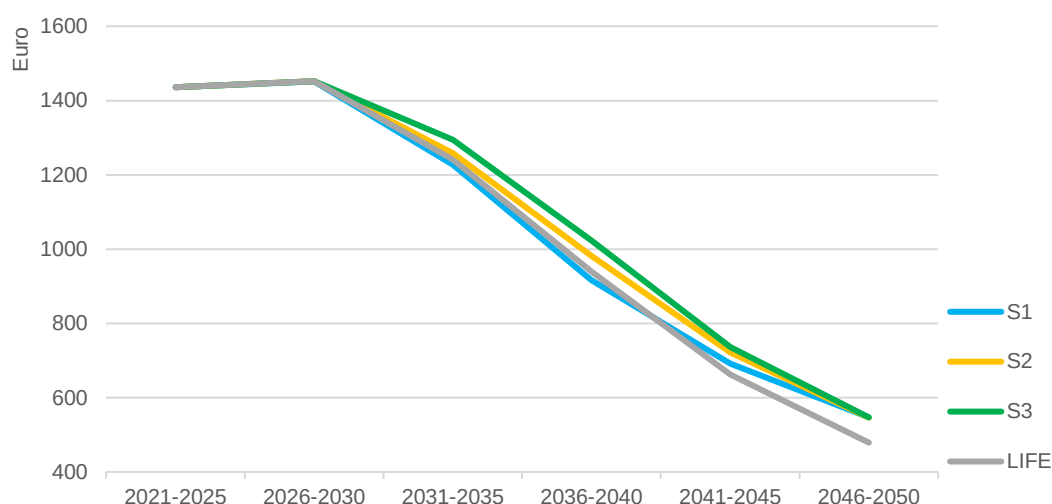


Note: Expenditures are expressed in EUR'2023.

Source: PRIMES.

Expenditures for transport-related energy purchases by households are projected to reduce from around EUR 1450 per year per household during 2021-2030 (21-23% of total transport expenditures per household) to around EUR 915-1025 per year per household during 2036-2040 (13-15% of total transport expenditures per household) and EUR 480-550 during 2046-2050 (around 7-9% of total transport expenditures), driven by the use of more energy efficient vehicles and multimodality. Scenario S1 shows the highest decrease in expenditures for energy purchases by 2040, around EUR 65 higher per year per household than in scenario S2 and around EUR 105 higher than in scenario S3 (see Figure 118). Expressed as share of private consumption, total annual expenditures on energy products are projected to decrease over time (from 3.2% during 2021-2025 to 1.7-1.9% during 2036-2040 and 0.8-0.9% during 2046-2050), due to the sustained increase in the private consumption over time.

Figure 118: Annual expenditures for transport-related energy purchases per household



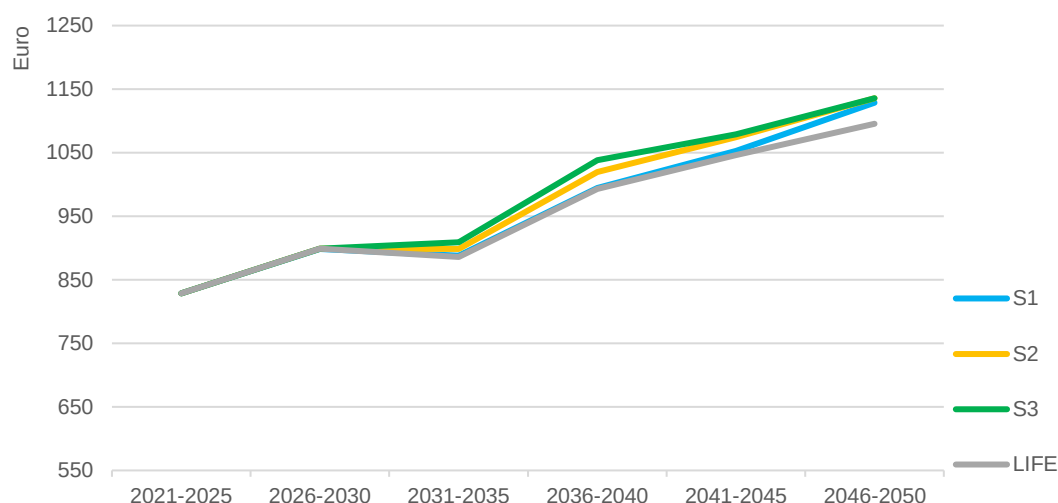
Note: Expenditures are expressed in EUR'2023.

Source: PRIMES

Annual expenditures on transport services are projected to increase from EUR 830 per

year per household in 2021-2025 (13% of total transport expenditures per household) to around EUR 995-1040 per year per household during 2036-2040 (14-15% of total transport expenditures per household) and around EUR 1095-1135 during 2046-2050 (17-18% of total transport expenditures), as shown in Figure 119. This projected increase is linked to higher use of public transport and multimodality. Expressed as share of private consumption, total annual expenditures on transport services are however projected to remain relatively stable over time at around 1.8-1.9% due to the sustained increase in private consumption.

Figure 119: Annual expenditures for transport services per household



Note: Expenditures are expressed in EUR'2023.

Source: PRIMES.

The concept of *transport poverty* describes the situation of people who are unable to meet the costs of private or public transport or do not have access (including availability), especially to public transport. The co-legislators agreed on a definition of transport poverty in the context of the Social Climate Fund⁽³⁰⁰⁾. No appropriate EU indicators currently exist to regularly monitor the affordability of transport services. However, according to the latest available data from Eurostat, 2.4 % of all people in the EU and 5.8% of those at risk of poverty cannot afford to use public transport regularly⁽³⁰¹⁾. In addition to costs, access to transport depends on other factors, including the quality and frequency of services, the state of the infrastructure and accessibility (both digital and physical). Due to the lack of data, it is not possible to assess the evolution of the transport

⁽³⁰⁰⁾ Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060: 'transport poverty' means individuals' and households' inability or difficulty to meet the costs of private or public transport, or their lack of or limited access to transport needed for their access to essential socio-economic services and activities, taking into account the national and spatial context.

⁽³⁰¹⁾ Information collected ad hoc by Eurostat in 2014. New data on affordability of public transport will be collected by Eurostat in 2024, as part of the new ad hoc module on access to services. See Commission Implementing Regulation (EU) 2022/2498 of 9 December 2022 specifying technical items of data sets of the sample survey in the income and living conditions domain on access to services pursuant to Regulation (EU) 2019/1700 of the European Parliament and of the Council.

poverty over time in the scenarios. It is however clear that up-to-date EU-level data on transport affordability is needed to closely monitor developments over time.

2.4.2. Electricity prices

Low-income households are particularly vulnerable to electricity price increases. The Commission proposal to reform the electricity market design on 14 March 2023 ⁽³⁰²⁾ aims at strengthening consumer protection, particularly for the most vulnerable households. With this reform, consumers would be entitled to secure fixed-price contracts, with the option of multiple or combined tailor-made contracts, as well as access to clearer pre-contractual information.

For the most vulnerables, a supplier of last resort would be selected so that no consumer ends up without electricity in case of supplier failure. This is complemented by an obligation on Member States to ensure that vulnerable customers are protected from electricity disconnections. Also, the proposal suggests allowing Member States to extend regulated retail prices to households and SMEs in the event of a crisis. The possibility to access renewable energy directly through participation in energy sharing arrangements allow all consumers to benefit from renewable energy, hence being less subject to electricity wholesale prices movements which depend on fossil fuel prices.

The Social Climate Fund ('the Fund') aims at addressing any social impacts that arise from the extension of the emissions trading system to the building and road transport sectors. This is achieved by financing temporary direct income support for vulnerable households and supporting measures and investments that reduce emissions in the road transport and buildings sectors. As a result, this contributes to reducing costs for vulnerable households, micro-enterprises, and transport users.

For the transport sector, the fund grants an improved access to zero- and low-emission mobility and transport with financial support to purchase low emission vehicles. It can also serve to provide free access to public transport or adapted tariffs for access to public transport.

2.4.3. Sectoral employment, skills and occupation groups

2.4.3.1. General impacts

As indicated in previous impact assessments and confirmed in Section 2.1.1, the transition to climate neutrality is projected to have a limited impact on aggregate employment, driven primarily by the expected impacts on GDP. However, the consequences of the transition on workers, the labour market and skills will still be significant. While some sectors including a large share of services activities ⁽³⁰³⁾, which represent a major share of the labour market, are likely to be affected marginally, other sectors will undergo very significant transformations whether in terms of employment levels or skills needs and occupations. A limited number of sectors accounting for a small

⁽³⁰²⁾ [Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Regulations \(EU\) 2019/943 and \(EU\) 2019/942 as well as Directives \(EU\) 2018/2001 and \(EU\) 2019/944 to improve the Union's electricity market design](#)

share of total employment will decline sharply, while significant employment opportunities should emerge elsewhere.

While macro-economic models project that the transition will have a limited effect on aggregate employment relative to a business-as-usual scenario, it is important to bear in mind the evolving general context, and in particular demographic and technological changes that impact the labor market independently from climate objectives and policies. The EU's population is projected to decline slowly from the mid-2020s onwards alongside continued ageing. As a result, the overall employment will be on a significant declining trend at EU level. The age dependency ratio is projected to increase from around 55% currently to around 75% by 2050, as the population of working age (15-64) declines by almost 13% (close to 37 million people). Other structural and technological changes will also affect the labour market and skills demand in fundamental ways. The rapid development and uptake of artificial intelligence could upend many services jobs that have been so far relatively sheltered from structural changes and that represent a large share of total employment in the EU.

In addition, it must be noted that the structure of employment in the EU has not been static in recent years. Even looking back only about a decade and in a context of a rising number of total jobs, significant changes have taken place in terms of employment by economic activity, by occupation and by wage dynamics. Services (market and non-market) activities currently represent close to 130 million jobs, or 65% of total EU employment, up from 60% in 2008 (Table 48). Public administration, education, health and social work account for nearly 40% of services employment.

In contrast, the share of industry and manufacturing in total employment declined by around 2 percentage points between 2008 and 2022 (to 16% of the total), even though the number of jobs has remained broadly stable in the past decade. Construction, architecture and engineering are another major source of jobs in the EU at around 8% of the total, though its share also declined by about 1 percentage point between 2008 and 2022. Finally, agriculture, fisheries and fishing, and fossil fuel extraction and refining have experienced a significant decline in the level and share of employment. While the share of agriculture employment remains significant at 3.5% of the total currently, employment in fossil fuel extraction and refining was down to about 370 000 jobs in 2022, 40% below the level in 2008.

Table 48: Employment by economic activity (million people and % of total)

	2010	2015	2020	2021	2022
Fossil fuel sectors	0.60	0.51	0.46	0.41	0.37
(% total)	(0.3%)	(0.3%)	(0.2%)	(0.2%)	(0.2%)
Other mining and extraction activities	0.32	0.30	0.30	0.30	0.33
(% total)	(0.2%)	(0.2%)	(0.2%)	(0.2%)	(0.2%)
Energy intensive industries	5.03	4.70	4.90	4.87	4.98
(% total)	(2.7%)	(2.5%)	(2.6%)	(2.5%)	(2.5%)
Manufacturing of transport equipment (incl. parts and accessories)	3.44	3.84	4.15	4.05	3.84
(% total)	(1.9%)	(2.1%)	(2.2%)	(2.1%)	(1.9%)
Manufacturing of electrical equipment and other machinery	3.97	4.34	4.57	4.57	4.58
(% total)	(2.2%)	(2.3%)	(2.4%)	(2.4%)	(2.3%)
Other manufacturing	18.07	17.60	17.96	17.77	18.08
(% total)	(9.8%)	(9.5%)	(9.4%)	(9.2%)	(9.2%)
Electricity, gas, steam and air conditioning supply	1.47	1.37	1.46	1.50	1.48
(% total)	(0.8%)	(0.7%)	(0.8%)	(0.8%)	(0.7%)
Construction and architecture services	16.29	14.89	15.37	15.68	16.25
(% total)	(8.9%)	(8.0%)	(8.0%)	(8.1%)	(8.2%)
Transport and storage	9.43	9.67	10.06	10.26	10.50
(% total)	(5.1%)	(5.2%)	(5.2%)	(5.3%)	(5.3%)
Services	113.92	118.28	123.20	124.85	128.15
(% total)	(62.0%)	(63.7%)	(64.2%)	(64.7%)	(65.0%)
Water supply, sewerage, waste management	1.37	1.47	1.61	1.62	1.64
(% total)	(0.7%)	(0.8%)	(0.8%)	(0.8%)	(0.8%)
Agriculture, forestry and fishing	9.79	8.76	7.72	6.98	6.91
% total	(5.3%)	(4.7%)	(4.0%)	(3.6%)	(3.5%)

Source: Eurostat. ⁽³⁰⁴⁾

The recent trends in sectoral employment in the EU are mirrored in the evolution of employment by occupations (Table 49), which also reflects the rising trend in tertiary educational attainment among the population in general and among those aged 25-34 in particular. For the latter, attainment in tertiary education rose from 23.1% of the total population in 2002 to 42% in 2022. The increase was particularly sharp among women with a rate of 47.6% in 2022, compared to a rate of 36.5% for men. The share of professionals and managers in total employment increased by 4.5 percentage points in the past decade to 26.7% of the total in 2022. This contrasts sharply with occupations whose share in total employment declined over the same period, mainly service and sales workers, crafts and trade, elementary occupations and agriculture, forestry and fisheries. The absolute number of workers with these occupations has nevertheless remained broadly stable (except skilled workers in agriculture) as total employment was on a rising trend.

⁽³⁰⁴⁾ The table is based on an aggregation of NACE 2 sectors. Fossil fuel sectors (B05, B06, C19); other mining and extraction activities (B07, B08, B09); energy intensive industries (C17, C20, C21, C23, C24); manufacturing of transport equipment (C29, C30); manufacturing of electrical equipment and other machinery (C27, C28); other manufacturing (all other C codes); electricity, gas, steam and air conditioning supply (D35); construction and architecture services (F41, F42, F43, M71); transport and storage (H49 to H53); services (all codes not listed in other sectors); water, treatment and waste (E36 to E39); agriculture, forestry and fishing (A01, A02, A03).

Table 49: Employment by occupations

	Million people			% of total		
	2011	2015	2022	2011	2015	2022
Managers	9.90	9.49	9.93	5.4%	5.1%	5.0%
Professionals	30.87	33.24	42.61	16.8%	17.9%	21.6%
(Science and engineering)	(5.25)	(5.41)	(7.00)	(2.9%)	(2.9%)	(3.6%)
Technicians	29.27	30.76	31.46	15.9%	16.6%	16.0%
(Science and engineering)	(7.33)	(7.25)	(6.86)	(4.0%)	(3.9%)	(3.5%)
Clerical support	18.27	18.06	19.79	9.9%	9.7%	10.0%
Service and sales	30.77	30.93	31.29	16.8%	16.7%	15.9%
Skilled workers in agri, forest. and fish.	7.72	7.24	5.47	4.2%	3.9%	2.8%
Craft and trades	23.50	22.86	22.86	12.8%	12.3%	11.6%
(Building)	(7.96)	(7.40)	(7.75)	(4.3%)	(4.0%)	(3.9%)
(Electrical and electronic)	(2.89)	(3.05)	(3.07)	(1.6%)	(1.6%)	(1.6%)
(Metal, machinery and related)	(7.49)	(7.28)	(7.22)	(4.1%)	(3.9%)	(3.7%)
Plant and machine operators	14.49	14.43	15.01	7.9%	7.8%	7.6%
Elementary occupations	17.03	17.22	16.61	9.3%	9.3%	8.4%
(Mining, constr., manuf. and transport)	(5.36)	(4.91)	(5.38)	(2.9%)	(2.6%)	(2.7%)
Other	1.79	1.52	2.09	1.0%	0.8%	1.1%

Source: Eurostat. ⁽³⁰⁵⁾

Looking forward, modelling under JRC-GEM-E3 projects that recent trends in sectoral employment are set to continue at an accelerated pace (Table 50). These developments will also take place in the context of a decrease in the working age population and declining overall employment levels, contrary to what happened in the past decade when employment was still on a rising trend. Employment in fossil fuel industries will further decline to negligible levels from an already low level. The decline would take place faster still under a higher level of ambition in 2040. Employment trends in energy intensive industries and transport equipment are also projected to continue, in part as the EU economy continues to be more services-oriented. This is a constant across scenarios and there is little difference between S1 and the scenarios with a higher level of ambition in 2040.

Given the scale of services employment, given that services jobs are among those more marginally affected by the climate and energy transition and given that the long-term trend towards a rising share of services sectors in GDP is projected to continue to some extent, the share of market and non-market services jobs is projected to continue growing in the coming decades. The flipside of the increase in the share of services sector jobs is a gradual decrease in the share of employment in energy intensive industries, consumer goods industries and transport equipment. The share of employment in other equipment goods, however, is projected to remain stable as the transition should increase EU and

⁽³⁰⁵⁾ The table is based on ISCO-08 two-digit level occupations. Managers (OC1); professionals (OC2); professional (science and engineering) (OC21); technicians (OC3); technicians (science and engineering) (OC31); clerical support (OC4); services and sales (OC5); skilled workers in agriculture, forestry and fisheries (OC6); crafts and trade (OC7); crafts and trade (building) (OC71); crafts and trade (electrical and electronic) (OC74); crafts and trade (metal, machinery related) (OC72); plant and machine operators (OC8); elementary occupations (OC9), elementary occupations (mining, constr., manuf. and transport) (OC93); other (OC0 and NRP).

global demand for the type of equipment needed for decarbonisation. While output in these sectors is projected to grow significantly between 2015 and 2040 or 2040, they will be outpaced by overall GDP growth. In the context of a declining aggregate level of employment, driven by a shrinking labour force, it is therefore not surprising to see these sectors' share of employment (and absolute employment) decline over the coming decades.

In contrast, the shares of construction and transport activities are projected to increase moderately or remain stable. Output growth in these sectors in the period 2015-2050 is projected to outpace GDP growth, driving a reallocation of labour. These trends are not affected to any significant extent by the level of ambition in 2040 (Table 50), but they imply a reallocation of the labour force over time. Such a reallocation is typically not without frictions and costs, and it would require accompanying policies to ensure that reskilling and retraining opportunities are available for workers in need (see Annex 9).

Table 50: Sectoral employment, share in total employment (%)

	S3			
	2020	2030	2040	2050
Fossil fuel industries	0.13%	0.11%	0.05%	0.05%
Energy intensive industries	6.7%	6.5%	6.2%	5.9%
Transport equipment	2.1%	2.0%	1.9%	1.8%
Other equipment goods	6.3%	6.2%	6.1%	6.1%
Consumer goods industries	4.4%	4.2%	4.0%	3.9%
Transport	3.6%	3.9%	3.7%	3.7%
Construction	7.8%	7.6%	7.7%	7.7%
Market services	34.0%	34.6%	34.9%	35.3%
Non-market services	26.6%	27.1%	27.3%	27.5%
Agriculture	3.5%	3.2%	3.1%	2.8%
Forestry	0.4%	0.3%	0.5%	0.4%
Other	4.4%	4.3%	4.6%	5.0%

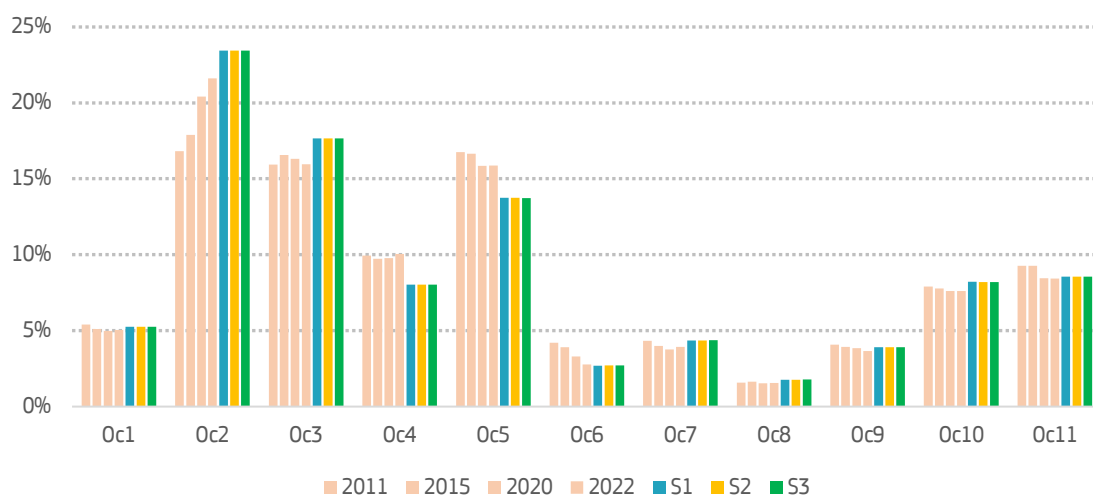
Source: JRC-GEM-E3 model. ⁽³⁰⁶⁾

The importance of reskilling and retraining in the course of the transition is further highlighted by projections based on the linking of the macro-economic simulation of the 3 main scenarios and the skills forecast from the European Centre for the Development of Vocational Training ⁽³⁰⁷⁾. These projections show that trends in the share of employment by occupation are broadly projected to continue up to 2040, and that the 3 main scenarios are extremely similar in terms of their impacts on occupation requirements. Two key occupational groups are projected to experience a significant increase in their share of total employment, i.e., professionals and technicians. In the crafts and trade group, occupations related to buildings as well as plant and machine operators are also projected to experience an increase in employment share relative to 2022 (Figure 120). In contrast, the shares of clerical support as well as services and sales occupations are projected to decline significantly.

⁽³⁰⁶⁾ The sectoral classifications resulting from the JRC-GEM-E3 modelling differ to some extent from those based on NACE 2 sectors.

⁽³⁰⁷⁾ [Cedefop skills forecast: green and digital transitions to have positive employment impacts.](#)

Figure 120: Historical and projected shares of employment by occupations in 2040 (% of total)



Oc1	Managers	Oc7	Building
Oc2	Professionals	Oc8	Electrical and electronic
Oc3	Technicians	Oc9	Metal, machinery and related
Oc4	Clerical support	Oc10	Plant and machine operators
Oc5	Service and sales	Oc11	Elementary occupations
Oc6	Skilled workers in agri, forest. and fish.		

Source: JRC-GEM-E3 model and CEDEFOP skills forecast.

Useful as they are to assess broad economic trends and, in particular, interactions between a range of factors and developments, macro-economic models are not in the best position to assess the impact of transformations within sectors. A bottom-up analysis of sectors that will be particularly relevant for the transition is therefore provided below, linking projections from the PRIMES model and further building on the results from JRC-GEM-E3. An assessment is provided for the automobile sector, construction and heating systems, and the deployment of renewable power generation.

2.4.3.2. Automobile sector, construction, heating and electricity

Regulation (EU) 2023/851 amending Regulation (EU) 2019/631 imposes a ban on the sale of new non-zero emission cars and vans in the EU from 2035 onwards. This implies a major transformation of the automobile manufacturing sector and has implications across the whole value chain. A version of the JRC-GEM-E3 model was augmented with an explicit representation of vehicle manufacturing and an upgrade of the modelling of vehicle purchase and operation, as electric vehicles (which were assumed as the zero-tailpipe emission technology deployed) have different needs not only in terms of manufacturing, but also operation and maintenance. On this basis, Tamba & al. find that transport electrification alters supply chains and leads to structural shifts in employment from traditional vehicle manufacturing towards battery production, electricity supply and

related investments ⁽³⁰⁸⁾. They find that, in the medium term, reaching a given climate target with limited road transport electrification has negative impacts on GDP compared to an alternative option with higher electrification as further efforts are then needed in other sectors with potentially higher abatement costs.

Importantly, the authors find that the shift towards the production of electric vehicles implies a small net increase in employment in the car manufacturing sector overall, driven primarily from costs reductions over time (including learning in batteries and lower maintenance and operation costs) leading to increases in demand for vehicles. In turn, the net employment effect on the services side is projected to be negative due to the lower maintenance services requirements of electric vehicles compared to internal combustion engine ones. The batteries sector and power generation, in contrast, are positively impacted by the electrification of road transport.

As indicated above, the share of the construction sector in total employment is projected to remain broadly stable across all scenarios under the JRC-GEM-E3 model. A major driving force in construction employment, which currently represents about 16 million jobs, will be the need to achieve much higher renovation rates of the existing building stock over the next decade to improve energy efficiency and enable the transition to decarbonised heating systems (mainly heat pumps). The construction sector should also benefit from the building of new green infrastructure, including in power generation and transport. At aggregate level, the requirements for construction jobs will also be influenced by factors that are exogenous to the climate and energy transition, mainly a gradual decline in total population in the long term, ageing and patterns and choices in terms of geographic spread of the population or urban densification.

A sharp increase in renovation rates in the residential sector will be unavoidable as part of the transition to climate neutrality, regardless of the level of ambition for 2040. Annual renovation rates in 2011-2020 were about 0.8% of the residential building stock and were driven mainly by light renovations. Under S1, overall renovation rates are projected to double throughout the transition period to 2050, with a particularly high increase in medium renovations. S2 and S3 would require even higher renovation rates. This would imply more than 4 million renovations per annum on average in 2031-2050 under the 3 main scenarios, with a significant early push under S3, delay under S1 and a more even level of renovation across the two decades under S2 (Table 51).

What is particularly important in terms of employment is that this push in renovation is not only large in terms of scale and compared with previous decades, but also that it is to be sustained over several decades, starting in the current one already. This should therefore provide job opportunities with long-term prospects for a significant number of people. Based on an average labour intensity of 5 full-time jobs equivalent per million euro invested in renovation ⁽³⁰⁹⁾, the renovation drive alone could generate about 250 000 jobs over the period 2031-2050. This represents an additional 160 000 jobs compared to

⁽³⁰⁸⁾ Marie Tamba, Jette Krause, Matthias Weitzel, Raileanu Ioan, Louison Duboz, Monica Grosso, Toon Vandyck, [Economy-wide impacts of road transport electrification in the EU](#), Technological Forecasting and Social Change, Volume 182, 2022.

⁽³⁰⁹⁾ This corresponds to the average number of full-time jobs equivalent per million euro of turnover in the construction of residential and non-residential buildings in 2016-2020, as per Eurostat data.

the level in 2011-2020, as estimated on the basis of the same labour intensity per million euros invested. While this remains small compared to total construction employment (Table 48), it is nevertheless significant, and it is to be noted that this figure accounts only for the direct employment impact, without considering further effects along the value chain ⁽³¹⁰⁾. Similarly, to the investment requirements, the levels of job creation linked to the renovation drive are highest in 2031-2040 under S3, with S2 generating a more even impact across the two decades than S3 and S1.

Table 51: Average annual renovations in residential and tertiary sectors

	2011- 2020	2021- 2030	2031- 2040	2041- 2050
Residential				
S1 units	2.0	5.0	3.7	4.5
S1 floor	137	379	286	384
S2 units	2.0	5.0	4.2	4.0
S2 floor	137	381	331	343
S3 units	2.0	5.0	5.1	3.3
S3 floor	137	380	392	282
LIFE units	2.0	5.0	4.7	4.0
LIFE floor	137	378	370	342
Tertiary				
S1 units	62	155	86	149
S1 floor	24	66	41	79
S2 units	62	158	131	108
S2 floor	24	68	63	57
S3 units	62	162	187	55
S3 floor	24	69	88	30
LIFE units	62	156	165	86
LIFE floor	24	67	77	46

Note: floor stands for floor surface and is in million m², units in millions (residential) and thousands (tertiary).

Source: PRIMES.

Such significant needs for construction jobs will also require that training and skilling systems are put in place to ensure the availability of workers for all necessary occupations and at all levels of skills, including relevant craft and trades, developers and architects/engineers. The long-term visibility afforded by the sustained requirement in the sector should also enable the establishment of the necessary education and training programmes for the younger segments of the population. By nature, the renovation sector is also one where SMEs are likely to be particularly active, and where they should benefit from business opportunities.

A similar renovation drive will be necessary in the tertiary sector, where around 90 000 units are projected to be renovated on average per annum in 2031-2050 under S1, rising to an annual average of about 140 000 units under S3. While the number of units is much

⁽³¹⁰⁾ [SWD\(2021\) 453 final, part 1/4](#) provides an additional discussion of the employment impacts of renovations, focusing on the effect of the Commission proposal for a Directive of the European Parliament and of the Council on the energy performance of buildings (recast).

lower than in the residential sector, the floor area to be renovated is still large at around 14% of the floor area in the residential sector.

An additional driver of employment creation and skills requirement in the course of the transition to climate neutrality relates to the decarbonisation of heating and cooling systems, mainly via the installation of heat pumps. This should not only generate job creation in installation and maintenance, but also in manufacturing. The deployment of heat pumps in the residential and tertiary sectors will need to take place rapidly during the transition to climate neutrality, at an estimated average of more than 3 million units per annum in 2031-2050 in the residential sector and around 200 000 to 300 000 (larger scale) units in the tertiary sector. The deployment level is similar across scenarios.

To a large extent, heat pumps will substitute other types of heating equipment that would also require to be replaced at the end of their operational lifetime. Their installation will therefore only impact total employment in the sector at the margin, to the extent that installation may be more labour intensive than for other types of equipment and to the extent that the shifting to heat pumps may anticipate the end of the operational lifetime of the assets they replace. The impacts on the labour market would be significant, however, as the installation levels would require skills adaptation and retraining ⁽³¹¹⁾. Based on an estimated labour intensity ratio of 1 full time job equivalent for about 36 heat pumps installed annually ⁽³¹²⁾, around 100 000 full time installers would be required for the time period 2031-2050.

On the manufacturing side, the Commission estimated that producing the entirety of the heat pumps installed up to 2030 in the EU would lead to an increase of about 60 000 jobs ⁽³¹³⁾. The projections for the needs for heat pumps beyond 2030 indicate that the ramping up of production capacity and the associated job creation should be sustained in the long-term.

As far as power generation is concerned, the deployment of on-shore and off-shore wind and solar energy will rise sharply throughout the transition period to 2050. While S3 requires a faster ramp up of renewable electricity generation than S2 and S1, the three pathways rely on similar overall annual new capacity installation. Close to GWe 100 of net power capacity installation will be required for solar and wind energy. The employment opportunities generated by such a level of installation are very large, both in terms of installation and in terms of manufacturing. On the installation side, solar power is more likely to generate business opportunities and job creation among SMEs, while the deployment of wind turbines will be more tilted towards larger companies.

⁽³¹¹⁾ [The Employment and Social Developments in Europe 2023 Annual Review](#) (addressing labour shortages and skills gaps in the EU) provides first estimates of the job creation potential up to 2030 related to the deployment of certain clean technologies, as well as estimates of the necessary spending on retraining, reskilling and upskilling.

⁽³¹²⁾ The European Heat Pump Association's European Heat Pump Market and Statistics Report 2023 indicates that close to 3 million heat pumps were installed in the EU in 2022, with 67 000 installers employed in the sector (a ratio of 44 to 1). Similarly, a report from the Heat Pump Association projected the needs for heat pump installation and installers to decarbonise heating the UK up to 2035. Their projections indicate a ratio of 28 to 1 on average for the period.

⁽³¹³⁾ [SWD\(2023\) 68 final](#).

On the manufacturing side, the Commission also assessed the job creation potential from the domestic manufacturing of solar panels and wind turbines, in a 2030 horizon. While the solar PV manufacturing industry is extremely small in the EU currently, it estimated that around 66 000 jobs could be created in the sector if the EU were to become self-sufficient in the production of solar PVs. Continued needs in 2031-2050 for the installation of solar PVs at around the level needed to achieve the climate and energy targets under the Fit-for-55 legislation indicates that domestic demand will be sustained for an extended period of time and that employment in the sector could remain large if production capacity is ramped up. Similarly, it was estimated that around 40 000 additional jobs would be needed to make the EU self-sufficient in the production of wind turbines in a 2030 horizon. Given that the annual installation needs for wind power are projected to increase by around 60% between 2021-2030 and 2031-2050, one could foresee the creation of large additional employment opportunities in the technology in the horizon 2050.

As indicated in the same assessment, the scaling-up of manufacturing capacities would not only require investing capital in factories and technologies, but also to ensure that the workforce is available and that it has the necessary type and level of skills to operate in new sectors. The re-skilling and up-skilling investment needs, with a 2030 horizon, were estimated at up to EUR 4.1 billion. Extending this horizon to the 2031-2050 period would clearly also broaden the scope and the scale of skills-related investment needs, as the range of sectors affected widens and the overall capital investment needs remain large.

2.4.3.3.LIFE

Further labour market impacts from a higher uptake of circularity in the economy, as explored under the LIFE setting, could also be expected, even though macro-economic models are not well equipped to assess them. Enhanced circularity will likely entail job creation as well as job destruction in certain sectors, together with job substitution and redefinition. Labour market impacts can be expected to occur at three stages of the materials cycle: (1) as materials are transformed into products, infrastructure and assets, resource efficiency will shift the relative balance of companies' inputs from materials to labour; (2) while products are functional, value retention activities (repair, refurbishment, servicing, upgrading) and use-optimisation services (product-as-a-service and sharing models) imply job creation in proximity to where the products are consumed; and (3) when products and assets become waste, there are generally far more jobs generated through treatment at the higher echelons of the waste hierarchy, with one study showing that in dealing with 10 000 tonnes of waste, 1 job is created by incineration, 36 by recycling and between 300 and 800 by repair and re-use⁽³¹⁴⁾.

The CAPRI model provides indicators on employment effects from the LIFE setting. The results show limited labour impacts on agriculture. Total labour (in hours/ha) in the crop sector decreases by 0.6%, characterized by a decrease in labour related to cereals (-7%) and a slight decrease in labour on vegetables and permanent crops (-0.4%). Furthermore, a stronger decline in labour hours in cattle activities (-25%) and other animals (-24%) contributes to an overall reduction of total labour of 10.4% on all agricultural activities.

⁽³¹⁴⁾ [GAIA. Zero Waste and Economic Recovery. The Job Creation Potential of Zero Waste Solutions.](#)

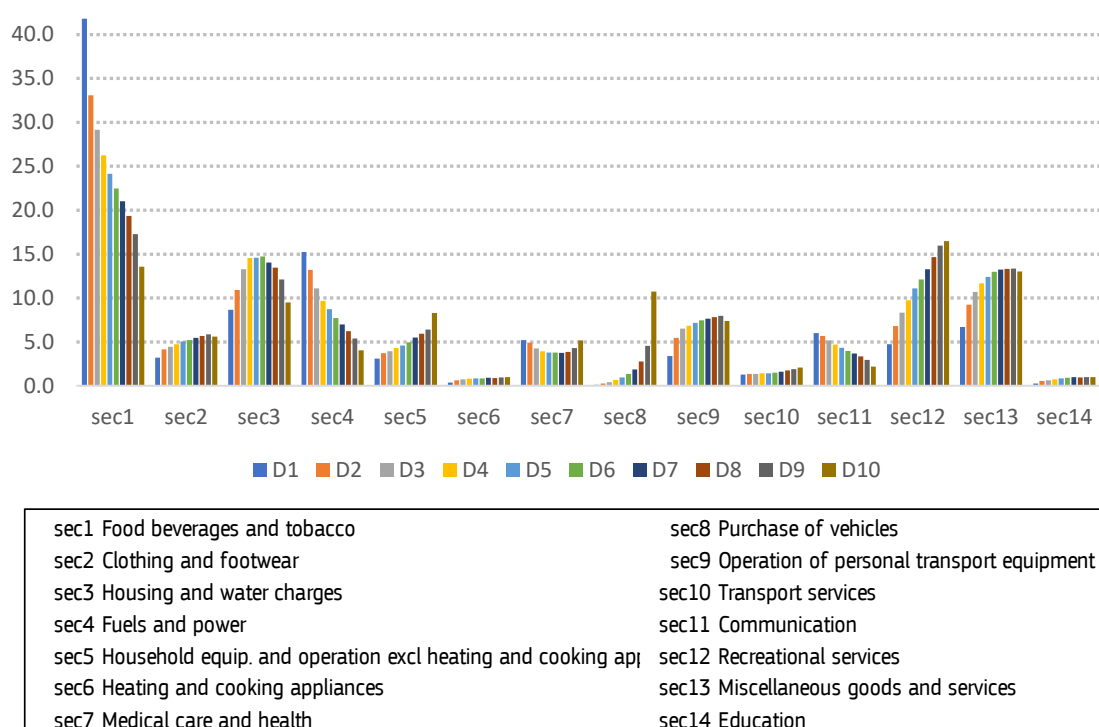
However, it needs to be considered that this assessment based on the CAPRI model ignores the labour requirements for management of second-generation lignocellulosic crops, payment for ecosystem services (PES), and carbon farming activities and it also does not reflect the additional labour requirements from the expansion of organic agriculture, both of which tend to alleviate the decline in agricultural labour use.

2.4.4. Changes in relative prices and distributional impacts

The transition to climate neutrality is susceptible to affect relative prices in the economy, as consumption and production patterns change in accordance with the GHG mitigation needs. Sections 1.1.1 and 1.1.2 assess the direct impact on households of projected changes in fuel expenses and electricity prices. The latter will become particularly important as household energy consumption is set to gradually shift overwhelmingly towards electricity. To complement this analysis, the JRC-GEM-E3 model was used to assess the potential impact on households of changes in relative prices across the economy. A macro-economic model is indeed best suited to capture the full effects and interactions across sectors that will affect relative prices.

Estimating changes in relative prices is a first step towards assessing the impact on welfare for households, as the latter have very different consumption patterns depending on their income or expenditure levels. Poorer households spend a higher share of their disposable income on basic necessities than households with higher income, including on energy consumption or housing and food, whose relative prices are more susceptible to be affected by the transition to climate neutrality (Figure 121).

Figure 121: EU household mean budget shares by expenditure decile, 2015 (%)



Source: Household Budget Survey.

Overall, relative prices are projected to vary relatively little across scenarios. The relative price of housing is nevertheless likely to be somewhat higher under S3 than under S2 in 2040, and slightly lower under S1 than under S2 as higher levels of renovation associate

with higher climate ambition increase costs for homeowners and renters alike. Similarly, the relative price of the operation of transport equipment is projected to increase with a higher level of mitigation in 2040. In contrast, the accelerated shift towards electrification and renewables power generation is projected to decrease the relative prices of fuels and power in S3 relative to S2, and increase it in S1 relative to S2 (Table 52).

Table 52: Changes in relative prices, S1 and S3 vs. S2 (% change)

	S1		S3	
	2040	2050	2040	2050
Food beverages and tobacco	-0.3%	0.0%	0.2%	0.0%
Clothing and footwear	-0.1%	0.0%	0.1%	0.0%
Housing and water charges	-0.5%	0.0%	0.7%	0.0%
Fuels and power	0.5%	0.5%	-0.9%	-0.6%
Household equipment	-0.2%	0.0%	0.1%	0.0%
Heating and cooking appliances	-0.2%	0.0%	0.1%	0.0%
Medical care and health	-0.1%	0.0%	0.1%	0.0%
Purchase of vehicles	-0.2%	0.0%	0.0%	-0.1%
Operation of transport equip.	-0.7%	0.0%	0.5%	0.0%
Transport services	-1.7%	-0.1%	0.9%	0.2%
Communication	0.0%	0.0%	0.1%	0.0%
Recreational services	-0.2%	0.0%	0.2%	0.0%
Miscellaneous goods and services	-0.1%	0.0%	0.1%	0.0%
Education	0.0%	0.0%	0.1%	0.0%

Source: JRC-GEM-E3.

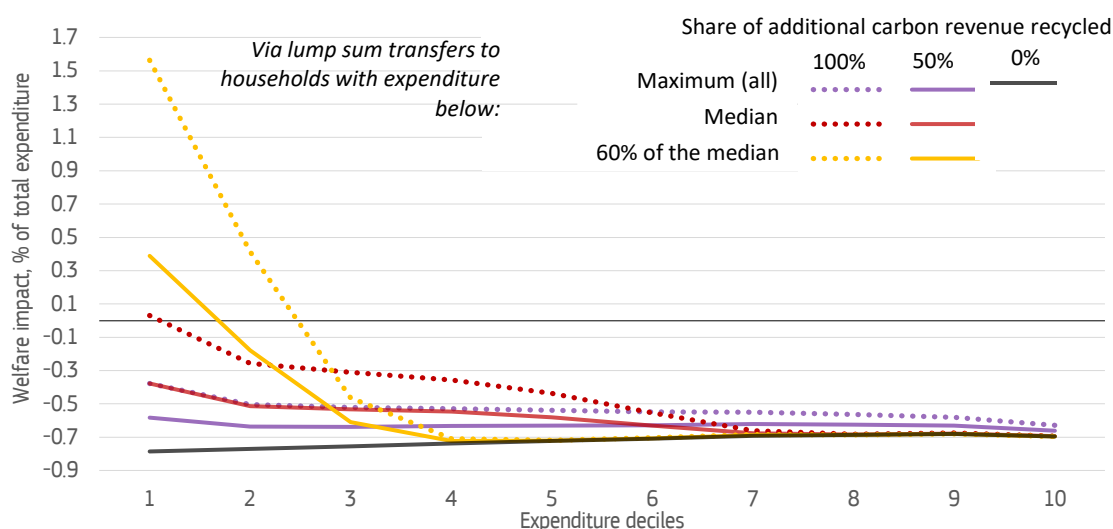
Linking these estimated changes in relative prices to micro-data from the household budgetary survey, the JRC estimated distribution impacts per expenditure and income deciles ⁽³¹⁵⁾. This work elaborates on what was done in the impact assessment for the 2030 Climate Target Plan and for the Council Recommendation on fair transition ⁽³¹⁶⁾. It improves the previous estimation of impacts by allowing the structure of household consumption to vary over time. Previous estimates instead used the household budgetary survey in a fully static manner, i.e., it assumed that the expenditure structure across income groups did not change over time, and it applied changes in relative prices across scenarios to the (static) historical expenditure structure from the data.

⁽³¹⁵⁾ The analytical tool was developed under [two joint projects](#) between the Directorate-General Employment, Social Affairs and Inclusion and the Joint Research Centre. The two projects are: “Assessing and monitoring employment and distributional impacts of the Green Deal (GD-AMEDI)” and “Assessing distributional impacts of geopolitical developments and their direct and indirect socio-economic implications, and socio-economic stress tests for future energy price scenarios (AMEDI+)”. The projects combine macro- and micro-economic modelling approaches to enhance the Commission’s analytical capacities for assessing and monitoring employment, social and distributional impacts of climate and energy policies.

⁽³¹⁶⁾ [Council Recommendation of 16 June 2022 on ensuring a fair transition towards climate neutrality \(2022/C 243/04\)](#). See also [SWD\(2021\) 452 final](#), which provides an overview and discussion of the available analytical evidence underpinning the recommended policy interventions.

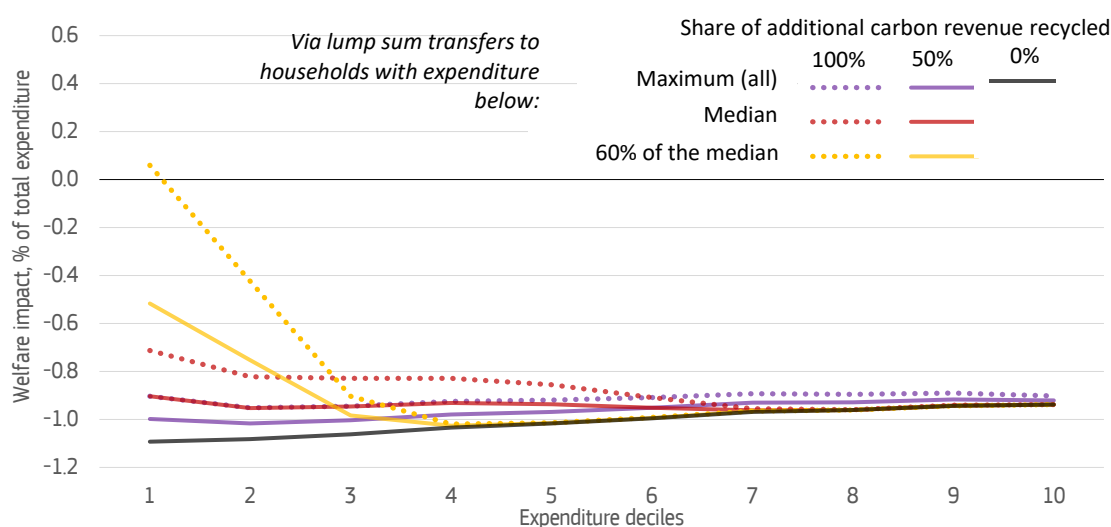
The estimates show that lower income households will be more affected than higher income households as the level of climate ambition rises, as measured in terms of compensating variation, i.e., the monetary transfer that would be necessary to maintain the same level of utility as under the previous set of relative prices. Assuming that none of the additional revenue from carbon pricing are redistributed to households to temper impacts, the welfare impact of S2 would amount to about -0.8% (% of total expenditure) for the lowest expenditure deciles, and about -0.7% for the highest expenditure decile (Figure 122). The effects would be larger under S3 at about -1.1% and -0.9%, respectively (Figure 123).

Figure 122: Change in relative welfare by expenditure decile, S2



Source: JRC.

Figure 123: Change in relative welfare by expenditure decile, S3



Source: JRC.

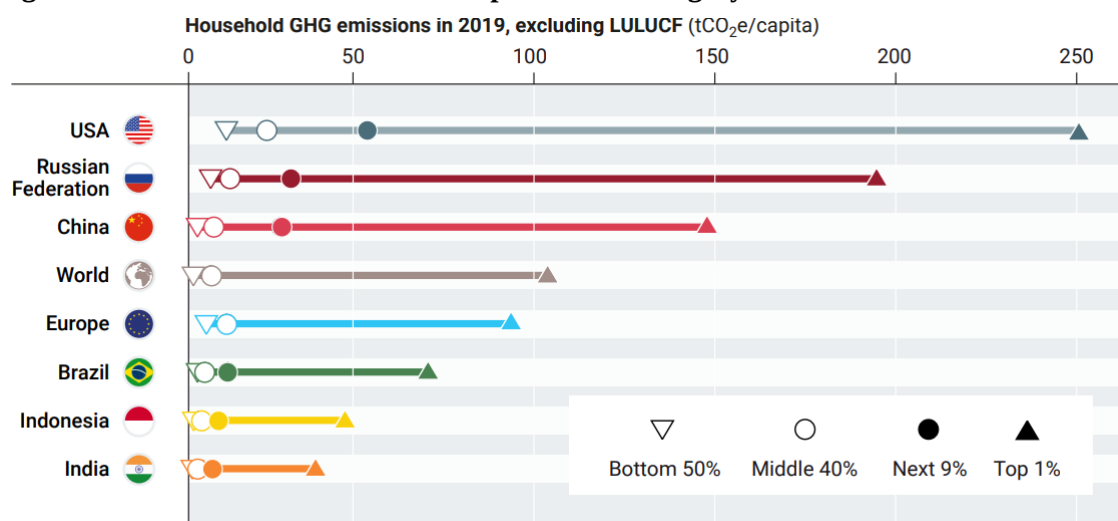
Redistributing some or all of the additional carbon revenue would sharply reduce this negative impact on the lower expenditure deciles, and it could even reverse it if the redistribution is targeted, e.g., to the households with expenditure levels below 60% of the median. Even a partial (50%) redistribution of additional carbon revenue would be sufficient to reverse the negative distributional impacts on the lowest expenditure deciles, if it is targeted on households with income below 60% of the median. It is important to note also that the estimates of the effectiveness of redistributing carbon revenues are

based on the use of only additional carbon revenue between S2 or S3 and S1. They do not account for full extent of carbon revenues, which would be much larger than the additional ones given that S1 already factors in the vast majority of carbon revenues.

2.4.5. The equity dimension

According to the UNEP Gap Report 2022 (Figure 124), there are high-emitting households in all major economies. Different levels of household GHG emissions exist both within and between countries. The low-emitting households have relatively close levels of emissions throughout countries, but the emission range for the top 1% emitting households is quite broad.

Figure 124: Household GHG emissions per income category



Note: Per capita emissions include emissions from domestic consumption, public and private investments, and imports and exports of carbon embedded in trade with the rest of the world. Households are ranked according to total emissions and divided accordingly into groups (e.g., the bottom 50 per cent refers to the 50 per cent of households with the lowest emissions in that country or region).

Source: UNEP Gap Report 2022

2.5. Regional impacts

2.5.1. Regional exposure to climate change

For the regional impacts of climate change, we refer to Annex 7 on the cost of climate change.

2.5.2. Regional exposure to the transition

The European Climate Law specifies that, “[when] proposing the Union 2040 climate target in accordance with paragraph 3, the Commission shall consider [...] fairness and solidarity between and within Member States”. The macro-economic modelling work conducted for 2030-2050 is at the EU and sectoral level (GEM-E3, E3ME, E-QUEST). It

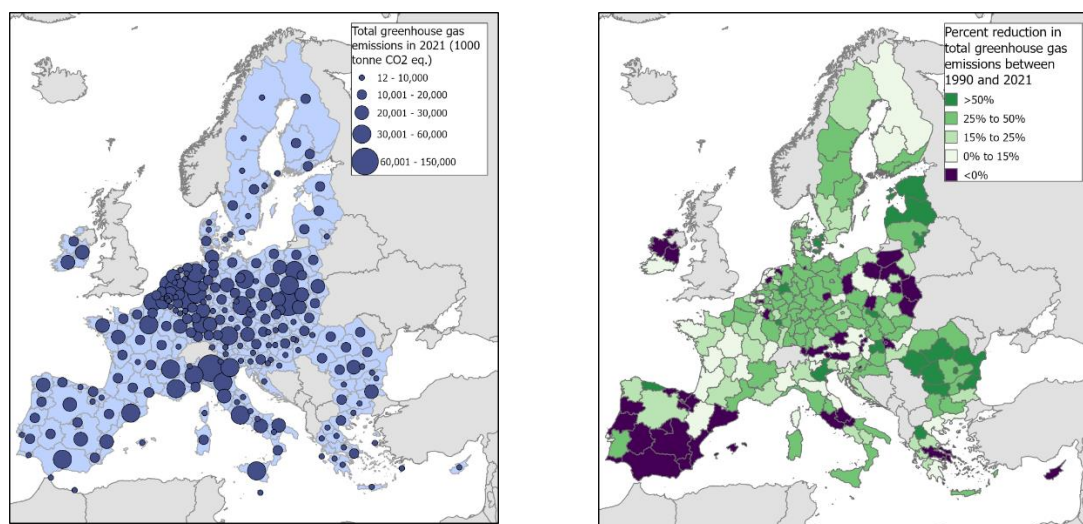
does not examine the impacts at the regional level. Below, we characterise regions as they stand today in order to anticipate their exposure to the transition. This is based on EDGAR, regional emissions inventory which monitors the emissions of greenhouse gases since 1990 for 26 broad sectors ⁽³¹⁷⁾.

2.5.2.1. GHG intensity of the regions

The total emissions at the regional level (Figure 125), the emissions per capita (Figure 126) as well as the emission intensity of the regions (Figure 127) show the diversity of circumstances in which regions are. These figures have to be interpreted carefully as some regions with relative low emissions levels may depend on some emission intensive industries (for example for power generation) that are located in other regions. Changes in regional emissions may be the result of the decarbonisation of economic activities but also of the closure, opening or relocation of activities, as well as of population migrations. Some regions, such as the capital region of Lithuania (Sostinės regionas) and Western Macedonia (EL), have seen their total emissions being reduced by about 70% in the last three decades. Others, such as the Groningen (NL) and central Greece (EL) regions, have a high emission intensity and have not yet shown a strong decarbonisation trend in the last decades ⁽³¹⁸⁾.

The total emissions at regional level reflect the economic activities of the regions and the emission intensity of these activities. For example, the regions with the highest per capita emissions are Zeeland (NL) and Western Macedonia (Greece). In Zeeland, 60% of emissions are caused by industry, while in Western Macedonia almost 70% of emissions are due to electricity generation.

Figure 125: Total emissions at regional level (left) and corresponding change since 1990 (right)



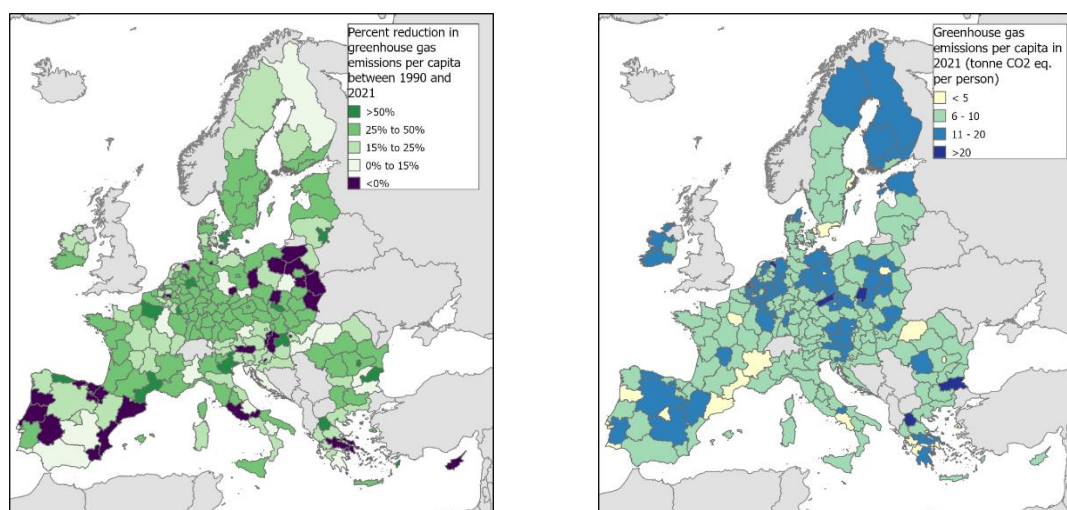
⁽³¹⁷⁾ Guizzardi, Diego; Pisoni, Enrico; Pagani, Federico; Crippa, Monica (2023): GHG Emissions at sub-national level. European Commission, Joint Research Centre (JRC) [Dataset] doi: 10.2905/D67EEDA8-C03E-4421-95D0-0ADC460B9658 PID: <http://data.europa.eu/89h/d67eeda8-c03e-4421-95d0-0adc460b9658>

⁽³¹⁸⁾ In the case of Groningen, emissions might decrease after the permanent closure of the region's gas field in 2023.

Note: leaving out aviation and shipping.

Source: EDGAR emissions database

Figure 126: GHG emissions per capita in 2021 and change in GHG emissions per capita between 1990 and 2021



Note: leaving out aviation and shipping.

Source: EDGAR emissions database

For 174 regions out of 242, emissions per capita (Table 53) in 2021 were above 5 tCO₂-eq per person), which is approximately the emission per capita level implied by the 2030 target. Among the 242 NUTS2 regions, 68 regions reached emission levels below 5 tCO₂-eq per person in 2021. Decarbonization is not a linear process. For the richest western Member States, regional emissions have mostly been declining. But for most of the countries that accessed the EU in or after 2004, the fall in emissions in the years after the collapse of the Soviet Union was followed by a relative stable trend or even an increase. In aggregate, out of the 242 NUTS 2 regions, 155 experienced a downward trend in emissions per capita since 1990, 74 since 2005, eight since 2010, and three since 2015. In two Polish regions, per capita emissions are still increasing.

Overall, between 1990 and 2021, emissions per capita in regions (see Table 53) have decreased. For example, in Denmark, the national average was 6.9 tCO₂-eq per person in 2021, with regional levels ranging from 3.2 to 13.2 tCO₂-eq per person, in comparison with a national average of 13.4 tCO₂-eq per person in 1990 and regional levels between 8.8 and 21.1 tCO₂-eq per person in that year. Only in Hungary the level of emission per capita in the less emitting region has significantly increased between 1990 and 2021 (from 2.9 to 4.5 tCO₂-eq per person). This is due to the installation and closure of coal fired power stations.

Table 53: National per capita emissions and range across regions

TCO ₂ -EQ PER PERSON	1990	2021
Austria	10.8 (4.5 - 15.4)	9.2 (4.2 - 13.7)
Belgium	14.5 (4.4 - 20.8)	10.8 (3.9 - 15.6)
Bulgaria	11.8 (7.5 - 21.5)	8.6 (5.8 - 20.5)
Croatia	7.5 (3 - 10.2)	6.1 (3.5 - 7.9)
Cyprus	9.3	9.5
Czechia	18.9 (7.4 - 39.2)	11.3 (4 - 27.9)
Denmark	13.4 (8.8 - 21.1)	6.9 (3.2 - 13.2)
Estonia	27.2	14.8
Finland	16.9 (2.1 - 22.1)	11.6 (1 - 13.8)
France	9.6 (0.1 - 33.2)	6.3 (0.1 - 21.6)
Germany	15.5 (6.5 - 30.6)	9.3 (4.7 - 19.7)
Greece	9.6 (3.7 - 101.2)	6.7 (3.8 - 33.4)
Hungary	9.3 (2.9 - 20)	7.1 (4.5 - 11.7)
Ireland	16.5 (10.8 - 23.5)	12.4 (8.7 - 16.4)
Italy	9.3 (4.9 - 16.8)	6.6 (4.1 - 13.3)
Latvia	10.5	6.2
Lithuania	12.9 (11.9 - 15.7)	8.4 (5.2 - 9.7)
Luxembourg	33.5	14.7
Malta	7.1	4.2
Netherlands	16.3 (10.4 - 64.2)	11.1 (5.8 - 35.2)
Poland	13.6 (5.2 - 28.2)	11 (4.6 - 22.8)
Portugal	5.9 (2.1 - 24.8)	5.4 (2.5 - 15)
Romania	10.1 (5.3 - 17.1)	6.2 (2.9 - 10.4)
Slovakia	14.2 (10 - 18.9)	8.8 (6.2 - 11.6)
Slovenia	11.6 (8.4 - 14.2)	9.1 (6.4 - 11.5)
Spain	7.4 (2.8 - 35.2)	6.3 (2.3 - 16.7)
Sweden	9.2 (6.6 - 17.2)	5.8 (3.9 - 13.7)

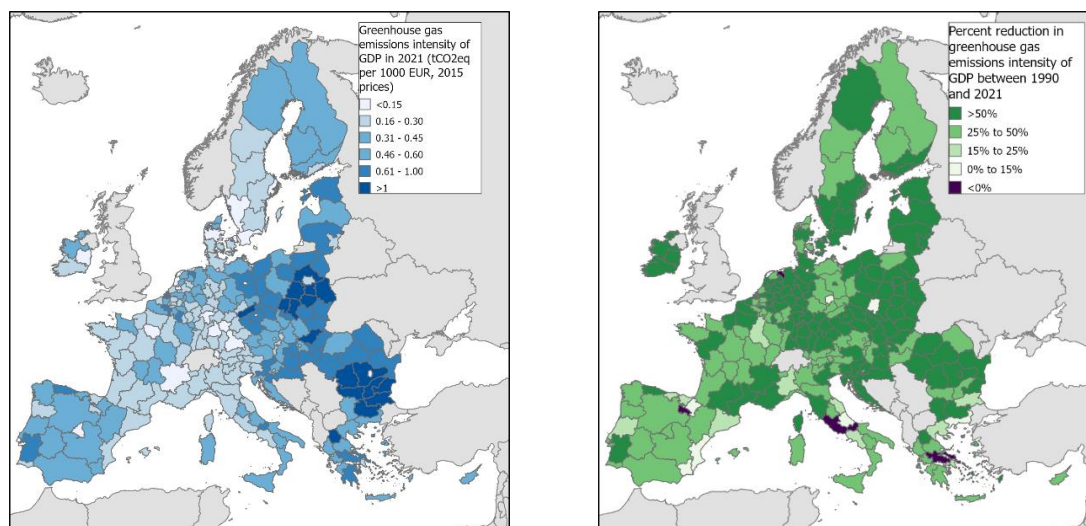
Note: For countries with one region only, a figure instead of a range is reported.

Source: EDGAR emissions database

In 214 out of the 242 EU regions, the GHG intensity (emissions per regional economic output) is above 0.15 (Figure 127), i.e. above the EU average that is compatible with an at least 55% net GHG emission reduction by 2030 ⁽³¹⁹⁾. However, in all but eight regions emission intensity has declined since 1990. In fact, more than half of the EU's regions (122 out of 242) have seen their emission intensity decrease by more than 50% since 1990, including in several regions that had a very high emission intensity such as Świętokrzyskie (PL) and Western Macedonia (EL).

⁽³¹⁹⁾ The figure of the EU average GHG intensity compatible with the 55% target depends on the computation method and on the GDP estimates used. Other computations can give an average of 0.10 tCO₂eq per 1000 euros instead of 0.15.

Figure 127: Emission intensity (left) and corresponding change since 1990 (right)



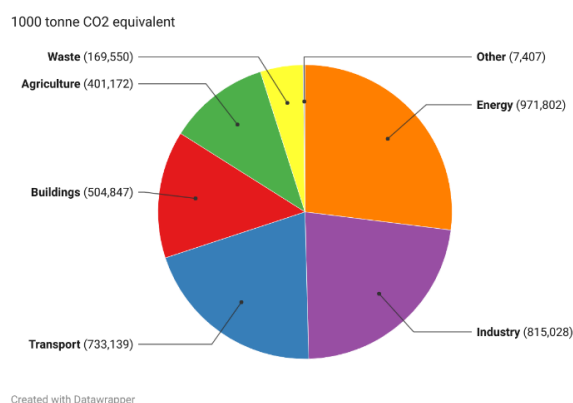
Note: leaving out aviation and shipping

Source: EDGAR emissions database

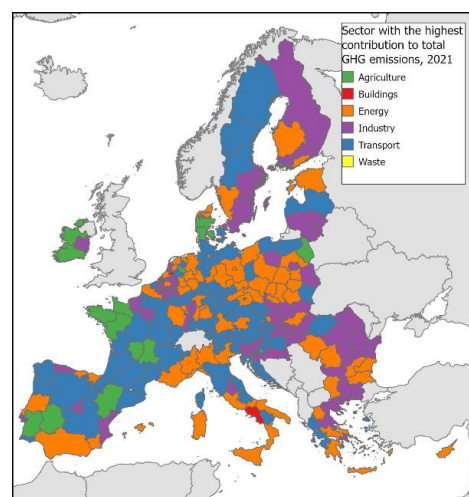
The exposure of regions to the transition is strongly dependent on their economic activities. While the energy, industry, transport, building and agriculture sectors respectively represent 27, 23, 20, 14 and 11% of total EU GHG emissions (Figure 128), the distribution of sectoral emissions in specific regions is more diverse. For example, the sector contributing the most to GHG emissions is agriculture (39%) in the west of France, industry (33%) in Romania, energy (34%) in most Polish regions, and transport (45%) in the north of Sweden (in the region Mellersta Norrland).

Figure 128: Greenhouse gas emissions by sector in the EU27 and sector with the highest contribution at the regional level in 2021

Total greenhouse gas emissions by sector in the EU27 in 2021



Note: leaving out aviation and shipping



Source: EDGAR emissions database⁽³²⁰⁾

Table 54 and Table 55 present the sectoral per capita emissions at the national level and the range of these across regions in each country, in 1990 and 2021 respectively. The

⁽³²⁰⁾ Emissions data in EDGAR include CO₂, CH₄, N₂O, F-gases.

national averages reflect the structure of the country's economy. For example, emissions in Ireland are largely driven by the agricultural sector (6 tCO₂-eq per person in 1990 and 4.6 in 2021). However, the ranges across regions show the diversity within country. For example, in France, the highest regional agricultural emissions amounted to 18 tCO₂-eq per person in 1990 and decreased to 9.5 in 2021.

For the energy and industry sectors, which have been largely covered by the EU Emissions Trading System (EU ETS) since 2005, the decarbonisation trend is clear. In 1990 national sectoral emissions per capita were ranging from 0.8 (France) to 6.2 tCO₂-eq per person (Czechia) for the energy sector and from 0.1 (Malta) to 6.8 tCO₂-eq per person (Czechia) for the industry sector. In 2021 these emissions are lower and closer to one another, from 0.3 tCO₂-eq per person (Lithuania) to 4.3 (Estonia) for the energy sector, and from 0.7 tCO₂-eq per person (Malta) to 4.7 (Estonia) for industry. Due to the regional concentration of some activities, disparities across a country's regions can be large. For example, in the Netherlands regional emissions from the energy sector range from 0.4 – 22 tCO₂-eq per person and from industry from 1.2 - 21.4 tCO₂-eq per person.

Emissions from the transport and building sectors will be covered by the ETS2. To address potential social impacts of this new instrument, the Social Climate Fund will finance temporary direct income support for vulnerable households and support measures and investments that reduce these emissions (see more details in the enabling framework in Annex 9).

Table 54: Sectoral per capita emissions and range across regions in 1990

TCO ₂ -EQ PER PERSON	AGRICULTURE	BUILDINGS	ENERGY	INDUSTRY	TRANSPORT	WASTE
Austria	1.2 (0 - 1.9)	1.8 (1.2 - 2.3)	1.9 (0.3 - 4.2)	3.2 (1.1 - 7.3)	1.8 (0.3 - 2.8)	0.8 (0.1 - 1.8)
Belgium	1.2 (0 - 4.4)	2.7 (2 - 3.2)	2.6 (0.1 - 5.3)	5.3 (1.5 - 11.7)	2 (0.5 - 6.3)	0.7 (0.3 - 2.4)
Bulgaria	1.4 (0.7 - 1.7)	0.9 (0.8 - 1)	5 (1 - 15)	2.7 (0.8 - 3.8)	0.7 (0.6 - 0.9)	1 (0.5 - 1.4)
Croatia	1 (0.1 - 1.5)	0.9 (0.5 - 1.1)	1 (0.4 - 1.5)	3.6 (1.7 - 5.4)	0.8 (0.2 - 1)	0.2 (0.2 - 0.2)
Cyprus	0.8 (0.8 - 0.8)	0.3 (0.3 - 0.3)	3 (3 - 3)	2.6 (2.6 - 2.6)	2.1 (2.1 - 2.1)	0.6 (0.6 - 0.6)
Czechia	1.7 (0 - 3.8)	3 (2 - 3.3)	6.2 (1.4 - 27.4)	6.8 (3.2 - 24)	0.7 (0.2 - 1)	0.4 (0.2 - 1)
Denmark	2.4 (0.2 - 4.4)	1.7 (1.6 - 1.8)	4.9 (1.7 - 12.9)	1.9 (1.2 - 2.9)	1.9 (1 - 2.5)	0.4 (0.2 - 0.7)
Estonia	1.9 (1.9 - 1.9)	1.3 (1.3 - 1.3)	16.8 (16.8 - 16.8)	4.5 (4.5 - 4.5)	1.5 (1.5 - 1.5)	1.1 (1.1 - 1.1)
Finland	1.3 (0.3 - 2.5)	1.9 (0.1 - 2)	3.8 (0.7 - 6.2)	4.1 (0 - 6.4)	2.2 (1.2 - 3.7)	3.5 (0 - 4.6)
France	1.5 (0.1 - 1.8)	1.8 (0 - 2.6)	0.8 (0 - 3.3)	3 (0 - 7.4)	1.9 (0.6 - 3.6)	0.4 (0.1 - 3.6)
Germany	1.1 (0 - 4.1)	2.8 (1.8 - 3.3)	4.8 (0.4 - 17.8)	4.2 (1.6 - 9.6)	2 (0.5 - 4.4)	0.6 (0.1 - 3.2)
Greece	0.9 (0 - 2.8)	0.9 (0.6 - 1.2)	3.5 (0 - 88.6)	2.7 (1.1 - 7.4)	1.2 (0.5 - 2.5)	0.4 (0.1 - 1.1)
Hungary	1.1 (0 - 1.9)	2 (1.1 - 3)	2 (0.1 - 8.5)	2.7 (0.8 - 8.1)	0.8 (0.2 - 1.1)	0.6 (0.5 - 0.9)
Ireland	6 (2.7 - 9.7)	3.1 (2.8 - 3.6)	3.1 (0.2 - 7.7)	2.4 (1.3 - 3.1)	1.4 (1 - 1.9)	0.6 (0.3 - 1.5)
Italy	0.7 (0.1 - 1.9)	1.4 (1.3 - 1.6)	2.2 (0.1 - 6.2)	2.9 (1.3 - 6)	1.7 (0.9 - 5.6)	0.5 (0.1 - 1.5)
Latvia	2.4 (2.4 - 2.4)	1.4 (1.4 - 1.4)	3.7 (3.7 - 3.7)	1.6 (1.6 - 1.6)	1.1 (1.1 - 1.1)	0.2 (0.2 - 0.2)
Lithuania	2.4 (0.8 - 2.9)	2 (1.6 - 2.1)	3.3 (1 - 10)	3.2 (2 - 3.6)	1.5 (1.1 - 1.7)	0.4 (0.1 - 0.5)
Luxembourg	1.7 (1.7 - 1.7)	3.5 (3.5 - 3.5)	4.6 (4.6 - 4.6)	16.3 (16.3 - 16.3)	7 (7 - 7)	0.3 (0.3 - 0.3)
Malta	0.3 (0.3 - 0.3)	0.3 (0.3 - 0.3)	5 (5 - 5)	0.1 (0.1 - 0.1)	1.3 (1.3 - 1.3)	0.1 (0.1 - 0.1)
Netherlands	1.5 (0.3 - 4.2)	2.6 (2.3 - 3.9)	2.9 (0.5 - 9.7)	6.3 (1.5 - 41.9)	1.8 (1.2 - 5.3)	1.2 (0.1 - 5.9)
Poland	1.3 (0.3 - 4.5)	1.5 (1.4 - 1.7)	5.9 (0.4 - 15.4)	3.9 (0.9 - 16.5)	0.5 (0.3 - 0.8)	0.5 (0.1 - 3.1)
Portugal	0.8 (0 - 4.8)	0.4 (0.3 - 0.6)	1.5 (0 - 13.7)	1.6 (0.7 - 2.9)	0.9 (0.4 - 1.9)	0.6 (0.2 - 1)
Romania	1.4 (0.1 - 1.8)	0.8 (0.5 - 0.9)	3.2 (0.3 - 11.4)	4 (1.7 - 7.1)	0.5 (0.2 - 0.6)	0.2 (0.1 - 0.3)
Slovakia	1.3 (0.4 - 1.5)	3.3 (3.2 - 3.4)	2.6 (0.5 - 3.8)	5.5 (3.1 - 9.5)	0.8 (0.7 - 0.9)	0.7 (0.2 - 1)
Slovenia	1.4 (1 - 1.7)	1 (1 - 1.1)	3.1 (1.2 - 4.7)	4.1 (3.3 - 4.8)	1.3 (1.3 - 1.4)	0.6 (0.6 - 0.6)
Spain	1 (0 - 4.1)	0.6 (0.4 - 0.7)	1.7 (0 - 11.2)	2.4 (0.8 - 20.8)	1.4 (0.7 - 3.5)	0.4 (0.1 - 1.1)
Sweden	1 (0.1 - 2.2)	1.3 (1.2 - 1.4)	1 (0 - 2.5)	2.5 (1.2 - 5.6)	2.2 (1 - 5.5)	1.2 (0.6 - 1.5)

Note: leaving out aviation and shipping

Source: EDGAR emissions database

Table 55: Sectoral per capita emissions and range across regions in 2021

TCO ₂ -EQ PER PERSON	AGRICULTURE	BUILDINGS	ENERGY	INDUSTRY	TRANSPORT	WASTE
Austria	0.8 (0 - 1.3)	1 (0.8 - 1.2)	1.4 (0.4 - 2.2)	3.1 (1.5 - 6.3)	2.5 (0.4 - 4.3)	0.3 (0.1 - 0.6)
Belgium	0.8 (0 - 2.7)	2 (1.6 - 2.4)	1.3 (0.1 - 2.1)	4.1 (1.5 - 8.2)	2.1 (0.4 - 6.3)	0.4 (0.1 - 2.4)
Bulgaria	0.8 (0.4 - 1.4)	0.3 (0.2 - 0.3)	3.2 (0.1 - 14.3)	2 (1.1 - 3)	1.3 (1 - 1.8)	0.9 (0.4 - 1.2)
Croatia	0.7 (0 - 1.3)	0.8 (0.6 - 0.9)	0.7 (0.4 - 1)	2 (1.2 - 3)	1.5 (0.3 - 1.9)	0.4 (0.4 - 0.5)
Cyprus	0.6 (0.6 - 0.6)	0.6 (0.6 - 0.6)	3.2 (3.2 - 3.2)	2.3 (2.3 - 2.3)	2 (2 - 2)	0.8 (0.8 - 0.8)
Czechia	0.8 (0 - 1.7)	1.2 (1.1 - 1.4)	4.2 (0.8 - 19.8)	2.9 (1.5 - 6.8)	1.7 (0.4 - 2.6)	0.5 (0.1 - 1.3)
Denmark	1.8 (0.1 - 3.5)	0.6 (0.6 - 0.7)	1.2 (0.4 - 3.4)	1.3 (0.8 - 2.9)	1.7 (0.8 - 2.4)	0.2 (0.2 - 0.3)
Estonia	1.3 (1.3 - 1.3)	0.7 (0.7 - 0.7)	4.3 (4.3 - 4.3)	4.7 (4.7 - 4.7)	2 (2 - 2)	1.7 (1.7 - 1.7)
Finland	0.9 (0.1 - 1.8)	0.7 (0.1 - 0.9)	2.5 (0.5 - 4.2)	4.3 (0 - 6.3)	1.7 (0.7 - 3.2)	1.4 (0 - 2.2)
France	1.1 (0.1 - 9.5)	1.1 (0 - 1.6)	0.6 (0 - 3.4)	1.5 (0 - 3.6)	1.7 (0.5 - 3.6)	0.4 (0.1 - 1.7)
Germany	0.7 (0 - 2.4)	1.5 (1.1 - 1.7)	2.8 (0.4 - 7.7)	2.3 (0.9 - 5.6)	1.7 (0.4 - 3.8)	0.3 (0.1 - 1)
Greece	0.6 (0 - 2.2)	0.5 (0.5 - 0.6)	1.9 (0.1 - 23.3)	2 (0.8 - 4)	1.1 (0.4 - 2.8)	0.5 (0 - 1.5)
Hungary	0.8 (0 - 1.4)	1.3 (1.2 - 1.4)	1.1 (0 - 3.4)	2.2 (1.3 - 4.2)	1.4 (0.4 - 2.2)	0.2 (0.2 - 0.3)
Ireland	4.6 (2 - 7.7)	1.7 (1.7 - 1.7)	1.9 (0.8 - 3.3)	1.9 (1.6 - 2.1)	2 (1.4 - 2.8)	0.2 (0.2 - 0.4)
Italy	0.6 (0.1 - 1.7)	1.2 (1.2 - 1.4)	1.6 (0.3 - 5.2)	1.4 (0.8 - 2.4)	1.5 (0.9 - 4.8)	0.3 (0.1 - 0.9)
Latvia	1.3 (1.3 - 1.3)	0.7 (0.7 - 0.7)	0.9 (0.9 - 0.9)	1.3 (1.3 - 1.3)	1.5 (1.5 - 1.5)	0.4 (0.4 - 0.4)
Lithuania	1.5 (0.5 - 1.9)	0.6 (0.5 - 0.6)	0.3 (0.1 - 1)	3.2 (1.6 - 3.9)	2.2 (1.3 - 2.6)	0.5 (0.2 - 0.6)
Luxembourg	1 (1 - 1)	2.4 (2.4 - 2.4)	0.4 (0.4 - 0.4)	2.5 (2.5 - 2.5)	8.3 (8.3 - 8.3)	0.1 (0.1 - 0.1)
Malta	0.1 (0.1 - 0.1)	0.2 (0.2 - 0.2)	1.6 (1.6 - 1.6)	0.7 (0.7 - 0.7)	1.3 (1.3 - 1.3)	0.2 (0.2 - 0.2)
Netherlands	1 (0.2 - 2.9)	1.6 (1.5 - 2.3)	2.7 (0.4 - 22)	3.9 (1.2 - 21.4)	1.6 (1 - 2.8)	0.3 (0.1 - 1.2)
Poland	1 (0.2 - 3.3)	1.4 (1.2 - 1.6)	3.8 (0.5 - 12)	2.8 (1.3 - 6.1)	1.7 (1 - 2.6)	0.2 (0.1 - 0.8)
Portugal	0.7 (0 - 5)	0.4 (0.3 - 0.5)	0.9 (0 - 2.1)	1.6 (0.9 - 3.3)	1.4 (0.5 - 3.2)	0.5 (0.2 - 0.9)
Romania	0.9 (0.1 - 1.1)	0.7 (0.6 - 1)	1.2 (0.1 - 5.7)	2.1 (0.9 - 3.3)	1 (0.3 - 1.3)	0.4 (0.2 - 0.9)
Slovakia	0.5 (0.2 - 0.6)	1 (1 - 1)	1.2 (0.2 - 1.7)	4 (1.9 - 6.8)	1.5 (1.1 - 1.8)	0.6 (0.2 - 0.9)
Slovenia	1 (0.7 - 1.3)	0.6 (0.6 - 0.6)	1.8 (0.5 - 2.9)	3.1 (2.3 - 3.7)	2.4 (2.1 - 2.6)	0.3 (0.3 - 0.3)
Spain	0.9 (0 - 4.4)	0.6 (0.5 - 0.8)	1 (0.1 - 3.9)	1.6 (0.7 - 8.3)	1.6 (0.7 - 4.4)	0.5 (0.1 - 1.6)
Sweden	0.7 (0.1 - 1.6)	0.3 (0.2 - 0.4)	0.8 (0.1 - 2.6)	1.9 (1.2 - 4.6)	1.4 (0.5 - 4.1)	0.8 (0.7 - 1.5)

Note: leaving out aviation and shipping.

Source: EDGAR emissions database

2.5.2.2. Regional dependency to sectors that will need to transform

Regions with a relatively high share of employment in sectors significantly impacted by the transition are more exposed to the transition. This includes the regions with a high share of employment in sectors which are being phased out in several countries (mining of coal, lignite and oil shale; extraction of crude petroleum, natural gas and peat; and refining of petroleum products), in energy intensive sectors, as these will have to produce the same goods differently (manufacturing of chemicals and chemical products, manufacturing of other non-metallic mineral products, manufacturing of basic metals),

and in sectors that will have to produce different goods (manufacturing of motor vehicles, trailers and semi-trailers) ⁽³²¹⁾.

In 2020, only two EU regions (NUTS-2 level) had employment shares of more than 1% in terms of direct employment in coal and lignite mining, crude petroleum and natural gas extraction. The region with the highest employment share (3.67%) in these sectors is Śląskie/Silesia, in Poland due to its relatively high activity in coal and lignite mining. The other region is Sud-Vest Oltenia in Romania where the mining and fossil fuel extraction sectors employ 1.12% of the work force. The local impact on regions reliant on these sectors is significant as those sectors have a central role in local economies, driving indirect employment as well. Therefore, the employment and social consequences of the decline in extraction activities needs to be mitigated, in line with the European Green Deal's objective to leave no region behind (see Annex 9).

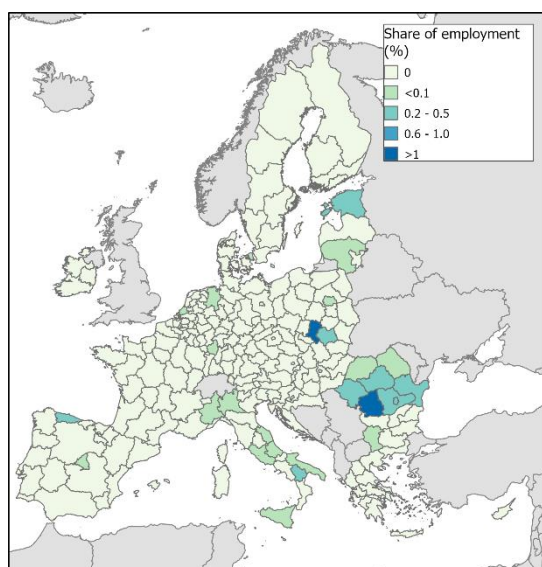
When considering the energy intensive industries or industries that will have to produce different goods (e.g., automobile sector), it becomes apparent that more regions will be affected. Out of the EU's 27 member states, 23 have regions where more than 1% of the working population was employed in 2020 in such a sector. The regions with the highest exposures in 2020 were Śląskie (PL) (10.2%), Közép-Dunántúl (HU) (9.6%) and Střední Čechy (SK) (9.40%). The regions with a relative high employment in carbon intensive manufacturing are also significantly exposed to the transition. For example, for the territories involved in the automobile sector, the move to the manufacturing of electricity vehicles will require companies from the supply chain to adjust their business models.

The development of an industrial carbon management system will require the development of a full supply chain and of the necessary infrastructure to link CO2 emitting energy supply and industrial sites to carbon storage or usage sites (notably to produce e-fuels). The territories with strong presence of energy intensive industries (e.g., cement production, chemicals industries, etc) will have to anticipate and develop the corresponding capacities.

⁽³²¹⁾ See also OECD (2023), Regional Industrial Transitions to Climate Neutrality, OECD Regional Development Studies, OECD Publishing, Paris.

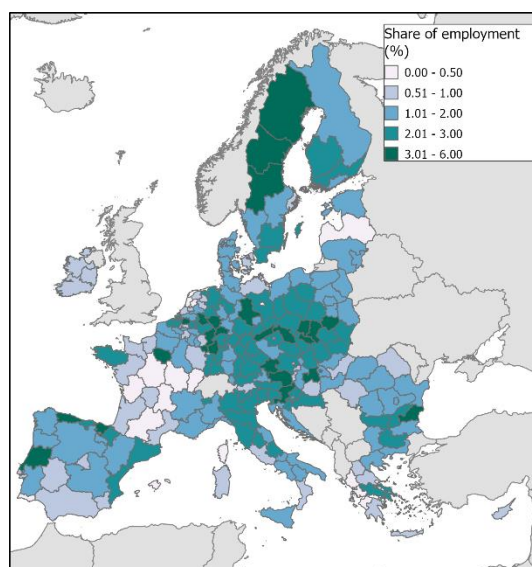
Figure 129: Share of employment in sectors most negatively impacted

(a) Regional exposure to sectors expected to decline



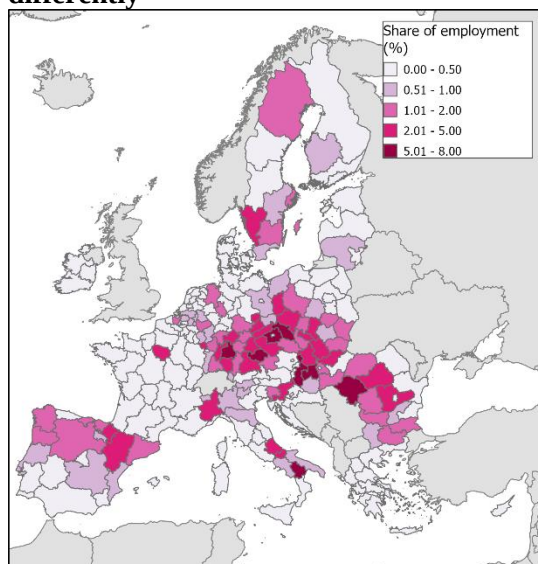
Share of total employment in mining of coal and lignite (B06) and extraction of crude petroleum and natural gas (B07) in 2020

(b) Regional exposure to energy intensive sectors



Share of total employment paper and paper products (C17), coke and refined petroleum products (C19), chemicals and chemical products (C20), other non-metallic mineral products (C23) and basic metals (C24) in 2020

(c) Regional exposure to sectors that will have to produce the same goods differently



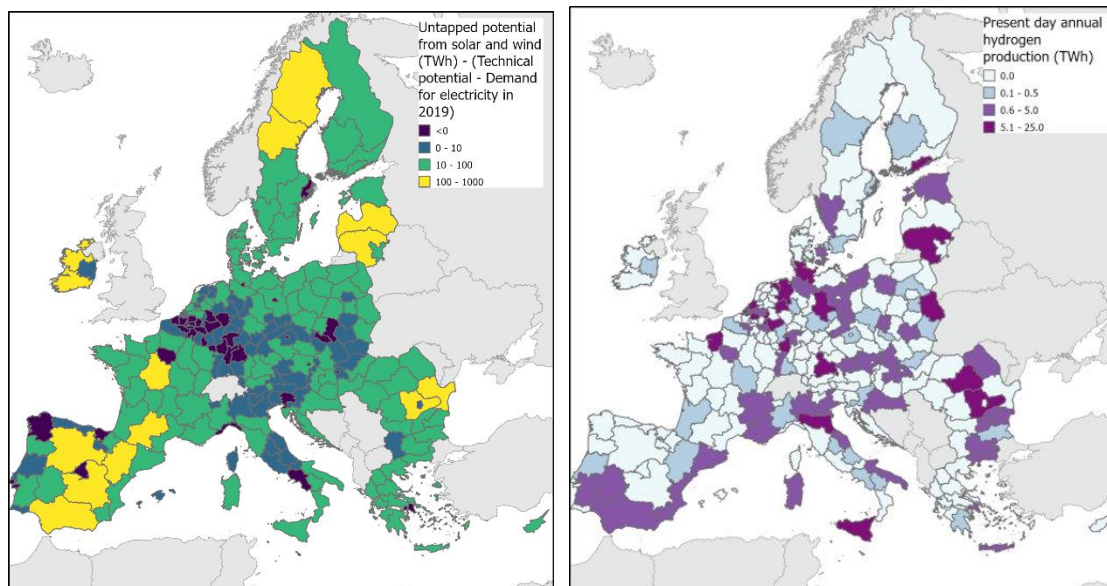
Share of total employment in motor vehicles, trailers and semi-trailers (C29) in 2020

Source: Eurostat structural business statistics and labour force survey

The transition is also an opportunity for new activities or sectors to develop. For example, while Sweden's Upper Norrland and Middle Norrland regions have a relatively high share of employment in carbon-intensive manufacturing sector, they are also areas where the technical potential for electricity from renewable was more than 100TWh

higher than the actual demand in 2019 (see Figure 130). The untapped potential for electricity production from renewable energy technologies is mostly in rural areas. The Member States with the highest absolute green hydrogen potential are Spain (1388 of excess TWh), France (917), Romania (493) and Poland (456). The three EU regions with the highest absolute potential are all located in Spain: Castilla y León (488), Castilla-La Mancha (366), and Aragón (263).⁽³²²⁾

Figure 130: Untapped potential for electricity production from solar and wind in 2019 (left) and present-day annual hydrogen production (right) in EU regions.

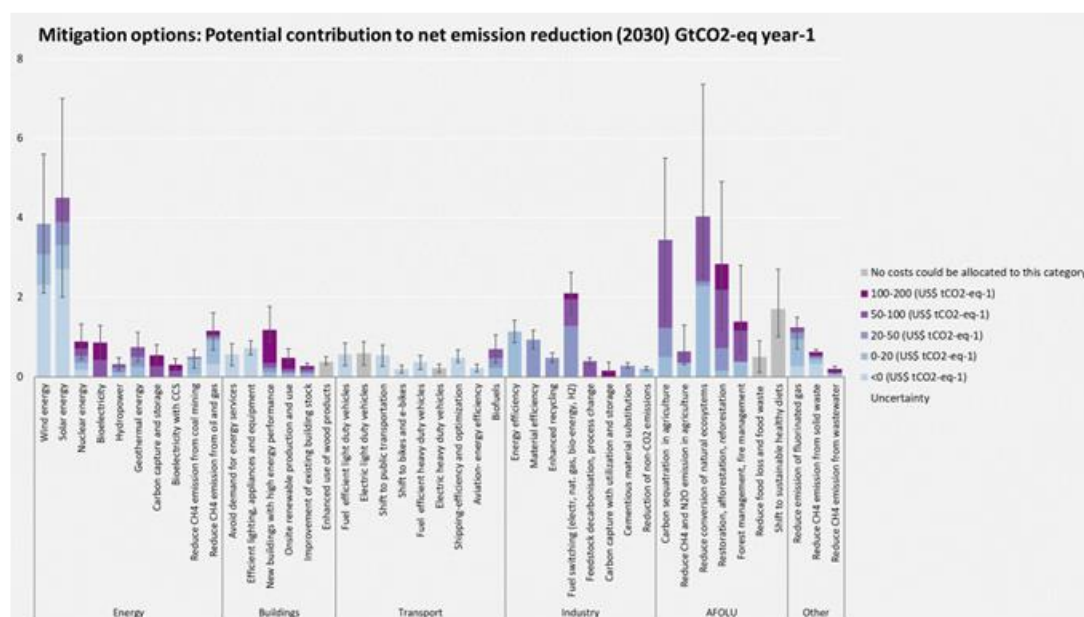


Source: Data from Kakoulaki et al., 2021. Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables, *Energy Conversion and Management* 228 (2021) 113649

The potential contribution of the various economic sectors to EU net emission reduction (Figure 131) suggests that rural areas can significantly contribute to emission reductions, for example by carbon sequestration in agriculture. Nature-based removals activities like afforestation and nature restoration may spur investment and economic activity in these areas.

(322) According to Kakoulaki et al. (2021), the technical potential for wind and solar for the EU amounts to 9040 TWh, which is 6441TWh more than the current demand. 10% of this excess (i.e., 644 MWh) is in coal regions in transition with hydrogen infrastructures.

Figure 131: Potential contribution of the various economic sectors to the EU emission reductions



Source: Global outlook based on the IPCC mitigation report (323)

Contrary to coal mining, the mining of elements that are useful for the low-carbon transition (e.g. lithium used for batteries) is a growing sector. Many of the EU's regions have a history of raw materials extraction. The possibility to use former mining sites for the extraction or treatment of elements needed for the decarbonisation is worth being examined. It has the potential to create economic value and employment in historical mining regions, which are often declining as a consequence of deindustrialisation. This may be particularly the case for regions with deposits of high-volume commodities such as iron and copper, given these typically co-occur with critical raw materials⁽³²⁴⁾. Several regions who are not former coal mining regions are considering new mining activities (e.g., Norte in Portugal).

A downside of the mining of critical raw materials is that it is highly capital intensive and account for a relatively small share of employment in the countries. It also imposes environmental costs⁽³²⁵⁾.

The innovation capacities, the level of instruction, and the quality of infrastructure are examples of parameters that contribute to the preparedness of the regions for the transition. Regarding innovation, the ten regions that have contributed the most to the

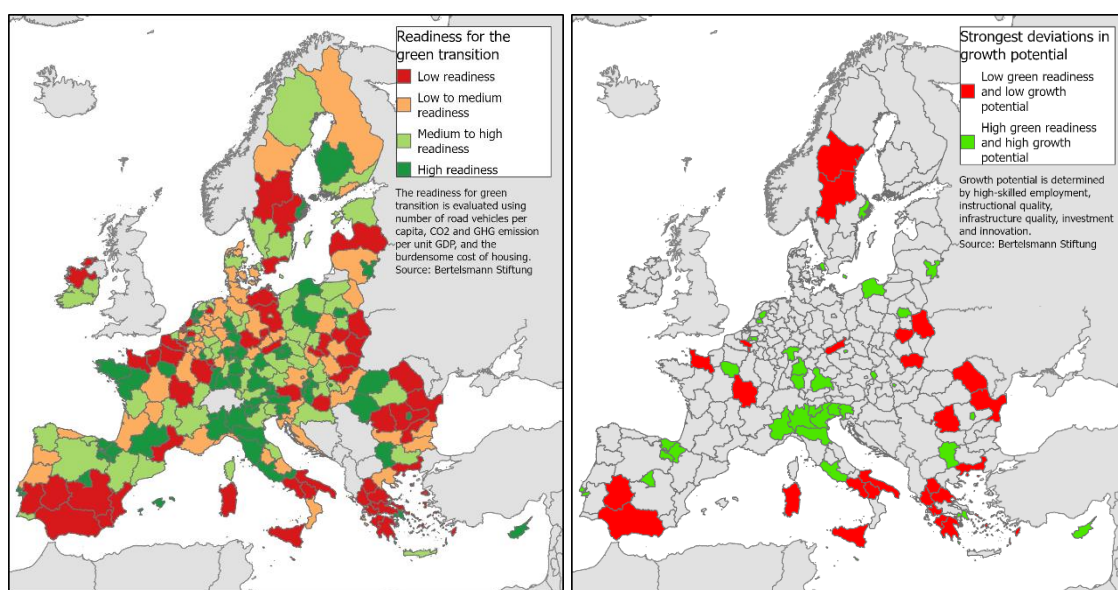
⁽³²³⁾ IPCC. Climate Change 2022. Mitigation of Climate Change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2022

⁽³²⁴⁾ Proposal for a Regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. Impact Assessment Report accompanying the document: SWD(2023) 161 final.

⁽³²⁵⁾ IRENA and ILO (2022), Renewable energy and jobs: Annual review 2022, International Renewable Energy Agency, Abu Dhabi and International Labour Organization, Geneva.

total number of patent application to the European Patent Office in the fields of climate change, environment, resource efficiency and materials over the period 2000-2018 are Île de France (FR), Cataluña (ES), Andalucía (ES), Comunidad de Madrid (ES), Lombardia (IT), Lazio (IT), Oberbayern (DE), Hovedstaden (DE), Zuid-Holland (NL), and Helsinki-Uusimaa (FI) ⁽³²⁶⁾. The study by Maucorps et al. (2022) ⁽³²⁷⁾ provides indicators of the regional readiness for the green transition (Figure 132). The best prepared regions are mainly metropolitan regions specialised in knowledge-intensive services while rural ones have lower growth potential. In regions such as Madrid (ES) and Attica (EL), a high potential for economic growth might be further increased by the green transition while in others such as Sicilia (IT) or Bourgogne (FR) an already low potential for economic growth might be further reduced by the green transition.

Figure 132: Regional readiness for the green transition and correlation with growth potential



Source: Bertelsmann Stiftung

The climate transition will have heterogeneous consequences for the EU's regions. It will both lead to new challenges and opportunities. For instance, the few EU regions significantly exposed to declining sectors and the more numerous regions which rely on energy intensive industries and sectors affected most by the transition will likely be more negatively impacted by the transition. In such regions and territories, the employees from these sectors will have a higher need of reskilling. On the other hand, regions will be able to take advantage of new opportunities offered by the transition. This is particularly the case for regions with higher levels of innovation capacities, which are likely to profit more from the transition than their less-innovative peers. But also, the numerous EU regions with an excess of RES electricity potential can benefit from the transition, for example by developing green hydrogen production. While some extractive facilities have

⁽³²⁶⁾ Science, Research and Innovation Performance of the EU, 2022 (SRIP) – Publications Office of the EU.

⁽³²⁷⁾ Maucorps, Ambre, R. Römisch, T. Schwab, N. Vujanovic, (2022). The Future of EU Cohesion. Effects of the Twin Transition on Disparities across European Region, Bertelsmann foundation.

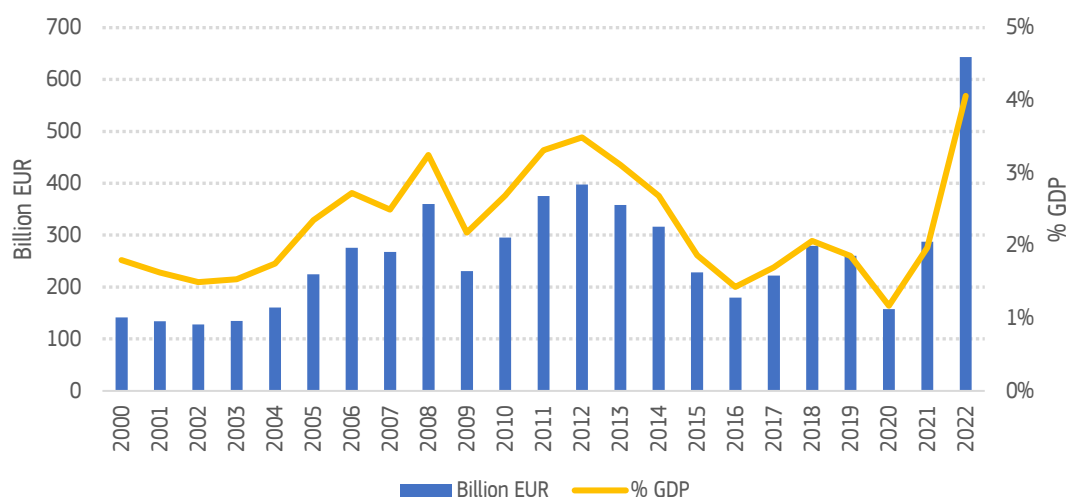
to close, others can be developed for the mining of critical raw materials. The transition to a low carbon economy might widen disparities between regions ⁽³²⁸⁾. Other EU policies such as the cohesion policy play an important role to address this. Annex 9 provides examples of EU and national measures and programmes that can support regions for the transition.

2.6. Energy security

2.6.1. Strategic independence and fuel imports – energy security ⁽³²⁹⁾

Imports of fossil fuels have historically weighed heavily on the EU's trade balance. On average in 2000-2021, gross imports of fossil fuels represented about 20% of total merchandise imports, equivalent to 2.8% of GDP. With the surge in energy prices in 2022, gross fossil fuel imports rose to more than EUR 800 billion, equivalent to 5.1% of GDP and 26.9% of merchandise imports, the highest level in the past two decades relative to GDP. On a net basis (imports minus exports), fossil fuel imports represented EUR 640 billion in 2022 or 4.1% of GDP, compared to an average of 2.2% of GDP in 2000-2021 (Figure 133).

Figure 133: Net fossil fuel imports, 2000-2022



Based on Eurostat's trade data for CN code 27, with the exclusion of codes 2712, 2714, 2715 and 2716.

Source: Eurostat

Figure 134 shows the monetary value of fossil fuels imports in the EU by 2050. Imports decrease significantly in volume between 2020 and 2030 (see Section 1.2) and the import bill is projected to decrease by almost 20% by 2030. This result depends on the assumed trajectories for fossil fuel prices (see Annex 6). These trajectories are input to the PRIMES energy model and significant uncertainties exist on the long-term evolution of fossil fuel prices.

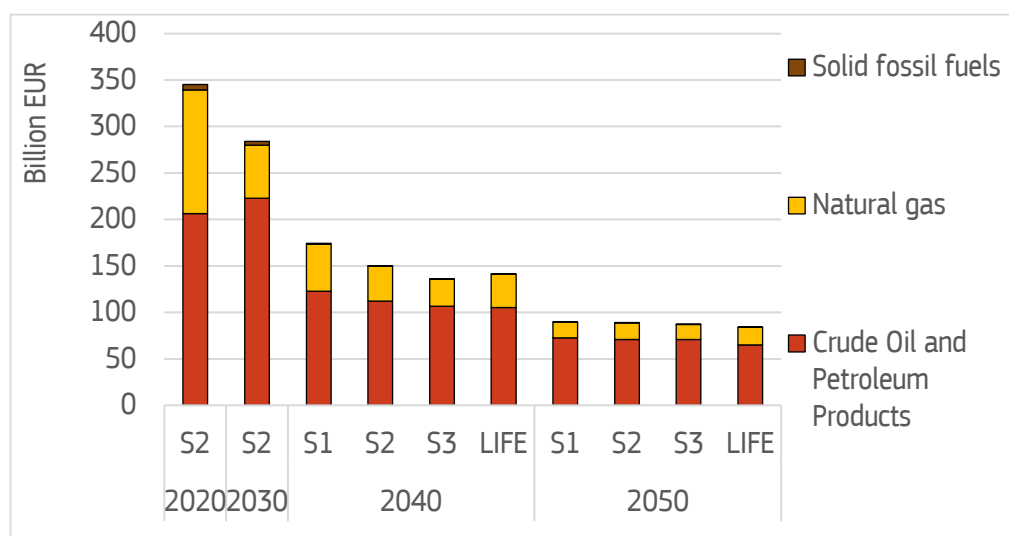
⁽³²⁸⁾ Santos A., J. Barbero, S. Salotti, O. Diukanova and D. Pontikakis. On the road to regional 'Competitive Environmental Sustainability': the role of the European structural funds, Industry and Innovation, 30:7, 801-823, 2023. DOI: 10.1080/13662716.2023.2236048

⁽³²⁹⁾ The model-based analysis is a technical exercise based on a number of assumptions that are shared across scenarios. Its results do not prejudice the future design of the post-2030 policy framework.

With the assumptions used, by 2040, the fossil fuel import bill will be 50% to 63% lower than in 2020 depending on scenarios. Decarbonisation of the energy system will save Europe approximately 1.3 trillion € in the 2031 – 2040 decade compared to 2021 – 2030. With the current assumptions about economic growth, fossil fuels import will decrease from 2.75% of GDP in 2020 to 1.9% in 2030 and to 1% in 2040. This will greatly reduce the economic impact of eventual disruption in fossil fuels supply.

By 2050, imports are dominated by the fossil fuel used for non-energy purposes and are almost 80% lower than in 2020 with very small differences across scenarios.

Figure 134: Annual fossil fuels imports



Source: PRIMES.

While the role of fossil fuels will decline, other dependencies will emerge in the coming decades. Imports of biomass are set to double from approximately 6 Mtoe in 2019 to 12 Mtoe in 2040. While non-existent today, imports of hydrogen and RFNBOs will also become significant reaching approximately 20 Mtoe in 2040 with negligible differences across scenarios. However, these imports will be small compared to the approximately 900 Mtoe of fossil fuels imported in 2019.

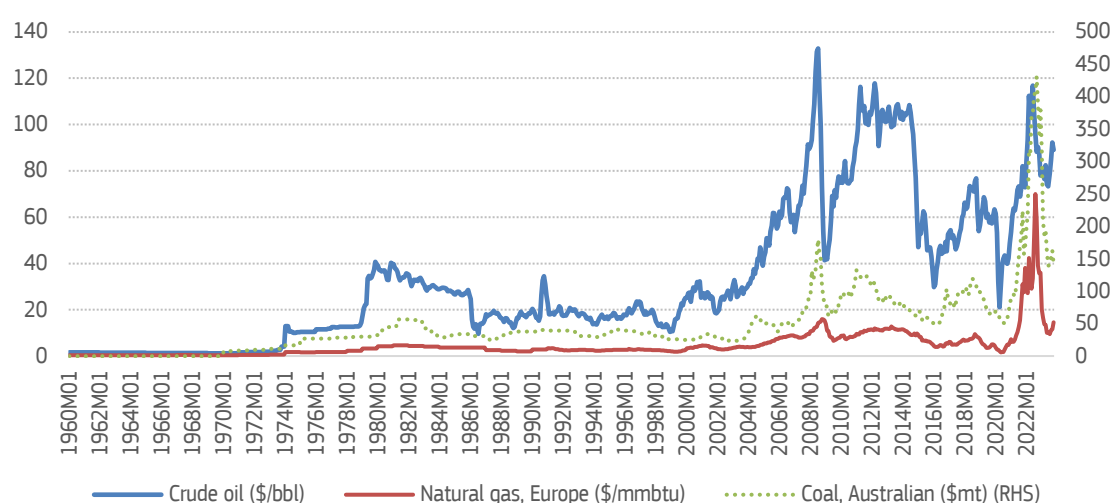
Other relevant dependencies that might emerge are those related to the raw materials needed for decarbonisation technologies. However, the economic consequences of these import will most likely be very different. The risks of import dependency do not depend only their share, but also on other parameters such as market concentration and substitution possibilities. Moreover, the economic implications of scarcity would be very different when dealing with a fuel or a component of specific equipment. Finally, the risk of dependency depends on the possibility to maintain strategic reserves and the cost of storing raw materials varies greatly. The sudden increase in the cost of a raw material used in manufacturing will not have the same macroeconomic impact as the recent stop of gas imports from Russia.

The high decarbonization levels and the corresponding high demand for deployment of renewables, storage and novel technologies may create new dependencies for raw materials or technology imports from other countries. This highlights the role for the Critical Raw Material Act, and the Net Zero Industry Act. The options with a less steeply increasing demand for renewables and novel technologies (e.g., S1) show a lower supply chain and dependence challenges than the higher ambition scenarios (e.g., S3).

2.6.2. Vulnerability to external shocks

Fossil fuel price shocks, particularly for crude oil, have affected the EU and world economy numerous times over the past 50 years or so. Crude oil prices were multiplied by a factor of around 10 within about a year following the first Arab oil embargo in the early 1970s. The Iranian revolution and the onset of the Iran-Iraq war led to another tripling of crude oil prices within a year at the end of the 1970s. Further shocks and high volatility in crude oil prices have continued ever since, with the Gulf War, the global financial crisis and shifts in policy from the Organization of the Petroleum Exporting Countries (Figure 135). While natural gas (in the EU) and coal prices remained more stable for several decades, they have also become more volatile. These past shocks and the most recent one triggered by the Russian war of aggression in Ukraine have generated large negative economic impacts at the global and EU level, alongside social hardship and a significant redistribution of wealth across countries.

Figure 135: Monthly fossil fuel prices (US\$, 1960-October 2023)



Source: World Bank Commodity Price Data.

As a major net fossil fuel importer, the EU has been particularly vulnerable to such price shocks. Reducing the dependency on imported fossil fuels would therefore bring clear socio-economic benefits via improved resilience and strategic autonomy. The JRC-GEM-E3 model was used to quantify the benefits of the transition to climate neutrality on key macro-economic variables. The model assessed the impacts of a doubling of fossil fuel prices (oil, coal and gas) at global level. Some geographic differentiation was integrated into the simulation, as domestic prices in energy-exporting countries were less affected than in net importing countries (including the EU). In one set of simulations, spillovers to electricity prices were not considered, while in the other set of simulations spillovers were integrated for Europe only.

The model simulated the impacts of these two sets of stylised shocks, should they occur in 2025 or in 2040. The JRC-GEM-E3 model mirrors the structure of the energy system as represented in the PRIMES scenarios, which means that a high degree of decarbonisation is achieved in 2040, but also that the EU economy has reduced its reliance on fossil fuels to a significant extent in 2025 compared to the 1990s. The impact of a given shock on the 2025 economy would therefore already be significantly lower than the impact on the 1990 economy.

Table 56 indicates that a doubling of fossil fuel prices in 2025, without spillovers to electricity prices, would generate a negative shock of about 0.8% on GDP, 2.6% on private consumption and 1.1% on employment, with an associated increase of 3.0% in inflation. The same shock in 2040, with the associated progress towards the decarbonisation of the energy system, would halve the negative impacts on the same broad macro-economic aggregates.

Table 56: Macroeconomic impacts of energy price shocks (deviation from baseline)

	Fossil only		Fossil + elec	
	2025	2040	2025	2040
GDP	-0.8%	-0.4%	-1.5%	-1.0%
Private consumption	-2.6%	-1.2%	-3.7%	-2.2%
Exports	0.9%	0.4%	0.5%	-0.2%
Imports	-2.4%	-1.2%	-3.0%	-1.9%
Employment	-1.1%	-0.5%	-2.3%	-1.6%
Consumer prices	3.0%	2.0%	3.9%	2.9%
Sectoral output				
Energy intensive industries	0.4%	0.2%	-1.3%	-1.8%
Consumer good manufacturing	-0.5%	-0.5%	-1.1%	-1.1%
Construction	-0.4%	-0.2%	-0.8%	-0.7%
Transport	-1.1%	-0.1%	-1.7%	-1.2%
Market services	-1.1%	-0.6%	-1.6%	-1.0%

Source: JRC-GEM-E3

It must be noted that the one-year GDP impact in 2040 of such a shock is significantly larger than the impact of increasing climate ambition from the level under S2 to that under S3, and that the same shock in 2025 would generate twice that impact on GDP. Similarly, the negative impact on private consumption from a fossil fuel price shock is much larger (both under the 2025 and under the 2040 setting) than the negative impact resulting from an increase in ambition from S2 to S3 (up to -2.2% for the fossil fuel price shock in 2040 compared to -0.5% for the impact of increasing ambition from S2 to S3).

In addition, a closer look at the dissemination channels of a global fossil fuel price shock shows that the EU's lead in decarbonising its economy entails competitiveness gains when/if such shocks arise. A global shock would indeed negatively affect not only the EU economy, but also the global economy and the EU's main trading partners. As a result, the size of the EU's export market would be negatively affected, yet the simulation shows that EU exports would increase overall and that the output of energy-intensive industries would increase somewhat (fossil fuel price shock only). The driving force behind this is the more advanced stage of decarbonisation of the EU economy relative to the rest of the world and hence its reduced vulnerability to increases in fossil fuel prices. EU companies would therefore be in a position to gain export market shares via increased competitiveness, while also gaining shares in the domestic market, to the detriment of imported goods. Decarbonisation therefore reduces the EU's vulnerability to fossil price shocks via two key channels: (1) a lower dependency on fossil fuels overall; and (2) a reduction in the negative impact of a fall in global GDP.

Integrating the effects of spillovers to electricity prices in the EU makes the impacts described above somewhat larger, but the main finding that a higher degree of decarbonisation of the energy system in 2040 than in 2025 shelters the EU economy

remains. Further simulations were done to assess the impact of a fossil fuel price shock in 2040 under three main scenarios. The difference between scenarios for the variables listed in Table 56 is small, but a higher level of ambition is nevertheless associated with a smaller impact of a fossil fuel price shock on GDP, private consumption, employment and consumer prices. For energy intensive industries, the positive impact of a higher ambition is more significant in terms of output as they gain further protection under S2 and S3 in case of fossil fuel price shock than under S1.

These modelling results should also be seen in the context of the support that Member States have provided to households and businesses to shelter them from the impact of the recent surge in energy prices following Russia's war of aggression in Ukraine. In response to the crisis, and to foster support measures in sectors which are key for the transition to a net-zero economy, the Commission adopted in March 2023 the Temporary Crisis and Transition Framework (TCTF), as subsequently amended. The TCTF replaces the former Temporary Crisis Framework (TCF) which was adopted in March 2022. The TCTF facilitates, on a temporary basis, the granting of the following types of aid: (1) limited aid amounts to companies affected by the crisis; (2) liquidity support in the form of subsidised loans or State guarantees; (3) aid to compensate for exceptionally high energy prices; (4) investment aid for accelerating the rollout of renewable energy, (5) aid for the decarbonisation of industrial production processes, (6) aid for the reduction of electricity consumption, and (7) aid for accelerated investments in sectors strategic for the transition towards a net-zero economy.

As of 23 January 2024, the Commission had issued 431 decisions approving 334 national measures for a cumulative amount of aid of EUR 777 billion. All Member States notified schemes under the TCTF. Although aid amounts approved are not evenly distributed among Member States, this may be due to a number of reasons, including that aid amounts approved do not equate to aid actually granted or disbursed. Based on a survey of Member States, the Commission estimates that approximately EUR 141 billion of aid was actually granted to companies, representing 19.3% of the aid approved by the end of June 2023 and corresponding to 0.6% of the EU27 GDP in 2022 and first half of 2023.

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PART 4/5

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IMPACT ASSESSMENT REPORT

Part 4

Accompanying the document

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS**

Securing our future
**Europe's 2040 climate target and path to climate neutrality by 2050 building a
sustainable, just and prosperous society**

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Annex 9: Enabling framework

1 THE INTERNATIONAL DIMENSION

The consequences of the triple planetary crisis of climate change, biodiversity loss and pollution pose an existential threat, particularly to the most vulnerable. All regions and citizens are directly affected by climate change, for example through job losses in climate-affected sectors such as agriculture, fisheries, and tourism. Unequal exposure and vulnerability to climate and environmental impacts of different regions and socio-economic groups worsens pre-existing inequalities and vulnerabilities. Yet, the impacts of climate change are not neutral, as for instance older people, persons with disabilities, displaced persons, or socially marginalised have different or less adaptive capabilities. The planet is warming at a higher speed than expected and all countries are affected by the impacts of climate change. Russia's war of aggression against Ukraine has caused human suffering and massive environmental damage, increased risks to nuclear safety in Ukraine and precipitated an energy and food crisis with global impacts.

As a consequence of the international commitments under the Paris Agreement, and to address the above-mentioned problems, a technological revolution is taking place, with massive investments in renewable energies in developed countries and in China, and in decarbonisation in most of the industrialised economies. With more ambitious environmental and climate policies in developed countries, the markets and investments are evolving, which requires an adaptation of production processes across value chains, thereby creating new gaps between frontrunners and the others and possible new dependencies. This is mobilising governments in different regions of the world, looking for reference models, expertise, and finance for developing greener production processes, diversifying their supply chains, and maintaining their access to markets, while reducing pollution and providing better access to energy in their territory.

At the same time, investments in fossil fuel energy continue at a high pace, and the EU REPowerEU plan and Fit-for-55 policies aim at smoothening the transition between fossil fuels and low-carbon energy sources, to become climate-neutral in 2050. By agreeing and delivering on the ambitious social and economic transformation, the EU and its Member States aim to inspire global climate action and demonstrate that moving towards climate neutrality is not only imperative, but also feasible and desirable. Supporting this global transformation, the EU and its Member States stand ready to engage with all Parties of the Paris Agreement to ensure the timely delivery of robust and ambitious long-term low greenhouse emission development strategies in line with the objectives of the Paris Agreement.

1.1 Climate and energy diplomacy *raison d'être*

In this context, the climate and energy diplomacy of the EU aims *inter alia* at engaging with partners worldwide to implement the Paris Agreement, to limit the global temperature increase to 1.5°C compared to pre-industrial levels, to support the most vulnerable, such as Least Developed Countries and Small Island Developing States in adapting to climate change effects, and to increase international climate finance for mitigation and adaptation. EU action also aims at supporting just transitions towards climate neutral and resilient economies and societies, by encouraging the deployment of renewable energies and increasing energy

efficiency with a view to phasing out fossil fuels. EU cooperation should encourage partners to embrace the opportunities of the green transition, including a safe and affordable access to green energy.

Climate diplomacy is also deployed to support energy security and the green transition in the Western Balkans and the Eastern Neighbourhood and will promote the green reconstruction of Ukraine. It further operates both at multilateral level, in all relevant international fora such as the UN, G20 and G7, OECD or regional organisations, and in bilateral contexts.

Bilateral climate diplomacy has been expanding in the recent years, as an external pillar of the European Green Deal. Climate diplomacy instruments support the multilateral climate negotiations as well as regulatory convergence by deepening mutual understanding about the EU and other countries' climate policies and objectives. They also allow for a strengthening of international cooperation.

While some third countries express concerns about the impact of elements of the European Green Deal measures, for example on their trade relations with the EU, other countries have also showed interest in better understanding the EU climate and energy policies, and learn from the EU's experience in developing a well-functioning carbon market, in modelling, in adaptation strategies, etc. Bilateral climate diplomacy thus allows to project and explain all the policy aspects of the European Green Deal, to create opportunities for cooperation and investments, for developing joint approaches and solutions, and for technical assistance, amongst other types of cooperation. Climate diplomacy instruments facilitate mutual understanding, keeping the channels open for exchanges, including of knowledge and trade. Climate diplomacy allows to avoid creating, or to overcome, new barriers emerging from different policy approaches.

Other international EU actions, such as on biodiversity loss, natural resource management and circular economy, are complementary of climate diplomacy, strictly speaking, as key parts of a holistic approach towards the achievement of the 2030 Agenda and the SDGs. The EU diplomacy in all relevant international fora, including the G7, G20, UNEA, WTO etc, advances an agenda in line with and in support of the implementation of the goals and targets of the Kunming Montreal Global Biodiversity Framework to halt and reverse biodiversity loss, and to promote the uptake of the circular economy and more in general the sustainable use and management of natural resources. An example is the key role played by the EU in the context of the UN Environment Assembly to achieve ambitious language on circular economy, sustainable consumption and production, nature-based solutions, and sustainable management of mineral resources in the Resolutions 4/1, 4/19, 5/5, 5/11 or 5/12.

Bilateral engagement between countries and regions in general will further expand with the uptake of the green transition in more countries, as mutual understanding, learning from each other and developing joint approaches are key for success and for leaving no-one behind. There is also demand from stakeholders, including businesses, for clear policy orientations and legal certainty. The EU is part of this active global diplomatic efforts (see e.g., Council Conclusions on Climate and Energy Diplomacy of 9 March 2023) and is willing to step up its engagement in areas such as cooperation on Emissions Trading Systems, energy transition, modelling, and adaptation. The Commission and Member States are active in different contexts, and ways of cooperating together to achieve common operational objectives should be further explored.

1.2 Climate diplomacy instruments

The European Commission is engaging in a broad range of High-Level Dialogues on topics related to climate and energy, amongst others, with third countries, such as Canada, Australia, Japan, New Zealand, China, India, Indonesia, Colombia, or Mexico. This allows for exchanging on respective climate policies and identifying areas for further cooperation. New High Level Climate Dialogues are being launched with Chile and Brazil.

The Green Alliances with Japan and Norway, as well as the Green Partnerships with Morocco and the Republic of Korea are recently designed instruments that allow the EU to strengthen cooperation with like-minded countries that either committed to climate neutrality by mid-century or are putting in place ambitious climate policies by 2030. Such alliances and partnerships provide for a reinforced platform of policy dialogue on reforms linked to the green transition, ad-hoc technical, financial assistance, and investments. They encompass climate but also energy and environmental policies in a whole-of-government approach, where all concerned ministries must participate. Green Alliances and partnerships put climate on the political agenda of the respective countries and provide a clear direction of travel.

The G7-led Just Energy Transition Partnerships (JETPs) with South Africa, Indonesia, Viet Nam, and Senegal are another powerful instrument to prompt sectoral reforms guided by climate ambition. Under shared responsibility between the G7 members, JETPs provide a platform by which partner countries can work with climate finance donor support, private sector investors, multilateral development banks (MDBs) and relevant actors to achieve a just energy transition. The EU Commission and EEAS are co-leading together with the UK on the JETP with Viet Nam.

The integration of the EU climate acquis into the European Economic Area and the EU accession negotiations are also two channels for extending the EU climate legislation to the neighbouring partner countries, including via the Energy Community.

Plurilateral initiatives have achieved significant success in advancing with the commitments set out under the Paris Agreement and the Convention on Biological Diversity. The EU has worked with partner countries to put forward the Global Methane Pledge, which now has over 150 participants and a dedicated secretariat. Likewise, the EU committed to put forward a pledge on Renewable Energy and Energy Efficiency at the upcoming COP 28 in the United Arab Emirates.

The EU is leading the international support for climate change action and works together both on a multilateral and bilateral level with global partners. The EU, its Member States, and its financial institutions, collectively known as Team Europe, is the leading contributor of development assistance and the world's biggest contributor of climate finance, with over EUR 23 billion public finance committed in 2021.

1.3 Engagement of the EU in multilateral fora

The European Commission and the High Representative will continue to work with Member States to mobilise all diplomatic channels – including within the United Nations, the G7, G20, the OECD and other international fora to achieve the ambitions set out in the Paris Agreement. The EU has been able to act as a bridge builder between different Parties and continues to ensure that the principles embodied in the Paris Agreement can be entrusted.

The United Nations Framework Convention on Climate Change (UNFCCC) process has achieved a lot in the recent decades. The Paris Agreement and Katowice rulebook provide a robust framework for climate action. The process is a unique framework within which we should continue to enhance international cooperation, catalyse increased Party and non-Party stakeholder ambition, transparency, and action, while providing a space to exchange experiences in transitioning to low greenhouse gas emission and climate resilient economies and societies.

The ambition cycle built upon the Global Stocktake under the Paris Agreement and the regular submission of NDCs and adaptation communications, as well as information on finance flows and the enhanced transparency framework will be the central feature in driving enhanced climate action and support to achieve the long-term goals of the Paris Agreement. The following work strands are playing a key role in engaging all Parties to the Paris Agreement in achieving the agreed upon objectives:

On Mitigation, the European Union is strongly advocating for an ambitious Mitigation Work Programme within the UNFCCC, focusing on delivering concrete solutions to close the ambition and implementation gap in this critical decade towards 2030 and incentivizing high ambitions.

On Loss and Damage at COP27 in Sharm el-Sheikh, the European Union played a leading, constructive role by presenting a bridge-building proposal and showing openness to what resulted in the establishment of the new funding arrangements, including a fund for assisting developing countries that are particularly vulnerable to the adverse effects of climate change, in responding to loss and damage. Following that decision, the European Union engages constructively in the Transitional Committee work to deliver on all elements of its mandate in line with our consistent commitment to scale up and strengthen support for the sources, funds, processes, and initiatives under and outside the climate regime that are at the core of funding arrangements for loss and damage.

On Adaptation, a steady progress has been made towards the Global Goal on Adaptation (GGA) by implementing the two-year Work Programme launched at COP26, the global commitment to double adaptation finance, the adoption of the 2021 EU Adaptation Strategy, and the continued adoption and revision of EU Member States' National Adaptation Plans and Strategies ⁽¹⁾. At COP27, and in the follow up intersessional Conference 58 in Bonn, Parties agreed on the possible structural elements of a GGA Framework for consideration and adoption at COP28. The Global Stocktake should enable Parties to analyse past efforts to increase resilience and implement adaptation actions while, at the same time, looking forward with increased ambition at all stages of the adaptation policy cycle (risk assessments, planning, monitoring and evaluation).

The FAC Council Conclusions on Climate and Energy Diplomacy approved in March 2023 were another strong political signal and set the course, together with the Environment Council Conclusions, for the EU to support the achievement of an ambitious outcome of COP28.

⁽¹⁾ See <https://climate-adapt.eea.europa.eu/en/countries-regions/countries>.

1.4 Climate change and international security

Current climate extremes, rising temperatures and sea levels, desertification, water scarcity, threats to biodiversity, environmental pollution and contamination are threatening the health and well-being of humanity, and can create greater displacement, migratory movements, pandemics, social unrest, instability, and conflicts. Europe's armed forces are also confronted with the changing and challenging operational conditions due to climate change. These new threats have already prompted allies and partners to update their policies too.

The EU sets out four priorities on Climate Change and Security, namely strengthening planning, decision-making and implementation; operationalising the response to climate and security challenges; enhancing the climate adaptation and mitigation measures of Member States' civilian and military operations and infrastructure; and reinforcing international partnerships. This is done through around thirty actions, including: establishing a data and analysis hub on climate and environment security within the EU Satellite Centre; deploying environmental advisors in the EU Common Security and Defence Policy (CSDP) missions and operations; setting up training platforms at national and EU level such as an EU Climate, Security and Defence Training Platform; developing thorough analysis and studies of related policies and actions, especially in vulnerable geographical areas such as the Sahel or the Arctic.

1.5 Climate change and trade

1.5.1 Trade policy

As the world aims to achieve the goals of the Paris Agreement, trade policy has a role to play in supporting an ecological and green transition not only within the EU but globally. This includes, for instance, accelerating investment in clean energy or the promotion of value chains that are circular, responsible, and sustainable. It also means creating opportunities for sustainable products and services to be traded more extensively.

As the EU continues to be a front runner with the Green Deal and its associated policy implementation, it places significant importance in supporting partner countries in building the necessary mechanisms, capacity and systems via technical exchanges, financial support, and diplomatic efforts.

Trade policy can serve as a platform to engage with trading partners on climate and environmental action, multilaterally e.g., in the World Trade Organization or bilaterally through our Free Trade Agreements. Commitments to sustainability have been continuously strengthened in EU trade agreements, in particular with regard to enhancing climate action through the recent Communication on Trade and Sustainable Development chapters in free trade agreements ⁽²⁾. The Commission has also stepped-up efforts to implement and enforce the sustainable development commitments of EU trade agreements. On climate change more specifically, the EU's most recent agreements all include a binding commitment of the Parties to ratify and effectively implement the Paris Agreement. For countries with which the EU has or is negotiating free trade agreements, climate policy dialogues are also pursued within the

⁽²⁾ COM(2022) 409 final

Trade and Sustainable Development sub-committees, complemented by institutional advisory and monitoring mechanisms. Joint Committees under the EU Strategic Partnership Agreements also provide a forum to review the respective climate, energy, and environmental policies. In addition to or in the absence of such existing frameworks, bilateral summits and other official visits create opportunities to exchange on climate policy issues.

Plurilaterally as well as multilaterally, the EU is involved in the trade and climate nexus. Within the WTO, the EU is working towards making the body a more relevant forum to tackle climate change. In the plurilateral context in the WTO, the EU is involved in discussion on environmental sustainability, ending plastics pollution and fossil fuel subsidy reform. Outside the WTO, the EU together with Ecuador, Kenya and New Zealand forged the Coalition of Trade Ministers on Climate⁽³⁾. The Coalition will provide political steer and guidance to boost inclusive cooperation on climate, trade, and sustainable development.

In trade related discussions in other plurilateral fora, the High Representative and the Commission have been additionally intensifying work and international outreach on ending environmentally harmful fossil fuel subsidies along a clear timeline, with the aim of setting milestones for their phase-out, including through the G7 and the G20, and in the context of the fossil fuel subsidies reform dialogue in the OECD. The EU also supports the modernisation of the OECD arrangements on officially supported export credits⁽⁴⁾. Furthermore, the EU is an active participant in the OECD's Joint Working Party on Trade and Environment that provides analytical work on the trade and environment nexus, including climate change.

1.5.2 Emissions accounting

Discussing the linkages between climate policy and trade also links to the differences between and complexities of accounting for production based vs. consumption-based emissions. Combining and comparing different types of emission accounting methods considering trade is valuable to consider the role of exporting industries and related value chains and their respective emissions⁽⁵⁾. The most common emission accounting method is production-based accounting (PBA). PBA accounts for territorial, production-based emissions and is used for official accounting and reporting (including the EU and international targets, e.g., under the UNFCCC). This is mainly due to sovereignty (the emissions for which a country can be held responsible) and measurement issues (allocating part of another country's emissions to a third country is technically complex).

Besides that, there are two ways of taking trade into account when estimating emission shares. Consumption-based accounting (CBA) assigns emissions where the final product is consumed, considering emissions along the entire value chain. It might penalise countries that are active in reducing emissions in sectors involved in international trade. This is because a country would see a part of its mitigation effort allocated to its export partners, while it would

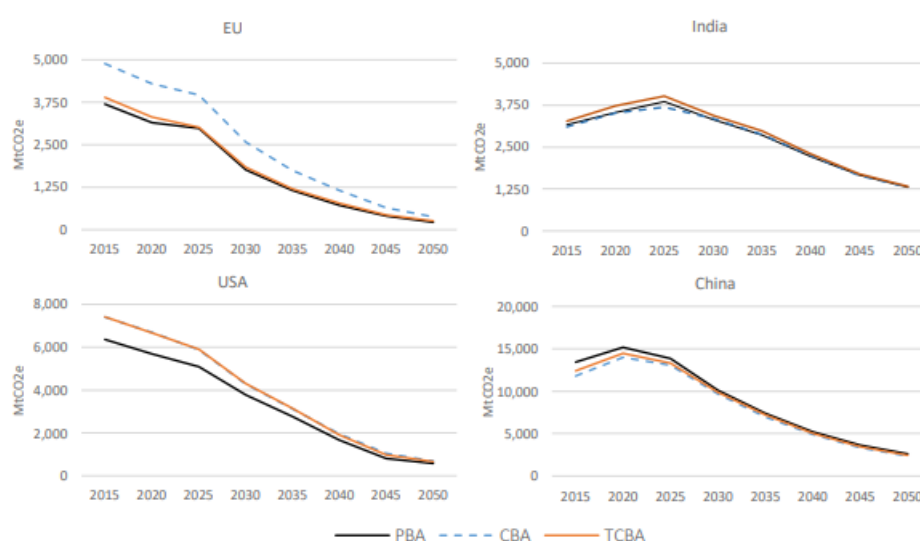
⁽³⁾ See <https://www.tradeministersonclimate.org/>.

⁽⁴⁾ See the Council Decisions of July 2023 in support of modernised export credits (10117/23 and 10121/23).

⁽⁵⁾ See, for example, Jakob et al., 2021, Sharing responsibility for trade-related emissions based on economic benefits, *Global Environmental Change* 66: 102207, <https://doi.org/10.1016/j.gloenvcha.2020.102207>.

be penalised for a lack of similar effort from its import partners. To correct for this effect, technology adjusted consumption-based accounting (TCBA) accounts for differences in technology of export sectors to adjust the CBA metric. Under TCBA, export-related emissions are subtracted based on the average carbon intensity for the relevant sector on the world market, rather than the domestic average, under the assumption that a similar good would have been produced at the average emissions intensity on the world market for that sector ⁽⁶⁾. This metric thus assigns lower emissions to a country than under CBA when its exports are cleaner than the world average, after accounting for sectoral differences in the composition of exports. The EU has reduced both its production-based and consumption-based emissions over the last decades ⁽⁷⁾. Including the TCBA method shows a strong reduction of the gap between EU GHG emissions comparing the PBA and CBA method. Figure 1 shows the GHG emission trajectories for the EU, the US, India, and China under the three methods for emission accounting (projections post-2020 are based on the JRC GECO 2022 1.5 scenario).

Figure 1: GHG emissions under different GHG emission accounting methods



Source: JRC-GEM-E3 model

Overall, assessing the interlinkages between climate policies and trade balances depends on various parameter and approximations, making long term outlooks on trade balances challenging. However, it is clear that with a transformation towards net-zero, fossil fuel-based sectors and products will naturally see a decline in demand, whereas sectors and products already in line with net-zero targets are expected to experience higher demand.

Lastly, EU's net-zero technology industry can contribute to global emission reductions outside EU when products and technologies are exported or when manufacturing in EU

⁽⁶⁾ Kander, A., Jiborn, M., Moran, D.D., Wiedmann T.O. (2015), National greenhouse-gas accounting for effective climate policy on international trade. *Nature Climate Change* 5: 431–435. <https://doi.org/10.1038/nclimate2555>.

⁽⁷⁾ See, for example, the estimates of CO₂ emissions embodied in international trade by the OECD, see <https://www.oecd.org/sti/ind/carbondioxideemissionsembodiedininternationaltrade.htm>.

replaces more polluting manufacturing outside EU. Such contribution to global emission reduction would be additional to the scenarios analysed in this impact assessment and further points at the significance of building on the capacity of the EU in raw materials and industrial clean manufacturing.

1.6 Global competition for raw materials

Demand for non-energy raw materials, such as metals and minerals, increases rapidly with climate ambition ⁽⁸⁾. Unlike fossil-powered technologies, the key technologies to decarbonise the power generation, industry, and transport sectors (namely wind, solar PV, batteries, and hydrogen) require large quantities of metals and minerals ⁽⁹⁾.

In view of the 2050 climate neutrality, the demand for renewable energy generation and decarbonised transport in the EU is expected to increase, and so too the demand of raw materials. Substituting materials and increasing material efficiency and circularity can mitigate the projected rise in demand to a certain extent, but these steps are not expected to reverse the trend (see Annex 6).

Markets are reacting to the current and forecasted increases in demand for critical materials, with significant increases in supply forecast. The market size of key energy transition minerals doubled over the past five years, reaching USD 320 billion in 2022. The IEA says supply of minerals critical to the energy transition could move close to levels needed to support climate pledges by 2030 after investment in critical minerals production jumped 30% last year to \$41 billion, having gained 20% in 2021. Exploration spending also rose by 20% in 2022, driven by record growth in lithium exploration. For lithium, the IEA forecasts supply by 2030 will reach 420,000 metric tons - only a touch short of demand estimated at 443,000 to meet government pledges ⁽¹⁰⁾.

As large uncertainty exists in future amounts of both the demand and supply of metals and materials for decarbonisation, this is reflected in the uncertain outlook for prices of these materials. Large short-term swings have been witnessed in the past due to unbalanced supply and demand market factors, e.g., lithium prices were at record highs at the start of 2023, but by April 2023 had approximately halved ⁽¹¹⁾. Likewise, silicon prices spiked four-fold in mid-2021, but by mid-2022 had returned to pre-spike prices ⁽¹²⁾.

A net-zero economy in the EU will need a secure supply chain able to meet increased product and material demand. Certain products and intermediate material – such as cement and steel – do not represent a supply concern since their manufacturing relies on raw materials that are relatively abundant on earth and whose manufacturing chain is geographically spread across world regions, including the EU. Other products and intermediate materials requiring raw

⁽⁸⁾ World Bank (2017). The Growing Role of Minerals and Metals for a Low Carbon Future.

⁽⁹⁾ JRC (2020). Critical Raw Materials for Strategic Technologies and Sectors in the EU.

⁽¹⁰⁾ IEA (2023). Critical Minerals Market Review 2023.

⁽¹¹⁾ BNEF (2023a). Battery Metals Monthly: Lithium Price Recovery Begins.

⁽¹²⁾ BNEF (2023b). Transition Metals Outlook 2023.

materials that are not available or manufactured in the EU in large quantities (critical raw materials or CRM) are at high supply risk. Supply risk factors can be country-level concentration of global production of primary raw materials and sourcing to the EU, governance of supplier countries ⁽¹³⁾ (including environmental aspects), contribution to recycling, substitution, EU import reliance and trade restrictions in third countries.

The EU currently relies almost exclusively on imports for many CRM. In fact, for 31 out of 82 individual materials or groups assessed, the import reliance is 100% at the extraction or processing stage, and above 80% for another 6 materials ⁽¹⁴⁾.

More importantly, within these imports, suppliers are highly concentrated ⁽¹⁵⁾, and the main suppliers are in many cases exposed to significant environmental, social and governance risks ⁽¹⁶⁾. In three cases, namely light REE, heavy REE and magnesium, the supply share of one country, China, is above 90%. This concentration expands along the value chain, with the processing stage being even more concentrated than the extraction stage for some materials, such as lithium. China controls 69% of the global capacity for refined lithium, 60% for refined cobalt, 79% for refined manganese ⁽¹⁷⁾. In addition to the concentration of supply in single countries, some actors have expanded their dominance of the global value chain by taking control of economic activities and assets in third countries, such as China controlling cobalt mines in Congo ⁽¹⁸⁾. As witnessed during the COVID-19 crisis and the energy crisis following Russian's military aggression against Ukraine, the consequences of excessive dependence on single suppliers can jeopardise the functioning on the single market and harm the EU's competitiveness.

⁽¹³⁾ Worldwide Governance Indicators (WGI): <http://info.worldbank.org/governance/wgi/>. Accessed on 18-04-2023.

⁽¹⁴⁾ European Commission (2020). Study on the EU's list of Critical Raw Materials – Final Report.

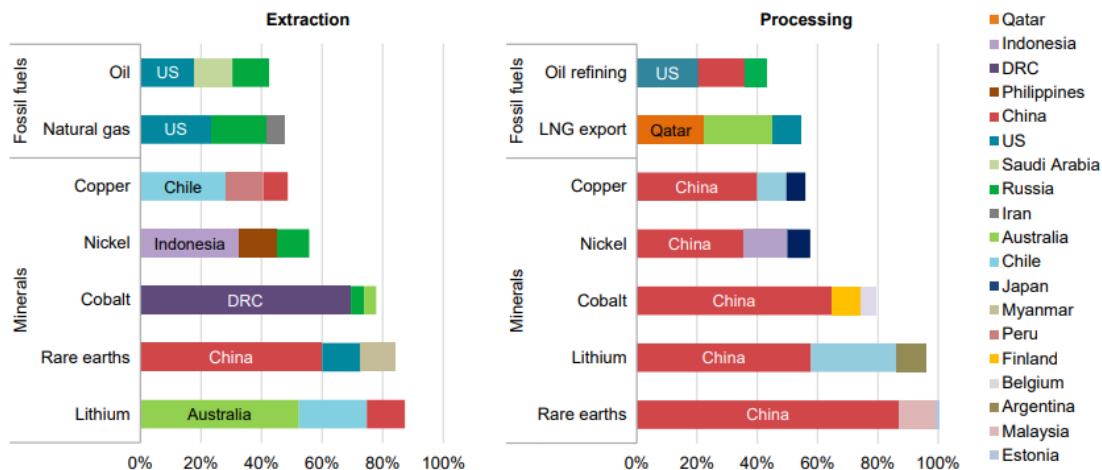
⁽¹⁵⁾ The share of the biggest supplier to the EU is 99% for the group of light rare earth elements (China), 98% for the group of heavy rare earth elements (China), 98% for borates (Turkey), 93% for magnesium (China), 85% for niobium (Brazil), 78% for lithium (Chile) and 68% for Cobalt (DR Congo), source: Study on the EU's list of Critical Raw Materials (2020): Final Report, European Commission 2020.

⁽¹⁶⁾ See IEA (2021) report on Clean Energy Minerals, page 126-131.

⁽¹⁷⁾ JRC (2023). Supply chains and materials demand forecast in strategic technologies and sectors in the EU. A foresight study.

⁽¹⁸⁾ Luc Leruth and Adnan Mazarei (2022). "Who controls the world's minerals needed for green energy?" <https://www.piie.com/blogs/realtime-economic-issues-watch/who-controls-worlds-minerals-needed-green-energy>. Accessed on 10-10-2023.

Figure 2: Major countries in extraction and processing of selected minerals and fossil fuels



Notes: LNG= liquefied natural gas. The values for copper processing are for refining operations. Data from: IEA (2020a), USGS (2021), World Bureau of Metal Statistics (2020), Adamas Intelligence (2020).

Source: Leruth and Mazarei (2022) ⁽¹⁹⁾.

EU reliance on CRM imports is also due to a lack of efficient use of domestic resources, both primary and secondary. The EU is currently a minor player in terms of extraction and processing of primary CRMs. Despite being highly recyclable, the share of recycled CRM is very low: this is because usually CRMs are used in low concentration as part of alloys, which make the recovery process complex, and, until recently, their limited demand did not justify investment in recycling infrastructure. Consequently, the share of CRM secondary production is minimal, and significant CRM resources leave Europe in the form of wastes and scrap.

The EU strategy to overcome the challenges related to the supply of critical raw material is described in the Critical Raw Material Act ⁽²⁰⁾, which aims to strengthen the different stages of the European critical raw materials value chain and diversifying the EU's imports of critical raw materials to reduce strategic dependencies by developing win-win partnerships on sustainable raw materials value chains with resource rich countries and negotiate trade agreements to facilitate trade and investment in CRM in third countries ⁽²¹⁾. For more details, see section 2.1. Circular economy measures, including product policies, can also help optimise the supply of critical raw materials, as they can lower primary CRM consumption and demand, and provide additional co-benefit in reducing biodiversity and pollution impacts stemming from CRM extraction and processing.

⁽¹⁹⁾ Luc Leruth and Adnan Mazarei (2022). “Who controls the world’s minerals needed for green energy?” <https://www.piie.com/blogs/realtime-economic-issues-watch/who-controls-worlds-minerals-needed-green-energy>. Accessed on 10-10-2023.

⁽²⁰⁾ COM(2023) 165 final

⁽²¹⁾ COM(2020) 474 final

2 AN INDUSTRIAL STRATEGY

Industry is one of the backbones of EU economy, and reducing its emissions is a key step toward the 2050 climate neutrality.

Decarbonisation of the industry is complex. While it includes the production of some commodities like metals and cement, the remainder of the sector's output is extremely heterogeneous, producing very different materials and end products. It covers a highly diverse set of input-output relationships that are highly integrated with the energy sector and the overall economy. Decarbonising industry also enables to reduce the embodied emissions in the products and equipment used in transport sector and the built environment. Given the heterogeneity of the industrial sector, it stands to reason that a wide variety of decarbonisation levers will be required, there is no silver bullet for complete industrial decarbonisation and more ad-hoc solutions that consider the specific characteristics of the sub-sectors needs to be implemented. An increasing number of technological solutions that result from net-zero technology compatible investments and innovation could provide mainstream solutions in many industrial sub-sectors by 2040, such as new manufacturing technologies, innovation in processes, use of alternative materials or sources and cleaner supply chain.

The climate transition represents a great opportunity for creating jobs and growth. The net-zero technology manufacturing industries, and its related ecosystem, are expected to undergo rapid growth in the coming decades. Innovative business models, such as circular practices and sharing economy, together with more responsible and sustainable consumer choices will steer industry toward more resource-efficient and less climate-intensive value chains.

Today, the EU is already a global leader in certain clean sectors and is well positioned to maintain its central role in the coming years. Embracing the industrial transition and encouraging the development of domestic green and circular industry will provide a competitive advantage to the EU. It will decrease resource dependency and spur innovation, making the EU stronger at global level. However, especially the US and China are investing heavily to compete on industrial decarbonisation solutions.

In response, between January and March 2023, the Commission tabled a number of proposals to strengthen the growth and innovative strategy from the European Green Deal. The Green Deal Industrial plan, adopted by the Commission on 1 February 2023 provides the overarching principles of this reinforced industrial strategy to make Europe the home of clean tech and industrial innovation. Additionally, provisions relevant for the EU industrial strategy are also included in the provisional agreement on the proposal for a revision of the Renewable Energy Directive (RED) proposed as part of the Fit-For-55 package as well as the revision proposed as part of the REPowerEU package, and for the revision of the F-gases regulations.

2.1 The Green Deal Industrial Plan

The **Green Deal Industrial plan** contains four pillars. The first one is to improve the regulatory environment to focus investment on strategic sectors and projects as well as accelerate permitting. The second pillar aims at speeding up investment and financing for clean tech production in Europe. To that end, the temporarily adapted state aid rules (Temporary Crisis and Transition Framework) and in the medium term an EU Sovereignty Fund (now announced on June 19, 2023, under the name the Strategic Technologies for Europe Platform or STEP) allow for financing with short term flexibility. The third pillar is skills with the establishment of Net-Zero Industry Academies to roll out re-skilling

programmes and facilitated access to EU labour markets for third country nationals. The fourth pillar is trade with the aim to maximise existing trade agreements, combat unfair trade practices and an emphasis on clean tech and net-zero industrial partnerships.

The Net Zero Industry and Critical Raw Materials Acts published together on March 16, 2023, were proposals announced under the first pillar on Regulatory Environment of the Green Deal Industrial Plan.

The **Net Zero Industry Act** proposal offers a predictable legal framework for net-zero industries in the EU. It focusses on ‘net zero technologies’ that will make significant contribution to decarbonisation and defines a list of ‘Strategic Net Zero technologies’ (solar photovoltaic and solar thermal; hydrogen electrolyzers and fuel cells; sustainable biogas/biomethane technologies; battery/storage technologies; heat pumps and geothermal energy technologies; grid technologies; onshore wind and offshore renewable, CO₂ capture and storage) which can receive particular support and are subject to a target to provide at least 40% of the EU’s annual deployment needs for strategic net-zero technologies by 2030. The Act also sets an EU objective to reach an annual 50Mt of CO₂ injection capacity in strategic storage sites in the EU by 2030, to be funded based on proportional contributions from EU oil and gas producers.

The main pillars of the Act are the setting of enabling conditions by improving the conditions for investment in net-zero technologies by enhancing information, reducing the administrative burden to set up projects and simplifying permit-granting processes. In addition, the Act proposes to give priority to Net-Zero Strategic Projects. Besides the CO₂ capture target, it also aims to diversify the supply for net-zero technologies and requires public authorities to consider sustainability and resilience criteria for net-zero technologies in public procurement or auctions.

It also enhances skills with new measures to ensure there is a skilled workforce supporting the production of net-zero technologies in the EU, including setting up Net-Zero Industry Academies, with the support and oversight by the Net-Zero Europe Platform. It also has specific measures to foster innovation by making it possible for Member States to set up regulatory sandboxes to test innovative net-zero technologies under flexible regulatory conditions. Finally, it sets up a Net-Zero Europe Platform to assist the Commission and Member States to coordinate action and exchange information, including around Net-Zero Industrial Partnerships. The Net-Zero Europe Platform will support investment by identifying financial needs, bottlenecks, and best practices for projects across the EU. It will also foster contacts across Europe's net-zero sectors, making particular use of existing industrial alliances.

Most of the net-zero technologies needed for the green transition use a number of critical raw materials in their manufacturing processes that are sources outside the EU. Ensuring adequate future supply of critical raw materials is necessary to achieve the 2050 climate neutrality target.

The Commission regularly publishes the list of critical raw materials for the EU, the last one dating from 2020 ⁽²²⁾, and recently forecasted future critical raw material trends ⁽²³⁾. These are factual tools to define challenges and identify opportunities to support EU policy development for critical raw materials in different domains (trade, research and innovation, industry, and sustainability).

The Critical Raw Material Act ⁽²⁴⁾ illustrates the EU strategy to develop win-win partnerships on sustainable raw materials value chains with resource rich countries and negotiate trade agreements to facilitate trade and investment in CRM in third countries ⁽²⁵⁾. These partnerships aim to contribute to the diversification of the EU's raw materials supply chain and enhance the sustainability of CRM production.

The **Critical Raw Materials Act** sets clear benchmarks for domestic capacities along the strategic raw material supply chain and to diversify EU supply by 2030:

- At least 10% of the EU's annual consumption for extraction,
- At least 40% of the EU's annual consumption for processing,
- At least 15% of the EU's annual consumption for recycling,
- Not more than 65% of the Union's annual consumption of each strategic raw material at any relevant stage of processing from a single third country.

In the same approach as with the Net-Zero industry act, it proposes to give priority to selected Strategic projects with support for access to finance and shorter permitting timeframes. Member States will also have to develop national programmes for exploring geological resources. It also aims to ensure that the EU can mitigate supply risks with the monitoring of critical raw materials supply chains and coordination of strategic raw materials stock among Member States. It emphasises the need for investing in research, innovation, and skills with the establishment of a large-scale skills partnership on critical raw materials and a Raw Materials Academy. Finally, it also has several measures to protect the environment and improve the circularity and sustainability of critical raw materials, in the EU and abroad. Member States will need to adopt and implement national measures to improve the collection of critical raw materials rich waste and ensure its recycling into secondary critical raw materials. Special provisions on permanent magnets ensure that products that contain them meet circularity requirements and provide information on the recyclability and recycled content.

The Regulation was accompanied by a Communication which actions by the Commission to improve international engagement to diversify the EU import of critical raw materials and to further develop strategic partnerships. It also lists a number of actions by the Commission to

⁽²²⁾ COM(2020) 474 final

⁽²³⁾ JRC (2023). Supply chains and materials demand forecast in strategic technologies and sectors in the EU. A foresight study.

⁽²⁴⁾ COM(2023) 165 final

⁽²⁵⁾ COM(2020) 474 final

improve the circularity of critical raw material, including a number of revisions of waste legislations.

The Critical Raw Materials Act helps the EU to move from a linear to a circular economic model of production and consumption. At its core, the **circular economy** seeks to reduce waste to a minimum, converting into valuable resources. Instead of take-make-dispose, it involves prolonging lifetime of products, reusing, repairing, refurbishing as well as sharing and leasing. Ecodesign is key to exploit the benefits of the circular economy at maximum. If this is no longer possible and a product reaches its end of life, recycling allows maintaining its materials within the economy. The circular economy will thereby create business opportunities and jobs while requiring fewer virgin materials and less energy. This can reduce greenhouse gas emissions, mitigate risks associated with the supply of materials, and protect the environment.

2.2 Energy measures supporting industry

Energy efficiency contributed significantly to decarbonisation of industry in the last years, encouraged both by the Energy Efficiency Directive⁽²⁶⁾ and other pieces of EU legislation and by technological progresses in industrial processes. The remaining potential for energy efficiency is still large⁽²⁷⁾, and the amended Energy Efficiency Directive⁽²⁸⁾, formally agreed on 24 July 2023, significantly raises the EU's ambition and places a strong emphasis on energy efficiency: the EU countries will be required to achieve an average annual energy savings rate of 1.49% from 2024 to 2030, up from the current requirement of 0.8%, driving energy savings in different sectors, including industry.

In 2021, electrification only accounted for 33% of final energy use in industry, while direct combustion of fossil fuels covers the remaining use⁽²⁹⁾. Fossil fuels are burned to provide industrial heat to many and varied applications ranging from low temperature heat in food preparation to high temperature heat in blast furnaces. Electrifying low and mid-temperature industrial heat with decarbonised electricity can lower industrial emissions today with currently available technologies. Low temperature heat may be provided by heat pumps, while heat for specific applications can rely on innovative, low-carbon technologies, such as electric arc furnaces, infrared heating, and induction heating. A 3-stage analysis of the technological potential for industry electrification in 11 industrial sectors in the EU (accounting for 92% of Europe's industry CO₂ emissions) shows that 78% of the energy demand is electrifiable with technologies that are already established, while 99% electrification can be achieved with the addition of technologies currently under development.⁽³⁰⁾,⁽³¹⁾.

⁽²⁶⁾ Directive (EU) 2023/1791

⁽²⁷⁾ U.S. DOE Advanced Manufacturing Office. Improving steam system performance: a sourcebook for industry, 2nd ed. Washington, D.C., 2012

⁽²⁸⁾ COM/2022/142 final

⁽²⁹⁾ Eurostat Energy Balances 2023

⁽³⁰⁾ Madeddu et al. (2022). The CO₂ reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environ. Res. Lett.* 15 124004. DOI 10.1088/1748-9326/abbd02

Fuels switching to renewable hydrogen and other decarbonised fuels (both e-fuels or biofuels) are also an option to decarbonise industrial applications where electrification and energy efficiency methods cannot be applied⁽³²⁾. Fuel switching from fossil fuels to renewable hydrogen or e-fuels can provide high-temperature heat with substantially lower emissions. The actual impact on emissions should also take into account considerations external to the industrial processes: the use of biomass should be sustainable and balanced with respect to the carbon sink needs and biodiversity constraints; the actual carbon intensity of e-fuels depends on the origin of the carbon⁽³³⁾.

The provisional agreement on the proposal for a revision of the Renewable Energy Directive (RED) proposed as part of the Fit-For-55 package as well as the revision proposed as part of the REPowerEU package, reached in the seventh trilogue on March 2023, includes the following relevant provisions supporting electrification and fuel switching in the EU industry:

- An EU indicative target of an increase of at least 1.6 percentage points in the share of renewable sources in the amount of energy sources used for final energy and non-energy purposes in the industry sector, as an annual average calculated for the periods 2021 to 2025 and 2026 to 2030.⁽³⁴⁾
- A binding national target of at least 42% on the contribution of renewable fuels of non-biological origin used for final energy and non-energy purposes in the hydrogen used for final energy and non-energy purposes in industry by 2030, and of at least 60% by 2035.⁽³⁵⁾
- An EU regulatory framework determining when renewable fuels of non-biological origin can count towards the abovementioned targets.

⁽³¹⁾ Beyond Zero Emissions (2022). *Zero Carbon Industry Plan. Electrifying Industry*.

⁽³²⁾ BNEF (2021). Hot Spots for Renewable Heat. Decarbonizing Low- to Medium-Temperature Industrial Heat Across the G-20.

⁽³³⁾ Commission Delegated Regulation (EU) 2023/1184

⁽³⁴⁾ Member States may count waste heat and cold towards the average annual increases referred to in the first subparagraph, up to a limit of 0.4 percentage points, provided the waste heat and cold is supplied from efficient district heating and cooling, excluding networks which supply heat to one building only or where all thermal energy is solely consumed on-site and where the thermal energy is not sold. If they decide to do so, the average annual increase shall increase by half of the waste heat and cold percentage points used.

⁽³⁵⁾ For the calculation of that percentage, the following rules shall apply: 10794/23 LZ/st 101 ANNEX TREE.2.B EN (a) For the calculation of the denominator, the energy content of hydrogen for final energy and non-energy purposes shall be taken into account, excluding: (i) hydrogen used as intermediate products for the production of conventional transport fuels and biofuels; (ii) hydrogen that is produced by decarbonizing industrial residual gases and is used to replace the specific gases from which it is produced. (iii) hydrogen produced as a by-product or derived from by-products in industrial installations; (b) For the calculation of the numerator, the energy content of the renewable fuels of non-biological origin consumed in the industry sector for final energy and non-energy purposes shall be taken into account, excluding renewable fuels of non-biological origin used as intermediate products for the production of conventional transport fuels and biofuels. (c) For the calculation of the numerator and the denominator, the values regarding the energy content of fuels set out in Annex III shall be used.

Emissions from **ozone depleting substances (ODS)** result in depletion of the ozone layer and have thus adverse impacts on our health, the biosphere, as well as having large economic implications. These gases have internationally been regulated under the Montreal Protocol on substances that deplete the ozone layer. This has been successful in rapidly reducing on a global scale the production, use and associated emissions of ODS. These gases are also often strong greenhouse gases. EU Regulation (EC) 1005/2009 (ODS Regulation) ⁽³⁶⁾ regulates the use of ODS in the EU and has phased out production and consumption of ODS in the EU. A recent revision of the ODS Regulation has further increased its ambition by targeting ODS banks in the EU, by requiring ODS to be recovered from old insulation foams when buildings are renovated or demolished. This aims to prevent the equivalent of 180 million tonnes of CO₂ or 32,000 tonnes of ozone depleting potential (ODP) emissions by 2050.

Fluorinated greenhouse gases (F-gases) typically replaced ODS when these were prohibited. There has been globally a rapid increase of F-gas use and emissions. The F-gases include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF₆). These gases, while not being ODS, are covered by the Paris Agreement because they are highly potent greenhouse gases. They have numerous applications in everyday life, for example in refrigeration, air conditioning, insulation, fire protection and as aerosol propellants. At EU level, F-gases currently account for 2.5 % of total GHG emissions.

In the EU, the emissions of these gases have only started to reduce since the introduction of the F-gas Regulation ⁽³⁷⁾. Since then, also internationally additional action was taken, with the inclusion of notably HFCs (the largest group of F-gases) into the Montreal Protocol as a controlled substance in 2019 with the aim of stopping global growth and achieving significant emission reductions by 2050.

More recently the EU's F-gas Regulation was updated and significantly strengthened in a provisional agreement with the co-legislators ⁽³⁸⁾. It will reduce between 2015 and 2050 the amount of HFC coming onto the EU market, expressed in CO₂-eq., by 95% by 2030 and by going to zero by 2050. This will bring an important contribution to the Fit for 55 goals and making Europe climate neutral by 2050.

2.3 Circular economy and sustainable products

Several trends are deeply transforming industry independently of the decarbonisation process. The fourth industrial revolution, with automation and innovative solutions like robotics and 3D printing are changing the way the end products are fabricated ⁽³⁹⁾, progressively shifting from mass production to mass customisation ⁽⁴⁰⁾. Technological improvements are improving

⁽³⁶⁾ Regulation (EC) No 1005/2009

⁽³⁷⁾ Regulation (EU) No 517/2014

⁽³⁸⁾ https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4781

⁽³⁹⁾ Huang RA. Multi-scale life cycle framework for the net impact assessment of additive manufacturing in the United States. Northwestern University, 2016.

⁽⁴⁰⁾ Pine, B. Joseph (1993). Mass Customization – The New Frontier in Business Competition. Harvard Business School Press, p. 13. ISBN 978-0-87584-372-8.

the material and resource efficiency of certain industrial processes: minimising material scrap at each step can reduce emissions associated with the process.

Following a circular economy approach, many industrial products can also be designed to improve their material efficiency, and in certain cases, to employ less-carbon intensive materials (material substitution). Currently, manufacturing and construction firms frequently choose to use more material to save labour, reduce legal or financial risks, simplify supply chains, or simply to conform with customary practices. This is particularly evident for cement and steel, where concrete mass in buildings could be reduced by up to 40% by using high strength concrete only where needed⁽⁴¹⁾ and metal in common products like cars and structural beams, could be reduced by 30%⁽⁴²⁾.

Certain end products in the building sector can maintain the same structural properties while manufactured with less-carbon intensive material: concrete and steel can be substituted by timber-based products⁽⁴³⁾, while cement can be partially replaced by supplementary cementitious materials up to a 40% content⁽⁴⁴⁾.

Demand-side intervention, materialising through the principle of sufficiency, are also important levers of the decarbonisation of industry⁽⁴⁵⁾. Sufficiency, defined as collective and individuals' practices to minimise demand while delivering human wellbeing for all within planetary boundaries⁽⁴⁶⁾,⁽⁴⁷⁾,⁽⁴⁸⁾, influences directly on the request for end products and influence industrial activity⁽⁴⁹⁾. The economy shifts from mass production to mass customized services and sharing practices⁽⁵⁰⁾, where flexible, shared and integrate products

⁽⁴¹⁾ Fishedick M, Roy J, Abdel-Aziz A, Acquaye A, Allwood J, Ceron J-P, et al. Industry. Climate change 2014: mitigation of climate change (fifth assessment report), Cambridge, U.K.: IPCC; 2014. p. 739–810.

⁽⁴²⁾ Allwood J.M., Cullen J.M., *Sustainable materials without the hot air*, Cambridge, England: UIT Cambridge Ltd., 2015.

⁽⁴³⁾ Heeren N., et al. 'Environmental impact of buildings—what matters?,' *Environ. Sci. Technol.*, 49:9832, 2015.

⁽⁴⁴⁾ Scrivener K.L., et al. *Eco-efficient cements: potential economically viable solutions for a low-CO2 cement-based materials industry*. Paris, France: UN Environment Program, 2017.

⁽⁴⁵⁾ IEA, *Net Zero by 2050. A roadmap for the Global Energy Sector*, 2023.

⁽⁴⁶⁾ The concept of planetary boundaries defines a safe operating space for societies, by proposing boundaries for anthropogenic perturbation of nine critical Earth-system processes: climate change, ocean acidification, stratospheric ozone, global phosphorus and nitrogen cycles, atmospheric aerosol loading, freshwater use, land use change, biodiversity loss, and chemical pollution. Crossing such boundaries can lead to catastrophic impacts for societies.

⁽⁴⁷⁾ Raworth. *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist*, 2017.

⁽⁴⁸⁾ Rockström J. et al., 'Planetary boundaries: Exploring the safe operating space for humanity.' *Ecol. Soc.* 14, 32, 2009.

⁽⁴⁹⁾ It is assumed that the decrease in end-user demand of certain products will impact proportionally net trade, resulting in identical changes in domestic production and industrial activity.

⁽⁵⁰⁾ David, M. "Sharing: post-scarcity beyond capitalism?". *Cambridge Journal of Regions, Economy, and Society*. 10 (2): 311–325, 2017. doi:10.1093/cjres/rsx003.

are produced locally with low unit cost and marketed as personalised custom services⁽⁵¹⁾. Reusing, repairing, renewing, and recycling existing products extends product's lifetime on the market. This results in more service provided for the same energy input and avoided emissions from product replacement, leading to lower industrial emissions and dematerialisation of the economy. Studies shows that smart strategies and reduced material consumption could shrink global GHG emissions by 39% and cut virgin resource use by 28%.⁽⁵²⁾

The Commission has highlighted the relevance of a circular economy in its Long-Term Strategic Vision on GHG Emissions Reduction as well as in the 2030 Climate Target Plan. To speed up the transition towards a circular economy, the Commission presented the new Circular Economy Action Plan in March 2020. Since then, several packages of measures have followed. The proposals target the design of products, empower consumers, encourage a sustainable consumption, and focus on resource-intensive sectors, such as electronics and ICT, batteries and vehicles, packaging, plastics, textiles, construction and buildings, food, and more.

In March 2022, the Commission proposed the new Ecodesign for Sustainable Products Regulation (ESPR)⁽⁵³⁾, which addresses product design and sets new requirements to make products more durable, reliable, reusable, upgradable, repairable, easier to maintain, refurbish and recycle, and energy and resource efficient. The proposal extends the existing Ecodesign framework⁽⁵⁴⁾ and is the cornerstone of the Commission's approach to more environmentally sustainable and circular products.

Future policies will build on these and other measures to help the EU achieving its 2050 climate neutrality target.

2.4 Industrial carbon management strategy

Complete decarbonisation of the industrial sector will also imply reductions in both energy and non-energy GHG emissions, where CO₂, and more general, carbon is part of the material processing or is used as feedstock for the final product. Industrial emission can be significantly reduced by adaptations in industrial processes and material compositions. Combining these emission reducing initiatives with circularity and carbon capture, including Carbon Capture and Utilisation (where CO₂ is used in materials), industries can mitigate most of its emissions.

Renewable hydrogen and other decarbonised fuels will become the chemical feedstock to replace conventional, high-emitting reactions in several industrial processes. For instance, in the steel sector, hydrogen can directly reduce the iron that is later transformed into steel, and large number of chemical processes can use hydrogen to substitute fossil input. In the cement sector, CO₂ is mainly released during the calcination process for clinker manufacturing for

⁽⁵¹⁾ Coletti, P., *Mass Customization. An Exploration of European Characteristics*, 2011.

⁽⁵²⁾ Circle Economy, *The Circularity Gap Report*, 2021.

⁽⁵³⁾ COM/2022/142 final

⁽⁵⁴⁾ C/2022/2026

clinker manufacturing, which can be mitigated via low-carbon energy input, like hydrogen, and material substitution in cement and further innovation in chemically binding CO₂ to materials.

Biomass may also be used in many industrial processes and materials, both as source of carbon but also of a range of other chemicals and molecules. However, limits exist on the quantity of biomass that may be sustainably produced, given competition with food, agriculture and biodiversity needs (⁵⁵).

CO₂ coming from industrial emissions can also be captured to supply carbon atoms where industry needs them (⁵⁶), coupling different sectors. The CO₂ captured can be combined with hydrogen to generate e-fuels but can also be stored in long-life products, such as plastics or minerals. For instance, renewable methanol (derived from H₂ and carbon neutral CO₂) can also be an excellent precursor for many end products used in the chemical sector. The annual global demand for chemicals and derived materials is estimated to rise to 1,000 million tonnes of carbon (Mt C) by 2050 (⁵⁷). When such products are recycled at the end of life, the same carbon can be re-captured and re-used, leading to a more circular use of the carbon and pave the way for negative industrial emissions.

Carbon capture technologies that can be used to produce e-fuels, or store carbon in products and materials are at prototype or demonstration stage today. With the proposed EU objective to reach an annual 50Mt of CO₂ injection capacity in strategic storage sites by 2030 based on funding obligations to EU oil and gas producers, the Commission has put a first step towards a comprehensive EU strategy to create a Net-zero industrial carbon management market by 2030. This market is projected to become capable to capture, transport, store or use several hundred million tonnes of CO₂ from fossil sources that cannot be avoided, from biogenic and from atmospheric origin by 2050 that are necessary to reach climate neutrality. The EU growing trend is in line with global projections, with the IEA showing around 6 GtCO₂ of carbon captured worldwide in 2050 (⁵⁸).

2.5 Aligning investments with climate neutrality

The EU's sustainable finance policies complement and enable sectoral policies outlined above by supporting companies and the financial sector in the alignment of private investments with the objectives of the European Green Deal. The EU has made considerable progress in implementing its sustainable finance agenda over the last five years. Milestones include the adoption of the Taxonomy Regulation (⁵⁹) and its various delegated acts covering six environmental objectives, including climate change mitigation and adaptation; the Sustainable

(⁵⁵) IPCC, *Special report: global warming of 1.5 °C*, 2019.

(⁵⁶) IEA. "World Energy Outlook". 2022.

(⁵⁷) Kahler et al. *Turning off the Tap for Fossil Carbon: Future Prospects for a Global Chemical and Derived Material Sector Based on Renewable Carbon*, 2021.

(⁵⁸) IEA (2023), Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach, IEA, Paris <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>, License: CC BY 4.0

(⁵⁹) Regulation (EU) 2020/852 amending Regulation (EU) 2019/2088.

Finance Disclosure Regulation (SFDR) ⁽⁶⁰⁾; EU climate benchmarks in the Benchmark Regulation ⁽⁶¹⁾; the European Green Bond Standard ⁽⁶²⁾; and the Corporate Sustainability Reporting Directive (CSRD) ⁽⁶³⁾. The mandatory European Sustainability Reporting Standards ⁽⁶⁴⁾ under the CSRD will enable companies to communicate sustainability information in a standardised way to a variety of lenders, investors, and other stakeholders. This includes the disclosure of transition plans for climate change mitigation, comprising implementing actions and related plans, to ensure that the business model and strategy are compatible with the transition to a sustainable economy and with the limiting of global warming to 1,5 °C in line with the Paris Agreement and the objective of achieving climate neutrality by 2050 as established in the Climate Law (Regulation (EU) 2021/1119), and, where relevant, the exposure of the undertaking to coal-, oil- and gas-related activities. A 2023 Commission Recommendation ⁽⁶⁵⁾ illustrates how the sustainable finance framework encompasses transition finance and explains how companies, investors and financial intermediaries can voluntarily use the current sustainable finance framework to finance their transition to a climate neutral and sustainable economy, while enhancing their competitiveness.

In particular, **green bond markets** have soared in recent years. Cumulative issuances of bonds aligned with the International Capital Market Association's (ICMA) Green Bond Principles, ⁽⁶⁶⁾ for instance, will very likely pass the EUR 1 trillion mark in 2023 (see Figure 3).

⁽⁶⁰⁾ Regulation (EU) 2019/2088

⁽⁶¹⁾ Regulation (EU) 2019/2089

⁽⁶²⁾ COM/2021/391 final

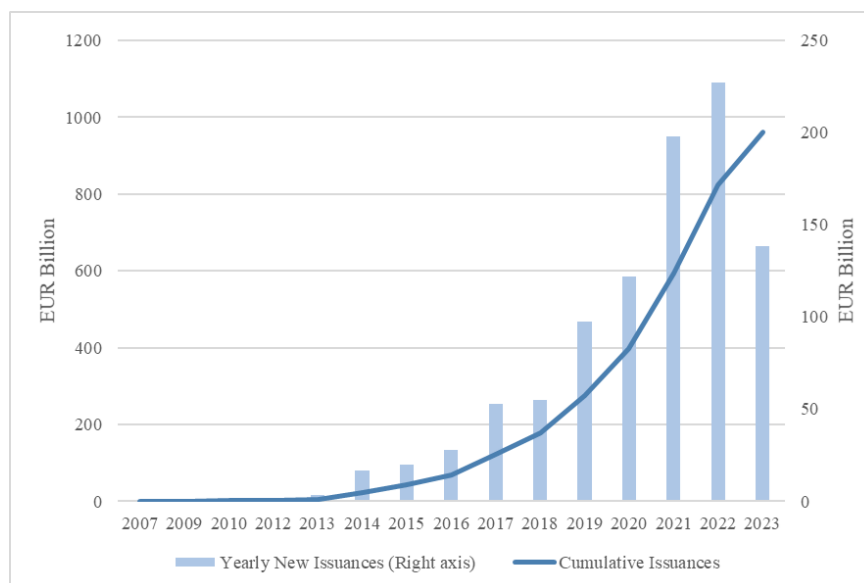
⁽⁶³⁾ Directive (EU) 2022/2464

⁽⁶⁴⁾ C/2023/5303 final

⁽⁶⁵⁾ Commission Recommendation on facilitating finance for the transition to a sustainable economy (C(2023) 3844).

⁽⁶⁶⁾ See <https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/>.

Figure 3: Issuance of green bonds in the EU

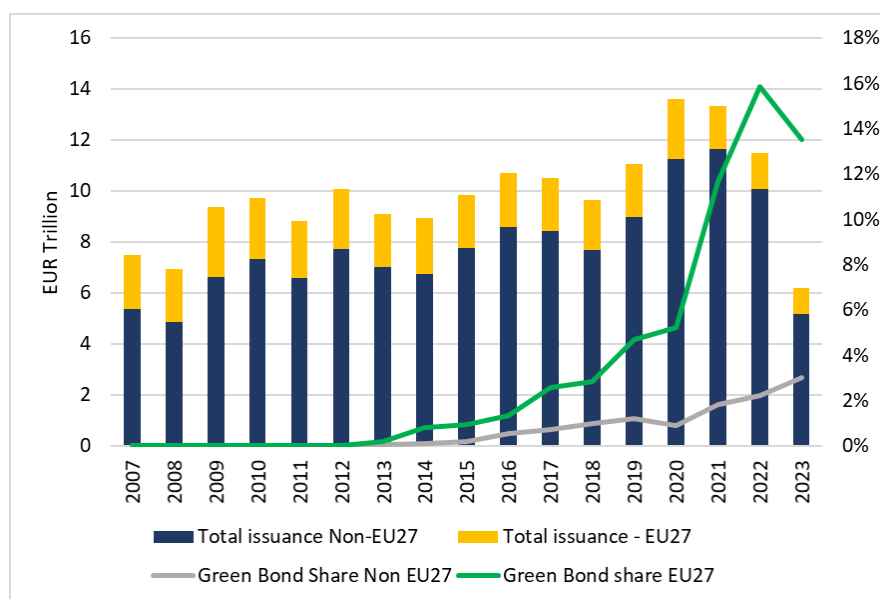


Note: Aligned with the ICMA's green principles, data as of 30 June 2023.

Source: Dealogic DCM and JRC calculations.

This increase in absolute green bond issuances is reflected in **green bonds' share of the corresponding bond market**. For EU and non-EU issuers, the share in the EU27 remained lower than 1% until 2013, but has significantly increased since then, and even more markedly from 2016, on the back of strong growth of the green segment. In 2022, green bonds accounted for 16% of newly issued bonds in the EU27, and only 2% of overall issuance in non-EU markets, confirming Europe's leading role in the sustainable debt capital market (see Figure 4).

Figure 4: Green bond share in total new issuance for EU and non-EU



Note: Data as of 30 June 2023.

Source: Dealogic DCM and JRC calculations.

Sustainability-linked bonds emerged in 2019 as a new financial instrument, complementing green bonds in green debt markets. These instruments have garnered a lot of interest from both issuers and investors given the ease of setting them up and their ability to incentivise the transition with contractual sustainability targets, which differentiates them from green bonds. However, their uptake is still limited compared to green bonds, having peaked in 2021 at EUR 51.8 billion, given the more recent development of this new type of assets.

It should be noted however that the “green-ness” of green bonds and sustainability-linked bonds remains cause for concern due to the risk of greenwashing in spite of the emergence of standards and principles that require third-party certification and adequate reporting. Political agreement was reached in early 2023 on the voluntary **EU Green Bond Standard**, which will rely on the EU Taxonomy and independent reviewers to provide guarantees with a high degree of confidence that financing raised compliant with this standard is genuinely ‘green’⁽⁶⁷⁾.

2.6 Research, development, and innovation

2.6.1 Role of research and innovation

Science is at the core of EU policymaking. Policies developed with an insufficient scientific basis are less likely to solve the underlying issue and more likely to give rise to unintended consequences. Research and innovation (R&I) is a key engine through which to foster Europe’s sustainable productivity growth, competitiveness, inclusiveness and fairness – it is a key enabler of the green transition.

⁽⁶⁷⁾ See https://finance.ec.europa.eu/sustainable-finance/tools-and-standards/european-green-bond-standard_en.

The urgency of the climate crisis requires an unprecedented mobilisation of R&I across all sectors to achieve transformative change in our society and economy. R&I is fundamental in many domains, notably in net-zero technologies, circular economy and sustainable bioeconomy including sustainable agriculture land-use and forestry, zero-emissions mobility, building techniques, and the adaptation to climate change to improve our preparedness for and response to climate-related extreme events.

The strategic orientations for the EU climate research and innovation investments are outlined in the Horizon Europe Strategic Plan 2025-2027 Analysis⁽⁶⁸⁾, as well as the climate R&I priorities crystallised from the process of developing the Horizon Europe Strategic Plan 2025-2027.

2.6.2 Research, development, and innovation for the Green Transition

R&I is critical to achieving the clean energy transition and meeting the objective of climate neutrality by 2050. This section first reviews the identified needs in terms of R&I to achieve the green transition of Europe.

The European Commission regularly collects and assesses evidence on the development and uptake of low-carbon industrial technologies. This includes industry's focus on R&D investment, Member States' engagement in relevant R&I, and local action to support industrial transformation⁽⁶⁹⁾.

2.6.2.1 Climate science

Advancements in climate science whilst creating a solid knowledge base remain essential to catalyse the transition towards a climate-neutral and climate-resilient society. The challenges outlined in the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) will need to be addressed with research that furthers our understanding of the changing climate and its implications. This will contribute to closing knowledge gaps, developing crucial tools to support decisionmakers in the design and implementation of effective mitigation and adaptation solutions at various time and spatial scales, whilst taking into account complementarities and trade-offs with other policy objectives.

2.6.2.2 Space data

Space data and services play a crucial role in enabling the achievement of climate neutrality targets. Integration of space technology with climate change mitigation efforts is indispensable for reducing greenhouse gas emissions and combating climate change. EU

⁽⁶⁸⁾ See https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/horizon-europe-strategic-plan-2025-2027-analysis-now-public-2023-05-25_en.

⁽⁶⁹⁾ Relevant monitoring tools include the EU Industrial R&D Investment Scoreboard, the Strategic Energy Technology Information System (SETIS), the Science, research and innovation performance of the EU (SRIP) reports, the Horizon Europe Results Platform, the Innovation Radar, the Global Industrial Research & Innovation Analyses (GLORIA) project, etc. They continuously improve their monitoring and assessment work including on breakthrough industrial technologies and innovation ecosystems, in collaboration with the European Innovation Council (EIC).

Space data and services are essential assets to supporting the implementation of the Green Deal.

Copernicus (Earth observation), Galileo and European Geostationary Navigation Overlay Service (EGNOS) (satellite navigation) supply the information companies need to monitor environmental indicators, to reduce their environmental impact, to become more sustainable and to drive their green transformation.

EU space data and services can contribute to the achievement of climate target and can be used for: Monitoring and Measurement of various parameters, including greenhouse gas concentrations, land use change, deforestation and ocean temperatures; Understanding Climate Patterns including analysing atmospheric circulation, ocean currents, and weather systems; Early Warning Systems for extreme weather events and natural disasters related to climate change, such as hurricanes, droughts, floods, landslides, wildfires, or storm surges; Carbon Accounting and Reporting by measuring and quantifying emissions from different sources, including deforestation, industrial activities, and transportation; Climate Modelling; International Cooperation; Climate Education and Awareness; Monitoring Deforestation and Land Use Change to enable targeted action to protect forests; Agriculture and Livestock Management to improve agricultural practices and livestock management, leading to reduced emissions from these sectors, Supporting Renewable Energy by helping identify suitable locations for renewable energy projects; Improving Transportation Efficiency by aiding the monitoring and optimizing transportation routes; Methane Detection; Forest Fire Detection and Management; and Environmental Policy and Decision-Making by providing valuable information to develop and implement effective environmental policies.

2.6.2.3 Technological approaches

The green transition relies on a range of innovations and technological solutions that together drive the path towards climate neutrality in a complementary manner. This section does not outline an exhaustive list of technologies that will enable the green transition. Rather it provides a selection of key technological solutions that are often at different stages of maturity and technological readiness level and that can decarbonise different sectors and parts of the economy.

Clean energy generation

Research and innovation will be crucial to support the transition of the energy system with the aim to reduce the overall energy demand, whilst ensuring that the supply of energy is independent, diversified, climate-neutral, and resilient to the impacts of climate change.

The reinforcement of the competitiveness of the European value chain relies on the development of clean, sustainable, and “circular by design” energy technologies. Diverse R&I activities on key clean energy technologies such as solar energy, wind energy, sustainable biomethane and advanced biofuels, hydropower, geothermal energy, heat pumps, ocean energy and synthetic renewable fuels are needed to achieve and eventually maintain the autonomy and competitiveness of the EU energy supply. At the same time, it needs to be ensured that ecosystems are not harmed in the process, and that the zero-pollution ambition of the European Green Deal is supported, whilst bringing social benefits for all.

Further, research and innovation activities are needed to advance the modernisation of the energy networks, grids, markets, and services, as well as to support energy system integration

and to accelerate electrification. Integrating demand response, lowering the cost of energy storage solutions at various timescales, while minimising the use of critical raw materials and ensuring their reuse and recycling, are key elements of the energy system.

Moreover, the output from research and innovation can accelerate the deployment of Carbon Capture, Utilisation and Storage (CCUS) in electricity generation, industry applications, and negative emissions technologies.

Electrification

Reducing emissions from industrial sectors will require coordinated action throughout value chains to boost and accelerate innovation and deployment of all mitigation options, including integration of renewable electricity. R & I still remains crucial for even ‘mature’ low-emission energy technologies such as heat pumps, as well as new technologies to electrify high temperature processes.

Buildings are responsible for around 40% of EU energy demand and are pivotal to the success of the energy transition and achievement of a climate neutral economy. Research and innovation is needed to achieve the full electrification of building systems with the integration of grid-compatible and flexible solutions that involve demand side management, energy storage, and electric vehicle charging.

Energy storage

R&I activities will allow for the development of lower cost and more sustainably produced battery technologies and other long-term storage technologies, not only in transport applications (road, maritime and aviation), but also in stationary storage applications, where new solutions, such as flow batteries, can play a key role in the development of resilient energy grids. Supporting local sustainable battery production capacity (including equipment and skills development) will be an important driver, but R&I will also need to focus on the replacement, reuse, recycling and end-of-life management of batteries and raw materials recovery.

Renewable hydrogen

Decarbonising the production of hydrogen used as an industrial feedstock, and for new uses as an energy carrier requires R&I for the scaling up of hydrogen production and the production of synfuels, and to develop large-scale hydrogen storage systems.

Whilst the technologies used to integrate green hydrogen into a carbon-free energy system are already available, innovation is needed for the scale-up, demonstration, and deployment of hydrogen-based systems in order to take advantage of European technological leadership.

Biotechnology and biomanufacturing

The advances in life sciences and information technology are leading to deeper understanding of functioning of living organisms and providing tools to influence biological processes. Increasingly biotechnology and biomanufacturing are becoming important EU assets to advance strategic autonomy and competitiveness and to enable timely solutions to urgent crises, including climate change or pandemics. However, despite the first-class research in biotechnology, the EU could enhance the efforts for deployment and commercialisation of

biotechnology solutions. An initiative is being prepared on EU Biotechnology and Biomufacturing.

2.6.2.4 Sustainable transportation

Transport is the only sector where greenhouse gas emissions are still above their 1990 levels (18% higher in 2021 relative to 1990). The transport sector (including international aviation and maritime) is responsible for 27% of GHG emissions in the EU (of which over 76.2% came from road transportation in 2021). Energy use of oil and petroleum products accounted for 90.7% of the final energy consumption ⁽⁷⁰⁾ in transport. Intensified R&I activities are needed, across all transport modes and in line with societal needs and preferences, for the EU to reach its policy goals towards net-zero greenhouse gas emissions by 2050, and to significantly reduce air pollutants towards the zero-pollution ambition.

As regards road transport, research and innovation actions must focus on contributing to the shift to zero-emission mobility by targeting cost- and energy-efficient zero-tailpipe-emission vehicles and their integration of these vehicles in the mobility system.

Road transport has the potential to be largely electrified as it provides high potential for absorbing renewable electricity at times when it is abundant and feed it back into a grid when there is scarcity. With the projected increase of electric vehicles already by 2030 it is necessary to ensure that they can contribute to optimising electricity grid in a cost-effective way by offering flexibility services such as energy storage capacity and demand response thanks to smart charging and bidirectional charging which are expected to become mainstream in the coming years. Moreover, private recharging infrastructure in buildings or depots for specific purpose vehicle fleets where electric vehicles typically park for extended periods of time are highly relevant to energy system integration and could contribute the most to optimising the electricity grid through the flexibility services thus reducing the need for additional investments to expand the grid due to increased electrification. In the rail sector, regenerative braking and energy buffers offer a large untapped potential for enhanced energy efficiency.

The European aviation sector aims to reach climate neutrality by 2050. This objective relies on the development of sustainable aviation fuels, and hydrogen-powered zero-emission aircraft and infrastructure. R&I actions on aviation need to develop integrated aircraft technologies for deep decarbonisation transformation and to reduce all negative non-CO2 impacts and emissions. Likewise, research and innovation is required to further advance net zero-emission solutions on new fuels, engines and ship designs in the shipping sector.

2.6.2.5 Circular industry

A functioning circular economy is one of the key objectives of the European Green Deal. Research and innovation is critical to achieving a circular economy by fostering new safe

⁽⁷⁰⁾ Final energy consumption excludes international aviation and maritime. The energy consumption in air transport and maritime are dominated by oil products.

ways of designing, producing, repurposing, reusing, repairing, and recycling. R & I is needed to reinforce our resilience and strategic dependency by decoupling economic growth from resource use.

There is much scope for improvement for design of circularity in terms of circularity technologies applicable to different value chains with special attention to disassembly, remanufacturing/upgrading, recycling, and ‘Zero-X’ – zero defects, zero breakdowns, zero waste.

It will be important to develop and test different circularity technologies in the context of the entire value chain and life cycle, with a view to facilitating deployment, further developing value chains for circularity.

Research will be needed to enable energy-intensive industries to embrace the circular economy as a key pillar in the design of their value chains. This will be fundamental to ensuring the efficient use of resources (material, energy, and water) by these resource-intensive industries. Particularly important in this context is the development of innovative upcycling of secondary raw material and of resource-efficient industrial processes.

Achieving circularity of both raw materials and advanced materials is a key challenge for the future. The establishment of new materials flows, as well as the advancement of the recovery, re- and up-cycling of materials from waste relies on R&I.

2.6.2.6 Sustainable circular bioeconomy

In “A Clean Planet for All: Long-term Strategy, 2018” Bioeconomy is one of the seven strategic building blocks towards a net zero GHG economy. Bioeconomy sectors mentioned in this IA (i.a. food and non-food bio-based value chains from agriculture, LULUCF, bioenergy) were included under Reaping the full benefits of Bioeconomy and creating essential carbon sinks for: sequester and store C in agricultural land, forestry and wetlands; substitute C-intensive materials; create new business opportunities; developing climate-friendly farming and forestry systems; unlocking the potential of aquatic resources; and substitute fossil fuels in power generation.

Innovation in the sustainable bioeconomy lays the foundations for the transition away from a fossil-based economy. Sustainable bio-based innovation is an important segment of the overall bioeconomy and takes into account sustainability in all its dimensions. Research and innovation need to contribute to scaling up the potential of bioeconomy to substitute GHG intensive products and materials, as well as to improving the circularity aspects of bio-based systems, with a particular focus on biowaste, waste management and valorisation, considering the whole life cycle of bio-based products and technologies. Moreover, the cross-cutting aspect of zero pollution in the sector has to be further implemented.

The EU agriculture sector is the only major agriculture system in the world that has reduced its GHG emissions (by 20 % since 1994). The development of sustainable agriculture and food systems is one of the main priority areas of action for the EU. Key research areas for agriculture include mitigation and adaption to climate change, enabling more sustainable farming practices, and fostering sustainable livestock systems.

Further R & I is needed in the forestry sectors in order to meet the expectations of the European Green Deal. Specifically, there is a need to foster multifunctional forests for future

generations through sustainable management approaches, technologies, innovative wood and non-wood products, prevention and management of forest disturbances, urban forestry, management of genetic resources, deployment of inclusive and fair value chains, and improved governance. Overall, a better understanding of consumption of these resources is needed to help shifting to more sustainable consumption patterns ⁽⁷¹⁾.

2.6.2.7 Socio-economic & behavioural R&I

Research and innovation must go hand in hand with social innovation, inclusiveness, and promotion of solutions that allow the integration of aspects going beyond functionality, whilst achieving efficiency, sufficiency, and sustainability. The important role of social sciences and humanities must be realised to advance behavioural change and social acceptance, trust, and uptake of solutions.

The necessary innovations to address key societal challenges, notably climate change, call for interdisciplinary approaches to research and innovation that combine knowledge from the social sciences and the humanities, including the arts and science, technology, engineering, and mathematics, while at the same time maintaining the human-centric focus.

Research is needed to evaluate the societal impact of climate change and the measures required to achieve climate neutrality and to prepare for adverse impacts and risks linked to climate change.

2.6.3 Advancing the European RDI system

2.6.3.1 Role of RDI

In 2019, the European Green Deal Communication emphasised the key enabling role of R&I in steering the EU towards climate neutrality by 2050 and pointed out the need for the R & I agenda to take a systemic approach to achieving the ambitious targets. Innovation is needed to develop and adopt cutting-edge clean technologies, transformative climate policies and novel practices tailored for a climate-neutral society. Achieving the goals of the Paris Agreement requires rapid and profound changes across all countries, sectors, and aspects of how the society operates and calls for mobilising R&I at the scale and speed that are commensurate with this challenge. Innovative net-zero solutions must not only be developed and deployed faster, but also have to be climate-proof. The problems at stake today are complex and interconnected, thus requiring solutions from multiple perspectives, disciplines, and sectors, maximising the co-benefits, and attenuating the trade-offs. Beyond delivering technological innovation, R & I policies are increasingly expected to provide novel instruments and to act as a lever for catalysing transformational change towards sustainable development, empowering individuals, and communities to meet societal needs and build sustainable, inclusive and resilient societies. All this will require sustained and more effective investments in research

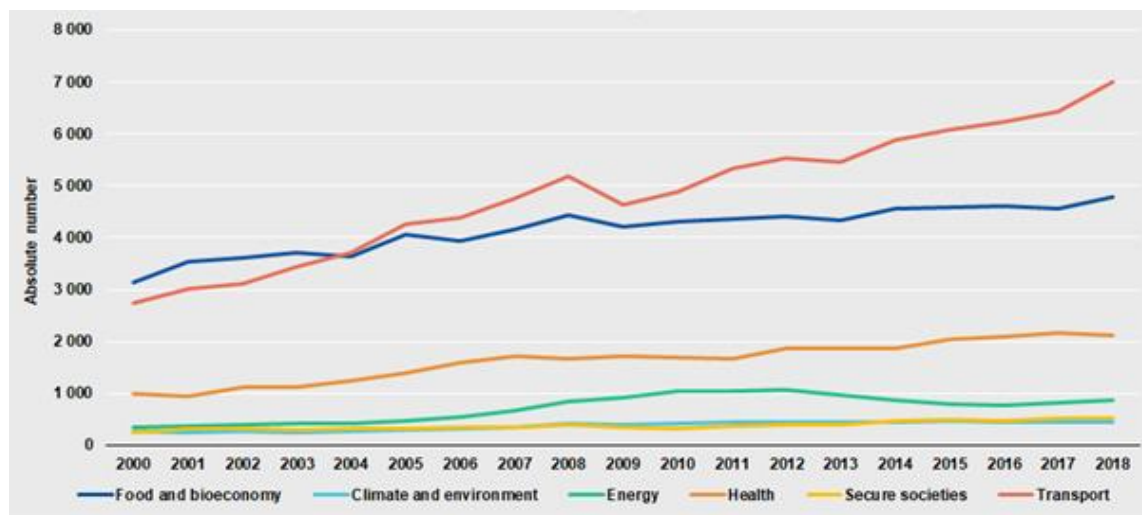
⁽⁷¹⁾ European Commission, Directorate-General for Research and Innovation, *European bioeconomy policy – Stocktaking and future developments – Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions*, Publications Office of the European Union, 2022, <https://data.europa.eu/doi/10.2777/997651>.

and innovation, from public and private sources alike, if the EU is to succeed in decarbonising at sufficient speed to fall in line with what the science says is necessary.

2.6.3.2 Where the EU is today

The EU has remained stable over time in terms of number of patent applications filed related to the societal grand challenge (SGC) “Climate and Environment” (Figure 5). The EU is still the top worldwide patent applicant in the field of “Climate and Environment” (23 %), but its share has declined (see Figure 6), underscoring the importance of stepping up the investments to secure Europe’s leadership in technologies needed for the transition.

Figure 5: Number of patent applications filed under the PCT in the EU by SGC



Note: Covers PCT patents at the international phase designating the European Patent Office. Fractional counting method used; inventor’s country of residence and priority date used.

Source: Own analysis based on Science-Metrix using the European Patent Office’s patent statistics database ⁽⁷²⁾.

European countries ⁽⁷³⁾ are also among the leaders of the green transition. From 2016 to 2021, Europe produced 30 % of all green inventions worldwide. Japan was second, with 21 %, followed by the United States (19 %) and China (13 %). The European lead is especially strong for domains such as green transport (41 %), biofuels (37 %) and wind energy (58 %). The production of solar energy technology or batteries is more evenly distributed among the largest and most innovative countries ⁽⁷⁴⁾.

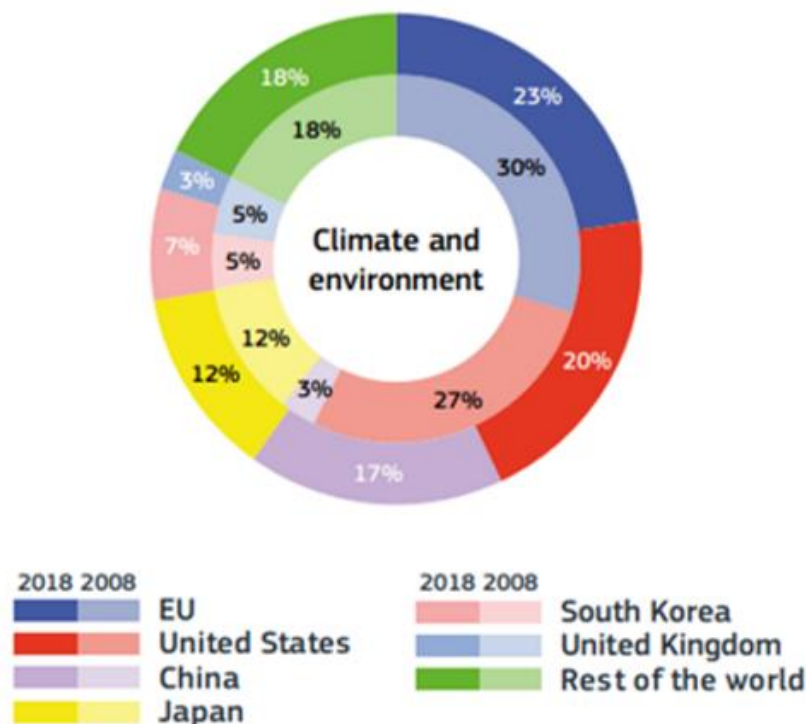
Europe has maintained a stable position in the green transition since 2004. In addition, although a slowdown can be observed during the 2007–2008 financial crisis, the rate of output of innovation has been relatively stable since 2014.

⁽⁷²⁾ European Commission, Directorate-General for Research and Innovation (2022). Science, research and innovation performance of the EU 2022 – Building a sustainable future in uncertain times, Publications Office of the European Union, Luxembourg, <https://data.europa.eu/doi/10.2777/78826>.

⁽⁷³⁾ Understood as the group comprising the EU-27, the United Kingdom, and the European Free Trade Association countries.

⁽⁷⁴⁾ See <https://www.paballand.com/asg/esir/fow/green-transition.html>.

Figure 6: Global patent applications for SGC “Climate and Environment”



Note: Filed under the PCT. 2008 (interior ring) and 2018 (exterior ring).

Source: Own analysis based on Science-Metrix using the European Patent Office's patent statistics database ⁽⁷⁵⁾.

The EU has put in place a number of instruments and funding programmes that aim to deliver research and innovation results, with a particular focus on the green transition:

- The **EU Framework Programmes for R&I** Horizon 2020 (2014-2020) and Horizon Europe (2021-2027) ⁽⁷⁶⁾, with the latter having a budget of EUR 95.5 billion, of which 35% are allocated to tackling climate change. Horizon Europe plays an important role in mobilising research and innovation in the most strategic areas for transitioning to climate neutrality and resilience, notably through its comprehensive portfolio of EU partnerships ⁽⁷⁷⁾ and missions ⁽⁷⁸⁾.

⁽⁷⁵⁾ European Commission, Directorate-General for Research and Innovation (2022). Science, research and innovation performance of the EU 2022 – Building a sustainable future in uncertain times, Publications Office of the European Union, Luxembourg, <https://data.europa.eu/doi/10.2777/78826>.

⁽⁷⁶⁾ See https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en.

⁽⁷⁷⁾ See https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/european-partnerships-horizon-europe_en

⁽⁷⁸⁾ See https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe_en

- The **European Institute of Innovation and Technology's (EIT) Knowledge and Innovation Communities (KICs)**, that comprises public-private partnerships on different societal challenges, including on climate ⁽⁷⁹⁾ and energy ⁽⁸⁰⁾.
- The **Innovation Fund** ⁽⁸¹⁾ under the Emissions Trading System (ETS), which is the EU fund for climate policy, and aims to bring to the market solutions to decarbonise European industry and support its transition to climate neutrality.
- The **European Regional Development Fund** ⁽⁸²⁾ (ERDF) and **Cohesion Fund** ⁽⁸³⁾ (CF) support Member States in advancing the transition to climate neutrality and other EU priorities. The funds will deliver at least EUR 78 billion in investment in climate action in 2021-2027 (30% of the total ERDF and 37% of the total Cohesion Fund budget allocation).
- The **LIFE Programme** ⁽⁸⁴⁾ is the EU's funding instrument for the environment and climate action.
- R&I is a key dimension of the **National Energy and Climate Plans** ⁽⁸⁵⁾ (NECPs). The inclusion of specific and measurable R&I objectives in the NECPs will help integrating national strategies and priorities at EU level in a 2030-2050 perspective.
- The EU is participating in international fora on innovation related to decarbonisation, in particular as a member of the **Clean Energy Ministerial** ⁽⁸⁶⁾ and of the **Mission Innovation** ⁽⁸⁷⁾.
- Furthermore, the EU supports the work of the **IPCC** ⁽⁸⁸⁾ which makes a major contribution to the advancement of climate science, which underpins evidence-based climate policies and global climate diplomacy. The support is channelled, inter alia, through the EU Framework Programmes for R&I ⁽⁸⁹⁾.

⁽⁷⁹⁾ See Climate-KIC | The EU's main climate innovation initiative, <https://www.climate-kic.org/>.

⁽⁸⁰⁾ See KIC InnoEnergy: a new approach to education, <https://eit.europa.eu/news-events/news/kic-innoenergy-new-approach-education>.

⁽⁸¹⁾ See 'What is the Innovation Fund?', https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/what-innovation-fund_en.

⁽⁸²⁾ See https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/european-regional-development-fund-erdf_en.

⁽⁸³⁾ See https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/cohesion-fund-cf_en.

⁽⁸⁴⁾ See https://cinea.ec.europa.eu/programmes/life_en.

⁽⁸⁵⁾ See https://energy.ec.europa.eu/topics/energy-strategy/national-energy-and-climate-plans_en.

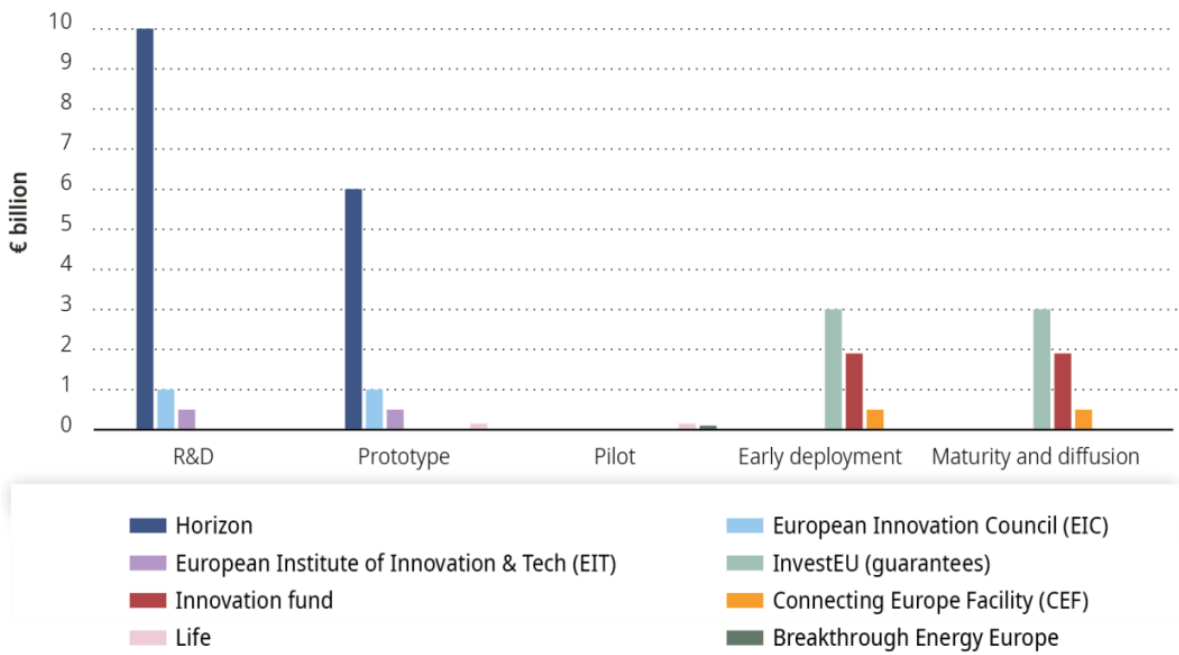
⁽⁸⁶⁾ See <https://www.cleanenergyministerial.org/>.

⁽⁸⁷⁾ See [Mission Innovation – Catalysing Clean Energy Solutions for All \(mission-innovation.net\)](https://mission-innovation.net/).

⁽⁸⁸⁾ IPCC — Intergovernmental Panel on Climate Change, <https://www.ipcc.ch/>.

⁽⁸⁹⁾ Factsheet EU research & innovation – Top funder of leading climate science, <https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/5417b4fd-c9fa-11ed-a05c-01aa75ed71a1>.

Figure 7: Available public funding by stage of the RD & D process



Note: Annualised estimates for the period 2021 – 2027, except from the Innovation fund which is annualized for the period 2020-2030 and the Breakthrough Energy Europe which spans over the 2018-2023 period, in 2022 EUR values.

Source: European Scientific Advisory Board on Climate Change (2024) ⁽⁹⁰⁾

2.6.3.3 Future R&I for EU decarbonisation & industrial growth

Even if the EU is positioned as a leader in terms of the green transition, continued investment into R & I progress and uptake are still critical for implementing the European Green Deal ⁽⁹¹⁾, and translating the leadership into environmental, economic, and social benefits.

To deliver on the green and digital transitions, systemic change should be fostered across our entire economy and all sectors, covering both production and consumption side, and with a focus on energy (as key enabler for electrification and decarbonisation of other sectors), energy-intensive industry, (large-scale) infrastructure, transport, food, agriculture and land-use, construction and buildings. Some innovations are market-ready, such as solar power, but many need to be improved and scaled up, while others still need to be invented to reach climate neutrality. In order to enable such systemic changes, unprecedented mobilisation of R&I is needed, with technological innovation complemented by social, governance and economic innovation, as well as behavioural research on accelerating the transition towards climate neutrality. Given the potential of demand-side mitigation ⁽⁹²⁾, research is needed to

⁽⁹⁰⁾ European Scientific Advisory Board on Climate Change (2024): Towards EU climate neutrality: progress, policy gaps and opportunities

⁽⁹¹⁾ European Commission, Directorate-General for Research and Innovation (2022), *Science, research and innovation performance of the EU 2022 (SRIP)*, Publications Office of the European Union, Luxembourg, <https://data.europa.eu/doi/10.2777/38888>.

⁽⁹²⁾ IPCC AR6 estimates that demand side mitigation could deliver 40–70% of emissions reductions by 2050.

better understand how lifestyle choices can contribute to climate objectives. Finally, in the context of this impact assessment, a defining element of the scenarios proposed is the ability to deploy novel technologies with important implications for choices on how to accelerate and scale up R&I to support the more ambitious options.

According to the Analysis for the Horizon Europe Strategic Plan 2025-2027⁽⁹³⁾, the following priorities for EU R&I were identified for delivering on the European Green Deal, many of relevance for addressing the climate change challenge:

- protect and restore natural capital;
- decarbonise the economy;
- accelerate the transition to chemicals and materials that are safe and sustainable⁽⁹⁴⁾;
- achieve a circular economy and the zero pollution ambition;
- modernise our infrastructures, buildings, and transport, and make them more resilient;
- protect the health and well-being of citizens and communities (including rural ones);
- design sustainable and resilient agriculture, forestry, fisheries and aquaculture, and food and water systems; and transform our ways of producing and consuming⁽⁹⁵⁾.

In the context of the transition to climate neutrality, it is also important for Europe to pursue reciprocal openness and a level playing field through strategic international R & I cooperation with like-minded partners.

2.7 SMEs

The transition implies challenges and opportunities for SMEs. At the stakeholder event organised by the Directorate General on Climate Action on June 9th, one SME mentioned that the reduction of activity in some sectors (for example in the supply chain for fossil fuel engines in the automobile sector⁽⁹⁶⁾) will be compensated by new opportunities (in growing activities (for example, demand for heat pumps in the residential sector).

⁽⁹³⁾ See https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/horizon-europe-strategic-plan-2025-2027-analysis-now-public-2023-05-25_en.

⁽⁹⁴⁾ European Commission, Directorate-General for Research and Innovation (2022), *Strategic research and innovation plan for safe and sustainable chemicals and materials*, Publications Office of the European Union, Luxembourg, DOI: 10.2777/876851.

⁽⁹⁵⁾ European Commission (2019), The European Green Deal, COM(2019) 640 final, <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN>.

⁽⁹⁶⁾ Less than 0.07% of SMEs in the EU are in the manufacturing of motor vehicles, trailers and semi-trailers; less than 0.06% are in the manufacturing of other transport equipment (Eurostat Structural Business Statistics). Around 3.4% are in the wholesale and retail trade and repair of motor vehicles and motorcycles. Other sectors involved in the supply chain of the automobile sector may be not impacted by the transition (e.g., textile manufacturing), negatively impacted (e.g., the manufacturing of compounds used in fossil fuel engines) or positively impacted (e.g., the manufacturing of batteries).

Specific measures and programmes exist to support SMEs in the transition (see SME test in Annex 4). In 2014-2020, the European programme for small and medium-sized enterprises (COSME) contributed to the climate mainstreaming objectives. The detail of measures and initiatives conducted under the programme are presented in the COSME 2020 Monitoring Report⁽⁹⁷⁾. To give a few examples, the Equity Facility for Growth (EFG) and the Enterprise Europe Network (EEN) paid attention to the challenges implied by the decarbonisation. The EEN helped SMEs to improve their energy and resource efficiency and reduce their emissions. The COSME Equity Facility for Growth (EFG) invested EUR 6.7 million in a Venture Capital (VC) fund dedicated to clean technologies. In the time period 2014-2020, the EFG facilitated more than EUR 62 million of investments in SMEs in the ‘Energy and Environment’ sector. The COSME programme is an experience to learn from for developing other comparable programmes in the next decades.

Aware of the impact that climate change may be for SMEs, the European Investment Bank (EIB) Group also pays attention to develop financing tools that are particularly adequate⁽⁹⁸⁾. It works with financial intermediaries that offer products targeting small and medium firms and micro-enterprises. Some of the instruments offered by the EIB Group typically helps more established small businesses while others focus on enterprises in earlier stages of growth.

The recent SME Relief Package⁽⁹⁹⁾ is expected to support SMEs in the transition to a low-carbon economy. Rules to ensure small businesses are paid in due time help them invest and innovate in sustainability and hire more employees⁽¹⁰⁰⁾.

In addition, depending on the regions and the sector in which SMEs operate, they may benefit from measures and programmes aimed at supporting specific regions and sectors throughout the transition (see Annex 9).

3 AN INCLUSIVE AGENDA

3.1 Just transition and social policy

The European Green Deal sets out the strategy for the Union to become the first climate-neutral continent and to transform the Union into a sustainable, fairer, and more prosperous society. It stresses that no person and no place should be left behind. Addressing from the outset the socio-economic impacts of the energy and climate transition and protecting households, exposed industries and workers throughout the process is a prerequisite for a fair and inclusive transition. It is clear by now that the impacts of the green transition on

⁽⁹⁷⁾ Report from the Commission to the European Parliament and the council. COSME 2014-2020. Programme for the Competitiveness of Enterprises and SMEs. 2020 Monitoring Report.

⁽⁹⁸⁾ Small and medium enterprises. Overview 2022. European Investment Bank Group.

⁽⁹⁹⁾ COM(2023) 535 final

⁽¹⁰⁰⁾ Di Bella, L., Katsinis, A., Lagüera-González, J., Odenthal, L., Hell, M., Lozar, B. Annual Report on European SMEs 2022/2023, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/028705, JRC134336.

businesses and employment will vary by sector, occupation, region, and country⁽¹⁰¹⁾. Restructuring and adjustment in the companies, sectors, and industrial ecosystems most affected by the transition will require the development of new business models while upskilling, reskilling or labour reallocations both across sectors and regions will be needed.

The transition will bring numerous benefits (job creation, healthier environment, cheaper and cleaner energy, better living comfort). Yet, ensuring a fair and inclusive transition will require to pay due attention to transforming sectors (automotive, agriculture, forestry, waste), the quality of jobs being created, the impact on various skills segments and the gender gap. Increased climate ambitions combined with important labour shortages, calls for timely investments in education and (re)skilling. Additional and targeted measures to address the distributional impacts of the transition, including social challenges such as energy and transport poverty aspects, are also required. Wide stakeholder involvement based on close cooperation with social partners and civil society is essential for ensuring a just and inclusive transition towards a climate neutral economy, especially in regions and sectors most affected.

3.1.1 How to accompany the transition?

To accompany the transition to a climate neutral economy, the EU has put in place a comprehensive enabling framework. Council Recommendation 2022/C243/04 adopted in 2022 provides Member States with comprehensive guidance on measures to address the employment and social aspects of climate policies. The objective of these measures should be to provide active support to quality employment, ensure access to quality education, training, and life-long learning, provide fair tax benefit systems and social protection, and ensure access to essential services. In 2023 and 2024, Member States are required to update their 2030 national energy climate plans (NECPs,) which are the central strategic planning tool under the Governance Regulation. In the Commission Notice 2022/C495/02, the Commission stressed the importance of considering fair transition aspects when designing policies and measures to advance towards climate neutrality.

3.1.2 Energy and transport poverty aspects

Energy poverty is exacerbated by the fact that the EU's population is projected to continue ageing and shrinking in the coming decades. This demographic change can have a significant impact on energy poverty as older people are particularly affected by it (lower incomes, live in poorly insulated homes and are more susceptible to health problems associated with cold homes). Climate change affects the poor at a disproportionately higher rate as they frequently suffer from poor health conditions and work outside more often⁽¹⁰²⁾.

In 2021, the European Commission launched the Energy Poverty Advisory Hub (EPAH), the leading EU initiative aiming to eradicate energy poverty and accelerate the just energy transition of European local governments. In April 2022, the Commission Energy Poverty and Vulnerable Consumers Coordination Group was established. It provides EU countries with a

⁽¹⁰¹⁾ SWD(2020) 176 final

⁽¹⁰²⁾ Meyer-Ohlendorf, Nils; Spasova, Deyana; Graichen, Jakob; Gores, Sabine (2023): Designing the EU 2040 climate target. Ecologic Institute, Berlin.

space to exchange best practices and increase coordination of policy measures to support vulnerable and energy-poor households. A new Social Climate Fund (SCF) ⁽¹⁰³⁾ will support vulnerable households, transport users and micro-enterprises affected by the introduction of emissions trading for fuels used in road transport and buildings. The aim is to help these groups reduce their reliance on costly fossil fuels by making buildings more efficient, decarbonising heating and cooling of buildings (including integrating energy from renewable sources) and increasing access to sustainable transport. In addition, the SCF can also support vulnerable groups through national measures via targeted and temporary direct income support.

3.1.3 Employment and skills related aspects

3.1.3.1 Better understanding of jobs and skills required

As the transition will have substantial effects on labour demand and skills in some specific regions, sectors, and occupations, it is essential to better understand and monitor where shortages are expected and who will be adversely affected. To better anticipate these changes, there is a need to develop up-to-date labour market and skills intelligence and foresight. More granular data (e.g., at regional, occupational, and gender levels), more precise definitions of green jobs and skills, as well indicators are required. Cooperation between public authorities at all levels and with social partners, civil society organizations, educational organisations and enterprises is important for improving the evidence base for a fair and inclusive transition. Several Commission initiatives have been laying the ground for further work in this area such as the recent GreenComp reference framework for sustainability competences ⁽¹⁰⁴⁾, the European Skills, Competences, and Occupations (ESCO) taxonomy on skills for the green transition ⁽¹⁰⁵⁾ and the CEDEFOP Green Observatory which tries to map skills needed in the EU job market.

3.1.3.2 Targeted upskilling and reskilling

To mitigate unemployment in declining sectors and address increasing labour shortages in key sectors for the green transition, it is essential to re- and upskill the workforce in impacted sectors and to ensure that educational programmes are labour market relevant. Today, 70-80% of people see the green transition as an opportunity but around 50% of people are not sure whether they have the rights skills ⁽¹⁰⁶⁾. Several EU Level initiatives seek to address the growing demand for “green” skills. The European Skills Agenda is the current five-year plan to help individuals and businesses develop more and better skills and thereby spur the green and digital transition. Actions within the EU Skills Agenda, such as the Pact for Skills, demonstrate the facilitating role that the EU can play in connecting Member States, education and training providers, industry, and social partners to effectively identify skills and learning

⁽¹⁰³⁾ Regulation (EU) 2023/955 of the European Parliament and of the Council of 10 May 2023 establishing a Social Climate Fund and amending Regulation (EU) 2021/1060.

⁽¹⁰⁴⁾ See https://joint-research-centre.ec.europa.eu/greencomp-european-sustainability-competence-framework_en.

⁽¹⁰⁵⁾ See <https://ec.europa.eu/newsroom/empl/items/741088/en>.

⁽¹⁰⁶⁾ Eurobarometer on fairness, inequality and intergenerational mobility.

pathways. The recent EU's Skill Partnership for the automotive ecosystem is a good example of a tailored approach to bridge the gaps and facilitate road transport electrification ⁽¹⁰⁷⁾. Skills are also at the centre of the Green Deal Industrial Plan with initiatives such as the skill academies for clean technology sectors, initiatives aimed at ensuring there is a skilled workforce supporting the production of net-zero technologies in the EU.

But equipping the workforce with the right set of skills is just one side of the coin. It needs to be complemented with measures supporting access to quality employment, in particular through public employment services, tailored job search assistance and other active labour market policy measures. The European Social Fund Plus, the EU's main instrument for investing in people, is becoming an increasingly more important tool in the current context. Within this framework, Member States have programmed around 6 billion € for the period 2021-2027 including in the area of skills development, green entrepreneurship, job search assistance, active labour market policies and social inclusion of people impacted by the transition. In addition, other funds such as the Recovery and Resilience Facility, Invest EU and the Just Transition Fund can support up- and reskilling. ⁽¹⁰⁸⁾

Finally, as the climate and energy transition affects women differently than men ⁽¹⁰⁹⁾, specific attention can be paid to the gender aspects in programmes and plans designed to facilitate and support the transition, for example in the NECPs ⁽¹¹⁰⁾.

3.1.4 Strategic cooperation and communication

Effective multilevel governance at the EU, national and regional levels is key for the kind of long-term systemic change that is needed to reconfigure production and consumption systems in impacted sectors ⁽¹¹¹⁾. From the outset, fair and inclusive transition objectives should be integrated into policymaking at all levels through an effective whole-of-society approach. Regional and local authorities need to play an active role in the development, implementation and monitoring of fair transition policies. Indeed, local authorities are the closest to citizens and implement 70% of all EU legislation, 90% of climate adaptation policies, and 65% of the Sustainable Development Goals ⁽¹¹²⁾. Active involvement of social partners, civil society, educational and training institutions, and those affected at different stages is essential for raising awareness and providing reliable information to the public, facilitating learning and

⁽¹⁰⁷⁾ Tamba, M., Krause, J., Weitzel, M., Ioan, R., Duboz, L., Grosso, M., Vandyck, T. Economy-wide impacts of road transport electrification in the EU, *Technological Forecasting & Social Change*, 182 (2022) 121803.

⁽¹⁰⁸⁾ An overview of all funds which can contribute to upskilling and reskilling is available on the following webpage: <https://ec.europa.eu/social/main.jsp?catId=1530&langId=en>.

⁽¹⁰⁹⁾ See EIGE (2023). *Gender Equality Index 2023. Towards a green transition in transport and energy*, Publications Office of the European Union

⁽¹¹⁰⁾ COM(2023) 796 final

⁽¹¹¹⁾ Eurofound and EEA (2023), *The transition to a climate-neutral economy: Exploring the socioeconomic impacts*, Publications Office of the European Union, Luxembourg.

⁽¹¹²⁾ Resolution of the European Committee of the Regions - The Green Deal in partnership with local and regional authorities (2020/C 79/01).

ensuring support across regions and economic sectors for the systemic changes to come. This requires investments in capacity development. To give an example of relevant initiative, the European works councils (EWCs) is a European representation of employees (over 17 million) at company level. They facilitate the information, consultation, and participation of employees with a focus on transnational issues. At the EU level, several tools exist. For example, the Council recommendation on social dialogue can help ensure that the new jobs for the green transition are quality jobs with good working conditions. It can support (re)skilling, job transitions and EU competitiveness. In the Communication on Enhancing the European Administrative Space (ComPAct) ⁽¹¹³⁾, the Commission sets out actions to reinforce the capacity of public administrations across Member States to manage the green transition, by up- and reskilling civil servants, mainstreaming the green transition into the policymaking cycle, and greening their own organisation and operations.”

3.1.5 Examples of fair and inclusive transitions

Promoting the exchanges of best practices while considering country specificities can help ensure successful transition across countries and regions.

Financial incentives for home renovation play a key role to support energy-poor and vulnerable households to achieve energy savings.

Germany’s transition away from coal for electricity generation entails significant structural change and economic and social challenges, with over 19,650 direct and 35,734 indirect jobs impacted in coal mining ⁽¹¹⁴⁾. In particular, the transition to clean energy is affecting three coal mining areas: the Lausitzer Revier, the Rheinische Revier, and the Mitteldeutsche Revier. Measures to address this challenge were designed. For example, the “adjustment allowance” (“Anpassungsgeld”) provides financial support to workers facing job losses. Under this scheme, former mining workers above the age of 50 and meeting certain conditions can receive a bridge aid for a maximum of five years until entitlement to benefits from the miners’ pension insurance. Furthermore, the federal government has pledged to support the affected states (“Länder”) with up to EUR 14 billion in financial transfers for regional investments until 2038 at the latest. The federal government will fund additional measures with up to EUR 26 billion, such as rail and road infrastructure, research institutions ⁽¹¹⁵⁾. The Just Transition Fund was also utilized to help the most affected regions.

One example of a successful transition in the energy sector is the offshore wind evolution of the city of Esbjerg in Denmark. Esbjerg underwent a fundamental transformation from servicing the oil and gas sectors over the past three decades to becoming one of Europe’s leading hubs for offshore wind. Reskilling and upskilling pathways were designed to absorb

⁽¹¹³⁾ COM(2023) 667 final

⁽¹¹⁴⁾ SWD(2020)504 final

⁽¹¹⁵⁾ SWD(2020)504 final

workers from the oil and gas industry to the offshore wind sector, which helped avoid high unemployment and economic stagnation of the region ⁽¹¹⁶⁾.

Poland is developing 120 Sectoral Skills Centres (SSCs) which will cover industries related to the green transition, i.e., in areas of renewable energy, environmental protection, environmental engineering and waste management. Practical trainings will target young people and people with disabilities, adults and teachers for vocational education and training ⁽¹¹⁷⁾.

Another successful example is the “*Contrat de Transition Écologique*” (CTE) initiated in France as a partnership programme between the State and local communities to help develop local projects that diversify the local economy, for sustainability and environmentally responsible development. Each contract lasts three to four years. The process started in 2018, experimenting with 18 territories and later expanding to 107 territories. This initiative shows how cooperation between the State, local authorities and local socioeconomic actors can support ecological action undertaken at national level and transpose it to the local level ⁽¹¹⁸⁾.

3.2 Regional policy and local action

Regional authorities play a crucial role in the climate transition because they are at the forefront of implementing climate change mitigation and adaptation measures. Each of them faces unique opportunities and challenges as they decarbonise their economies (see Annex 8) by 2040. To support regions with the implementation of locally tailored ambitious climate policies and measures, the EU has put in place a comprehensive and flexible enabling framework. This framework is supplemented by the initiatives and strategies developed by national and regional authorities. However, neither regional, nor national or EU authorities can act alone. It is vital that different levels of government coordinate their climate efforts, both within and across borders.

3.2.1 Available EU funding, objectives, and strategies

A significant share of the EU’s multiannual financial framework (MFF) for 2021-2027 and NextGenerationEU (€2.018 trillion in current prices) will directly support climate action in less developed regions. At least 30% of these two sources combined will be spent on fighting climate change ⁽¹¹⁹⁾. A significant share of these amounts should be spent by the end of 2029. The next, post-2027, long-term budget of the EU will be adopted under the next Commission mandate.

⁽¹¹⁶⁾ Implementation of just transition and economic diversification strategies. A compilation of best practices from different countries. United Nations Climate Change. Katowice Committee on Impacts. 2023.

⁽¹¹⁷⁾ Vocational education and training and the green transition - Publications Office of the EU (europa.eu). DOI: 10.2767/183713

⁽¹¹⁸⁾ Just transition interventions: report by the Katowice Committee of Impacts (created in 2018 in the framework of the UNFCCC with a mandate for monitoring response measures).

⁽¹¹⁹⁾ EU budget today. Midterm review of the MFF 2021-2027. https://commission.europa.eu/strategy-and-policy/eu-budget/motion/today_en.

The Governance of the Energy Union and Climate Action Regulation⁽¹²¹⁾ facilitates the involvement of all governance levels including regional actors in addressing energy and climate policies by creating a permanent Multilevel Climate and Energy Dialogue in Member States. Such a permanent and regular dialogue on climate and energy among all levels of governance and relevant stakeholders has delivered various benefits: continuous political support, ownership, feedback loops, shared responsibility as well as a better implementation of the necessary actions.

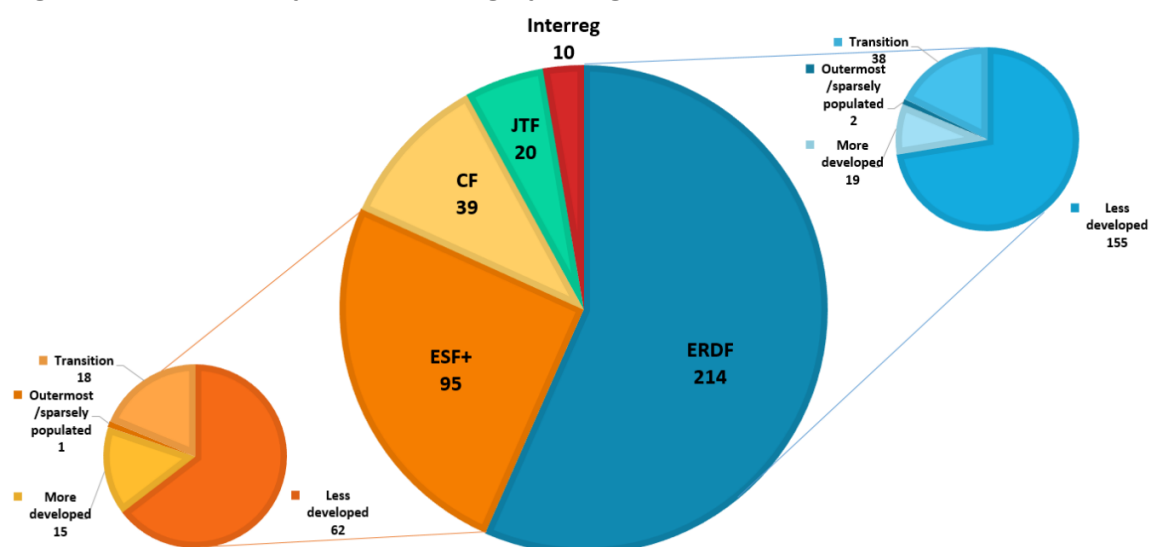
- the EU strategy for the Baltic Sea Region (EUSBSR, 2009);
- the EU strategy for the Danube Region (EUSDR, 2011);
- the EU strategy for the Adriatic and Ionian Region (EUSAIR, 2014); and
- the EU strategy for the Alpine Region (EUSALP, 2016).

The EU's cohesion policy aims to promote and support the overall harmonious development of all EU Member States and regions, making it a vital element of the enabling framework. The policy is implemented by Member States' national and regional bodies in partnership with the European Commission. It contributes to the goals of the Commission priorities, including the European Green Deal (EGD) and more specifically the transition to climate neutrality. Cohesion policy has been allocated a major share of the EU budget – currently €378 billion for 2021–27⁽¹²³⁾. Figure 8 indicates that most of the cohesion funds are targeted at less developed regions, which are regions with a GDP per capita under 75% of the EU average.

(¹²³) Inforegio – EU cohesion Policy: 2021-2027 programmes expected to create 1.3 million jobs in the EU.

- The European Regional Development Fund (ERDF), which invests in the social and economic development of all EU regions and cities;
- The Cohesion Fund (CF), which invests in environment and transport in EU countries with gross national income (GNI) per capita below 90% of the EU-27 average;
- The European Social Fund Plus (ESF+), which supports jobs and, more generally, a fair and socially inclusive society in EU countries (see the section “Just transition & social policy” in Annex 9 of this impact assessment);
- The Just Transition Fund (JTF), which supports regions most affected by the transition towards climate neutrality. It is one of the three pillars of the Just Transition Mechanism (see below);
- Interreg funds, which support territorial cooperation across EU borders as well as with certain neighbouring third countries.

Figure 8: Investment by fund and category of regions

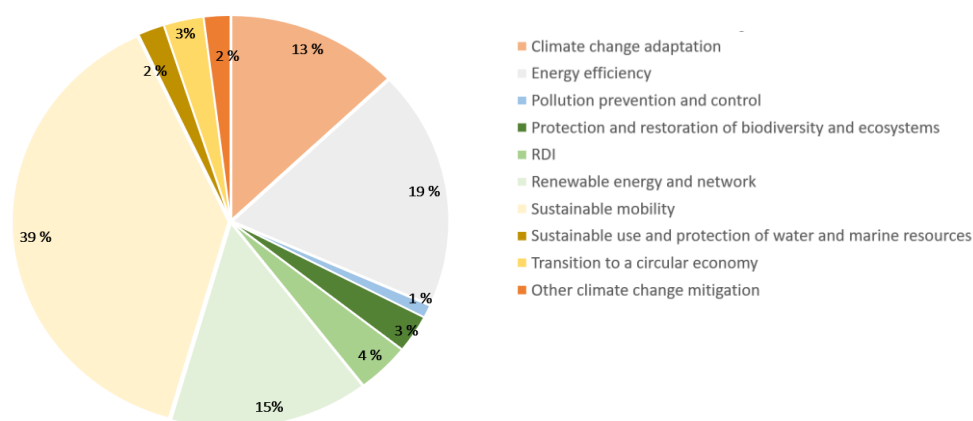


Note: billion EUR. ERDF: European Regional and Development Fund; ESF+: European Social Fund Plus; CF: Cohesion Fund; JTF: Just Transition Fund.

Source: European Commission.

With over EUR 118 billion in EU funded climate investments in the 2021-2027 programming period, cohesion policy is providing a significant contribution to the European Green Deal (EGD). The adopted 2021-2027 ERDF and CF programmes allocate respectively 33% and 56% of their funds to climate action, which exceeds the minimum regulatory commitments of 30% for ERDF and 37% for the Cohesion Fund. The major areas to receive support are energy efficiency; sustainable urban mobility; renewable energy and networks; and climate change adaptation (see Figure 9). In addition, 100% of the JTF’s funds benefit climate action. ESF+ will contribute to the creation of green jobs. Combined, these climate relevant investments will enable regions to significantly boost the implementation of the EU’s climate and environmental policies that aim to improve the life and prospects of people throughout the EU.

Figure 9: ERDF/CF climate expenditure by climate-relevant policy area



Source: European Commission.

The cohesion policy's enforcement mechanisms help to ensure climate action stays on track. For example, cohesion policy has introduced a climate adjustment mechanism that can introduce remediation measures when there's insufficient progress. Further, during the 2025 midterm review, the adopted programmes will be reviewed. This review will provide an opportunity to take account of the country-specific recommendations (CSRs), including those concerning climate policy, and of the progress made by Member States in implementing National Energy and Climate Plans (NECPs).

3.2.2.1 Just Transition Mechanism

In addition, the newly created Just Transition Mechanism (JTM)⁽¹²⁴⁾ provides targeted support to the regions most affected by the climate transition, for example those that must cease fossil-fuel related activities, transform and restructure carbon-intensive industries and/or diversify their economy, maintain social cohesion, invest in future-proof job opportunities, retrain the affected workers and youth to prepare them for future jobs.

The JTM consists of three pillars:

- JTF⁽¹²⁵⁾, which contributes to alleviating the socio-economic impacts of the transition to a climate-neutral economy and to support the economic diversification and reconversion of the territories concerned. The actions supported by the JTF should directly contribute to alleviating the impact of the transition by financing the diversification and modernisation of the local economy and by mitigating the negative repercussions on employment.
- A dedicated InvestEU 'Just Transition' scheme to support economically viable investments by private and public sector entities in a wider range of projects. The

⁽¹²⁴⁾ See https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/finance-and-green-deal/just-transition-mechanism_en

⁽¹²⁵⁾ Just Transition Fund: https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/just-transition-fund_en

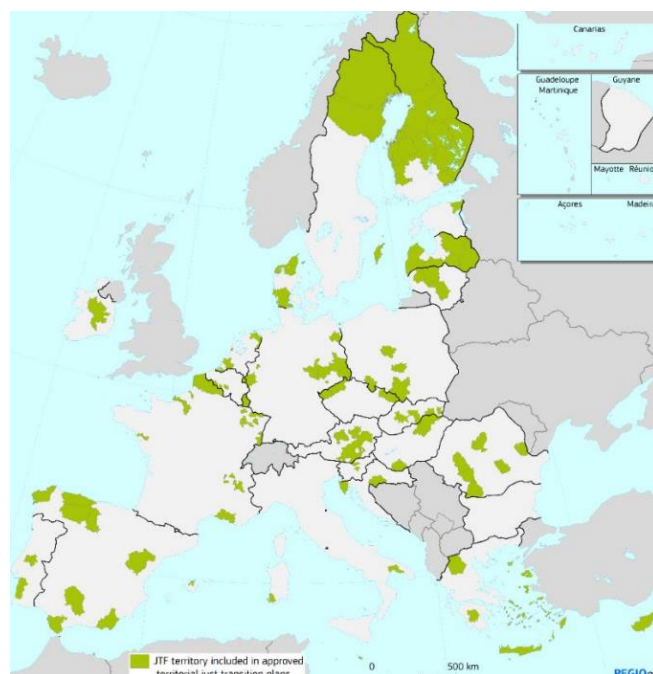
investments should foster economic growth and ultimately economic attractiveness of the Just Transition territories.

- The Public Sector Loan Facility for additional investments to be leveraged by the European Investment Bank (EIB). This helps public sector entities in the most affected regions to meet their development needs in the transition towards a climate-neutral economy.

3.2.2.2 Territorial Just Transition Plans (TJTPs)

The territorial just transition plans provide a novel model for the territorialisation of the climate action, by defining the territories which might receive financing from the JTM. These plans set out the challenges in each territory, as well as the development needs and objectives to be met by 2030. The territories eligible for support by the JTF are published on the Just Transition Platform website with the links to the plans ⁽¹²⁶⁾.

Figure 10: Overview of territories in approved territorial just transition plans (Sept. 2023)



Source: European Commission.

Box: An example of support by the JTF: the decarbonisation of the Swedish industry

The JTF is helping the Swedish industry transition to climate neutrality ⁽¹²⁷⁾, while maintaining competitiveness and sustaining economic and employment levels in the

⁽¹²⁶⁾ Inforegio - Just Transition Fund. https://ec.europa.eu/regional_policy/funding/just-transition-fund/just-transition-platform_en

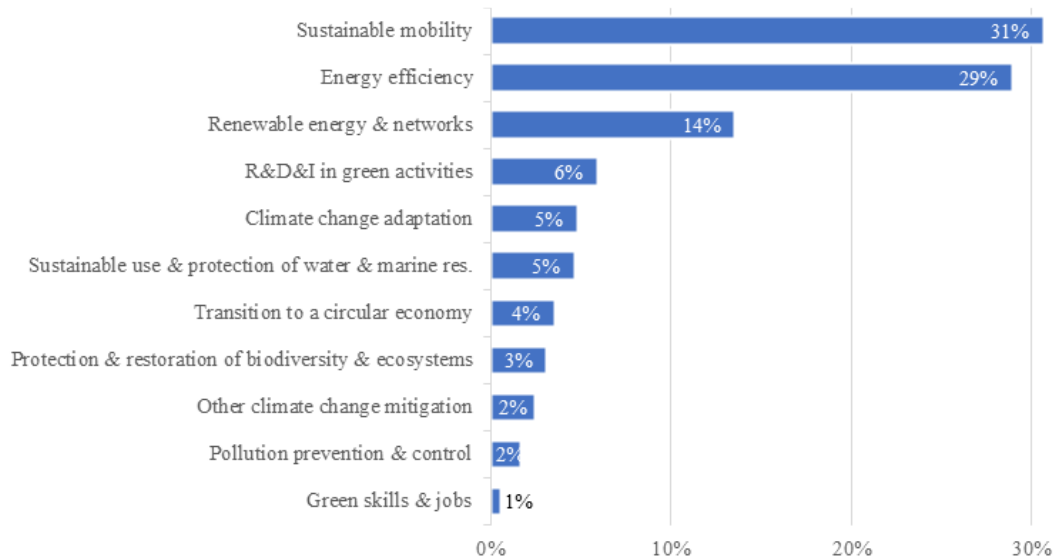
⁽¹²⁷⁾ EU Cohesion policy: €155.7 million climate transition Sweden. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5316

Norrbottnen, Västerbotten and Gotland regions. As industrial emissions account for 32% of Sweden's total greenhouse gas emissions, the transformation of the steel, mineral and metals industry is expected to have important socio-economic impacts. The JTF will help alleviate these impacts by investing EUR 155.7 million in research and innovation and in the retraining and reskilling of workers.

3.2.3 The Recovery and Resilience Facility

The Recovery and Resilience Facility (RRF) will help achieve the EU's targets to reduce net greenhouse gas emissions by at least 55% by 2030 and to reach climate neutrality by 2050. The RRF Regulation provides that the reforms and investments included in each of the recovery and resilience plans must reach targets for climate and digital expenditure. The measures supported by the RRF are contributing to meet the EU's climate ambition by promoting sustainable mobility, increasing energy efficiency, and promoting a higher deployment of renewable energy sources (Figure 11). They will also ensure progress towards climate adaption and other environmental objectives such as reducing air pollution, promoting the circular economy, or restoring and protecting biodiversity.

Figure 11: Breakdown of expenditure supporting the green transition, by policy area



Note: This chart shows a breakdown of the estimated contribution to the policy pillar according to a list of policy areas established by the European Commission. The percentage relates to the overall share of the plan tagged under this policy pillar.

Source: Recovery and Resilience Scoreboard.

The reforms and investments that support climate objectives in Member States' RRFs have exceeded the target of 37% of total allocation set in the RRF Regulation. Total estimated climate expenditure in the adopted plans amounts to EUR 204 billion, which represents about

40% of the total plans' allocation as calculated according to the climate tracking methodology (¹²⁸).

3.2.4 Other EU initiatives

There are several other EU funds, policies, and initiatives that support Member States and their regions with implementing climate policies (see below a non-exhaustive list of such initiatives). Not all these initiatives directly or exclusively target specific EU regions. However, they will all have an impact on climate action in specific regions.

3.2.4.1 Funding

The Modernisation Fund (¹²⁹) is a programme from the European Union to support 10 Member States to meet the 2030 energy targets by helping to modernise energy systems and improve energy efficiency.

The Innovation Fund (¹³⁰) is one of the world's largest funding programmes for the demonstration of innovative low-carbon technologies. The Innovation Fund's total funding depends on the carbon price, and it may amount to about €40 billion for 2020-2030 (assuming a carbon price of €75/tCO₂). In practice, the Innovation Fund allowances from the EU ETS are being auctioned based on the agreed schedule and the revenues perceived are used to provide support to innovative projects afterwards.

Connecting Europe Facility (CEF) is a key EU funding instrument to deliver the European Green Deal and an important enabler towards the Union's decarbonisation objectives for 2030 and 2050 (¹³¹). It supports the development of high performing, sustainable and efficiently interconnected trans-European networks in the fields of transport, energy, and digital services. The InvestEU Programme (¹³²) supports sustainable investment, innovation, and job creation in Europe. With the EU budget guarantee provided to International and National promotional banks, the InvestEU programme aims to trigger more than €372 billion in private investments to high EU policy priority areas. Its Advisory Hub will provide advisory support services to regional authorities.

(¹²⁸) The RRP's had to specify and justify to what extent each measure contributes fully (100%), partly (40%) or has no impact (0%) to climate objectives, using Annex VI to the RRF Regulation. Combining the coefficients with the cost estimates of each measure allows calculating to what degree the plans contribute to the climate target. Please note that the contribution to the green transition pillar is higher than the contribution to climate objectives as defined in Annex VI of the RRF Regulation, since methodologies differ. The differences arise mainly because all covered measures are considered to contribute with 100% of their estimated cost to the pillar, while some contribute only with 40% of their estimated cost to the climate objectives as defined in Annex VI of the Regulation. In addition, the green transition pillar also includes coefficients for environmental objectives that are wider than climate objectives as per Annex VI of the RRF Regulation.

(¹²⁹) See <https://modernisationfund.eu/>.

(¹³⁰) See https://cinea.ec.europa.eu/programmes/innovation-fund_en.

(¹³¹) See https://cinea.ec.europa.eu/programmes/connecting-europe-facility_en.

(¹³²) See https://investeu.europa.eu/investeu-programme_en.

The EIB⁽¹³³⁾ offers targeted support for projects in less-developed regions, including for green transition projects.

3.2.4.2 Fostering collaboration between regional authorities

Horizon Europe Mission on Cities⁽¹³⁴⁾ involves local authorities, citizens, businesses, investors as well as regional and national authorities to deliver 100 climate-neutral and smart cities by 2030 and to ensure that these cities act as experimentation and innovation hubs to enable all European cities to follow suit by 2050.

The EU Covenant of Mayors for Climate & Energy⁽¹³⁵⁾ is an initiative supported by the European Commission that brings together thousands of local governments that want to secure a better future for their citizens. Local governments voluntarily commit to implementing EU climate and energy objectives and the European Green Deal on the ground. The initiative is a first-of-its-kind bottom-up approach to energy and climate action. There are almost 11.000 cities committed to become climate neutral by 2050.

Regions4Climate⁽¹³⁶⁾ is developing innovative tools and collaborative practices to support European regions and communities in developing and implementing their own resilience plans that not only explicitly address social, environmental, and economic innovations but also inherently consider social equity and social justice concerns associated with resilience building.

The European Climate Pact⁽¹³⁷⁾ is a movement of people united around a common cause, each taking steps in their own worlds to build a more sustainable Europe. Launched by the European Commission, the Pact is part of the European Green Deal and is helping the EU to meet its goal to become climate-neutral by 2050.

3.2.4.3 Regional State Aid

The European Commission's regional state-aid⁽¹³⁸⁾ policy supports economic development and employment. The regional aid guidelines set out the rules under which Member States can grant state aid to companies to support investments in new production facilities in the less advantaged regions of Europe or to extend or modernise existing facilities.

3.2.4.4 Technical assistance

The Commission offers technical assistance to Member States and their regions, including through the following measures.

⁽¹³³⁾ See <https://www.eib.org/en/projects/regions/index.htm>.

⁽¹³⁴⁾ See Climate-neutral and smart cities, https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe/eu-missions-horizon-europe/climate-neutral-and-smart-cities_en.

⁽¹³⁵⁾ See <https://eu-mayors.ec.europa.eu/en/home>.

⁽¹³⁶⁾ See Regions4Climate - Building resilient communities, <https://regions4climate.eu/>.

⁽¹³⁷⁾ See https://climate-pact.europa.eu/index_en.

⁽¹³⁸⁾ See Regional Aid, https://competition-policy.ec.europa.eu/state-aid/legislation/modernisation/regional-aid_en.

The C4T Community of Practice ⁽¹³⁹⁾ is a community-based platform that aims to support EU Member States and regions to make a better use of EU funds for sustainability transitions. C4T engages national, regional, and local cohesion and sustainability transitions practitioners in sharing experience and good practices, creating partnerships and jointly identifying solutions. C4T also provides technical assistance to facilitate the development and/or implementation of sustainability transitions. C4T brings together beneficiaries involved in the implementation of transition measures with support from cohesion policy under Policy Objective 2 ‘A greener, low-carbon transition towards a net zero carbon economy and resilient Europe’.

EU Technical Support Instrument ⁽¹⁴⁰⁾ is the EU programme that provides tailor-made technical expertise to EU Member States to design and implement reforms. The support is demand driven and does not require co-financing from Member States.

The policy support facility ⁽¹⁴¹⁾ gives Member States and countries associated to Horizon Europe practical support to design, implement and evaluate reforms that enhance the quality of their research and innovation investments, policies, and systems.

The Climate Adaptation Platform for the Alps (CAPA) ⁽¹⁴²⁾ supports decision-makers in Alpine countries, regions, and municipalities in adapting to climate change by giving them access to knowledge resources and information that have been selected by experts based on relevance and usefulness criteria. It offers knowledge products for a broad spectrum of administrative and socio-economic sectors (agriculture, energy, health, water management, spatial planning, etc.). It puts strong emphasis on cross-sectorial aspects of adaptation.

3.2.5 *Example of a region that has received support: the Ruhr region*

The Ruhr region in North Rhine-Westphalia has traditionally been one of Europe’s industrial powerhouses, based on the extraction of coal ⁽¹⁴³⁾. Spanning roughly 2,700 km² the Ruhr Valley lies in the state of North-Rhine Westphalia, made up of 53 cities that came to depend on coal mining when it reached an industrial scale in the 1800s. At their height in the 1950s, the mines employed about 600,000 workers, entwining the region’s identity with coal. According to Reitzenstein et al. (2021), Galgoczi (2014), Sheldon et al. (2018), in the Ruhr region in 1957, 70% of the population was employed in coal, iron and steel industries (half in coal mining).

⁽¹³⁹⁾ See InfoREGIO - Cohesion for Transitions (C4T), https://ec.europa.eu/regional_policy/policy/communities-and-networks/cohesion-4-transition_en.

⁽¹⁴⁰⁾ See https://commission.europa.eu/funding-tenders/find-funding/eu-funding-programmes/technical-support-instrument/technical-support-instrument-tsi_en.

⁽¹⁴¹⁾ See <https://ec.europa.eu/research-and-innovation/en/statistics/policy-support-facility>.

⁽¹⁴²⁾ See <https://climate-adapt.eea.europa.eu/en/metadata/portals/climate-adaptation-platform-for-the-alps-cap/#:~:text=The%20platform%20provides%20resources%20about,analytical%20studies%20and%20policy%20reviews>.

⁽¹⁴³⁾ See https://economy-finance.ec.europa.eu/system/files/2022-12/dp176_en_green%20transition%20labour.pdf.

Cohesion policy supported many projects in the framework of a long-term strategy aimed at transforming the region, including the restoration of the river system, the construction of a bicycle network, the creation of landscape parks, and the conversion of former steel sites and railroads into lakes and green neighbourhoods. This is embedded in nearly three decades of EU funding to support the structural change of this old industrial region into a modern, green metropolis. This involved structural policies to support the specialization of the region, the development of new universities, infrastructures, in particular in renewable energy, and cultural activities. Several policies contributed to the successful transition in the Ruhr region. These include a consistent engagement of different levels of governments; a strong participation of social partners; targeted public sector investments; institutional cooperation; and effective labour market policies.

Coal mining has now completely disappeared but despite the loss in coal jobs, the overall number of jobs stayed constant. The support provided to the Ruhr region turned it into an exemplary territory for green infrastructures and an attractive area for companies.

In the 2021-2027 period, the Ruhr region is also one of the German territories benefitting from the JTF. The fund will help the region with investments in skills, green innovation, and environmental restoration. This contributes to cushioning the socio-economic impacts of Germany's coal phase-out.

3.3 Lifestyle and individual action

3.3.1 Sustainable lifestyle choices

Individual action is one of the key factors to efficiently mitigate climate change and protect the environment. Household consumption has been associated with up to 72% of global greenhouse gas emissions ⁽¹⁴⁴⁾, thus changes in individual and household lifestyles have an enormous potential to reduce GHG emissions.

Making more climate-friendly choices on an individual level requires a willingness to adopt new behaviours, but policy makers need to facilitate more climate-friendly lifestyle choices by removing barriers and creating incentives to set up proper framework conditions for new lifestyles ⁽¹⁴⁵⁾. Examples for an improvement of proper framework conditions for new lifestyles are increasing their availability (e.g., through improved access to public transport), incentivizing their use (e.g. reducing taxes on repair work to increase the longevity of products) or informing individuals about the environmental impact of their choices (e.g., reliable and trustworthy eco-friendly or energy efficiency labels, protection against false green claims, and reliable data on door-to-door transport emissions ⁽¹⁴⁶⁾).

Some examples for individual action in a non-exhaustive list are:

⁽¹⁴⁴⁾ Hertwich, E.G., Peters, G.P., 2009. Carbon footprint of nations: A global, trade-linked analysis. *Environ. Sci. Technol.* 43 (16), 6414–6420.

⁽¹⁴⁵⁾ Frederiks, E. R., Stenner, K., Hobman, E. V. 'Household energy use: Applying behavioural economics to understand consumer decision-making and behaviour', *Renewable and Sustainable Energy Reviews*, 41, 1385-1394, 2015.

⁽¹⁴⁶⁾ COM(2023) 441

- Sustainable lifestyle choices: individuals can make choices in their daily lives to reduce their carbon footprint such as reducing waste, consuming more sustainable and sufficient. This includes buying locally and environmentally friendly products and opting for long-lasting products, reducing single-use products, and opting for the reuse of products. Furthermore, citizens can choose a more sufficient lifestyle by buying less and repairing more as part of advanced circular economy practices.
- Sustainable transportation: walking, cycling, or using public transport instead of using a car can significantly reduce carbon emissions. Citizens can also advocate for ‘mobility as a service’ such as car- and bike-sharing options that aim to share transport modes between individuals and aim for a higher use intensity. An increasing concern on climate change and a shift in the social norm among citizens may incentivize citizens to use less flights in favour of more sustainable transport alternatives, like rail.
- Energy and housing transition: individuals may participate in the transition to renewable energy sources at the individual level through supporting community-based renewable energy projects, the installation of solar panels on their homes, or adopting energy efficiency measures in homes and businesses. This may also include a shift towards reduced floor area and a preference for renovation over new construction.

Results from the public consultation show that large parts of EU citizens are in general willing to adopt new lifestyles and to adopt a variety of individual actions to reduce their own carbon footprint (82%). The highest support was expressed for individual action towards a more circular economy such as repairing or reusing goods (88%)⁽¹⁴⁷⁾ and reducing wasteful consumption through the use of long-lasting appliances, clothing and other products (89%). High support was also expressed for a dietary change towards more climate-friendly diets (85%) and for the use of climate-friendly labels (82%) and the acceptance of renewable energy infrastructure in one’s municipality (80%).

However, it appears these changes in lifestyles and consumption patterns need support from policy makers⁽¹⁴⁸⁾, for example through a change in the choice architecture, incentives, available mobility alternatives, or urban planning⁽¹⁴⁹⁾. EU citizens indicated in the public consultation that number of policies would help them adopting a more climate-friendly lifestyle⁽¹⁵⁰⁾. Citizens indicated as most helpful, if prices of goods and services would reflect their climate impact to a better degree (Avg. = 4.43), the facilitation of personal investments in climate friendly solutions (Avg. = 4.27) and ensuring that the most vulnerable in society have access to climate-friendly products and services (Avg. = 4.19). On general, all types of

⁽¹⁴⁷⁾ Participants in the Public Consultation questionnaire were asked which of the listed personal actions they would be willing to take to fight climate change. Percentages indicate EU citizens willingness to take these actions.

⁽¹⁴⁸⁾ Scientific Advice Mechanism (SAM), ‘Towards Sustainable Food Consumption’, *Group of Chief Scientific Advisors Scientific Opinion*, No.14, 2023.

⁽¹⁴⁹⁾ IPCC AR6 WG III, Summary for Policy Makers.

⁽¹⁵⁰⁾ EU citizens indicated on a scale from 1 (not helpful) to 5 (very helpful) how much the following proposals would help them to reduce their personal climate footprint. Numbers in brackets show the mean value. The closer a mean value to 5 the more helpful it is assessed on average.

support to increase information, raising awareness and facilitating the access to climate-friendly solutions was rated positively (Avg. = 3.77 to 4.04).

3.3.2 Sustainable food consumption

A particularly relevant field for changing lifestyles is food consumption. With regard to demand-sided mitigation potentials associated with individual choices, behaviour and lifestyle changes, the IPCC has identified nutrition as the area with the biggest potential to reduce emissions⁽¹⁵¹⁾. Also, throughout the EU, food has both emerged as the consumption area of individuals with the highest environmental and climate impact⁽¹⁵²⁾, as well as a field that shows a notably high agreement for willingness to change throughout EU citizens. As an example, a high share of EU citizens indicated their inclination in the public consultation to eat food with a lower climate impact, such as plant-based, local, or sustainably produced food (85%). When looking more closely on food consumption habits of EU citizens, animal-based products (i.e., meat, dairy products, and eggs) stick out since they make up only about one quarter of the total amount of food consumed while contributing to more than 60% of the climate change impacts from food⁽¹⁵³⁾. This is due to the lower efficiency from an input/output perspective of animal-based products compared to other food products⁽¹⁵⁴⁾.

A voluntary change in food diets in societies is not uncommon. Food diets can change in a comparably short time and recent history underlines the potential for widespread changes, including on more diverse and healthier diets⁽¹⁵⁵⁾. Moreover low-meat diets increase in EU countries as some recent examples show. The number of products being labelled as vegetarian, or vegan has increased significantly⁽¹⁵⁶⁾ and with-it meat-alternatives in supermarkets. Meat consumption per capita in Germany declined in 5 years until 2022 by 13% for beef and cattle and by 20% for pork and is now at the lowest total consumption level since 1989.⁽¹⁵⁷⁾ One of the main reasons is that meat alternatives become increasingly available and plant-based diets increasingly popular among the population. On EU level, a

⁽¹⁵¹⁾IPCC AR6 WG III, Summary for Policy Makers Figure SPM.6

⁽¹⁵²⁾Five areas of consumption have been assessed: food, mobility, housing, household goods and appliances. Food makes up 48% of the consumption footprint on environmental impacts and 38% of the consumption footprint on climate change for an average EU citizen in 2021. See Sanyé Mengual E, Sala S, ‘Consumption Footprint and Domestic Footprint: Assessing the environmental impacts of EU consumption and production. Life cycle assessment to support the European Green Deal’, *Publications Office of the European Union*, 2023.

⁽¹⁵³⁾European Commission, Joint Research Centre, Sanyé Mengual, E., Sala, S., Consumption footprint and domestic footprint – Assessing the environmental impacts of EU consumption and production – Life cycle assessment to support the European Green Deal, Publications Office of the European Union, 2023, <https://data.europa.eu/doi/10.2760/218540>

⁽¹⁵⁴⁾Capone, R., et al., ‘Food System Sustainability and Food Security: Connecting the Dots.’, *Journal of Food Security*, 2, 1, 13-22, 2014.

⁽¹⁵⁵⁾Vermeulen, S.J., et al., ‘Changing diets and the transformation of the global food system’, *Ann. N.Y. Acad. Sci.*, 1478, 3-17, 2020.

⁽¹⁵⁶⁾FReSH insights report, ‘Consumption behavior and trends: understanding the shift required towards healthy, sustainable, and enjoyable diets’, *Geneva: World Business Council for Sustainable Development*, 2018.

⁽¹⁵⁷⁾BLE (2023), Press Release: Fleischverzehr 2022 auf Tiefstand.

slight general trend of dietary change is also visible. In the last five years before 2023, per capita consumption of meat declined by nearly 2% and consumption of fresh dairy products by 6%, a trend that is generally expected to continue in the future. This is in line with results from the public consultation.

Furthermore, the European Commission projects a shift from red meat to white meat ⁽¹⁵⁸⁾, which is associated with lower GHG emissions. The current changes in dietary preferences result from health considerations and consumer concerns about climate, animal welfare and environment. The increasing availability of protein alternatives also play a role in dietary changes. Importantly these meat alternatives can be vegetables, fish as well as artificial meat. However, to obtain a sustainable and healthy diet simply replacing meat with fish comes with its own concerns. Overexploitation is already impacting fish stocks, and more importantly Europeans consumption of fish should with regard to healthy diets not drastically increase. ⁽¹⁵⁹⁾

4 HEALTHY NATURE AND SUSTAINABLE CIRCULAR BIOECONOMY

Managing the land more sustainably is not only important for the achievement of climate targets but is also essential to ensure that the land sector can continue to provide food, biomass, freshwater and ecosystem services for generations to come, in the context of increasing global warming.

4.1 Current policy framework on carbon removals and agriculture GHGs

Management of land and biological resources within ecologic boundaries is one of the dimensions of bioeconomy policies. There are challenges to be addressed, such as the increased pressure on land for climate mitigation and adaptation and nature protection while supplying an increasing demand of biomass for food, materials (e.g., bioplastics, long-lasting wood products) and bioenergy. To ensure environmental integrity, there is a need to understand the status and resilience of terrestrial and marine ecosystems, including their services and related socio-economic costs and benefits.

The current policy framework addresses the climate change mitigation potential of sustainable land management practices through national targets. These targets are characterised by a separation between the agriculture sector and the Land Use, Land Use Change and Forestry (LULUCF) sector. The agriculture sector, which corresponds to non-CO₂ emissions mainly related to the raising of livestock, the use of fertilisers and the management of manure, is not governed by a specific sectoral target; its emissions are instead included in the national emission targets under the Effort Sharing Regulation together with other sectors. Recently, with the Fit-for-55 revision, Effort Sharing targets underwent a significant increase in ambition: emissions in these sectors will have to be cut by 40% (up from -29%) by 2030 as

⁽¹⁵⁸⁾ European Commission, DG Agriculture and Rural Development, ‘EU agricultural outlook for markets, income and environment, 2022-2032’, Brussels, 2022.

⁽¹⁵⁹⁾ Willet et al., ‘Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems’, Lancet, 2019.

compared to 2005 emission levels. The LULUCF sector mainly corresponds to CO₂ fluxes (i.e., emissions and removals) between soils, biomass and the atmosphere; with the LULUCF Regulation, the EU has recently agreed on a new target to achieve 310 MtCO₂ of net removals in 2030, and this target is distributed across Member States through binding national targets.

National targets can trickle down to the individual land managers through public-based or market-based incentives to take climate action. The Common Agricultural Policy (2023-2027 period), which includes several climate-related obligations and incentives, represents an important budget envelope that Member States can use to support farmers in adopting more sustainable land management practices and to help to achieve those national climate targets. Every EU Member State describes in a national CAP Strategic Plan how it intends to design CAP requirements and interventions to contribute (among others) to the objective of climate mitigation and adaptation. Under the enhanced conditionality, by 2025, land management practices minimising or avoiding carbon release will be applied on agricultural wetlands and peatlands in all EU countries. Member States are planning to support carbon removals and protection, and reduced methane and nitrous oxide from better use, management, and application of fertilisers on 35% of the EU's utilized agricultural area with practices beyond conditionality. Eco-schemes, agro-environment climate commitments and investments are broadly used to support practices such as agroforestry, afforestation, soil cover and reduced tillage, grassland protection, and management of peatland. Investments in improved manure storage and management, low emission slurry spreading, and anaerobic digesters have been planned to address livestock-related emissions, with some Member States planning other practices such as outdoor grazing, improvement of feeding plans and feed additives. Over 600 000 ha are planned to be supported for afforestation, agroforestry, restoration, and creation of landscape features. A specific article in the CAP Strategic Plan Regulation requires Member States to assess whether their CAP Strategic Plan should be amended according to recent agreements on more ambitious EU climate targets for the LULUCF and the Effort Sharing sectors.

The upcoming proposal for a legislative framework for sustainable food systems (FSFS) is one of the flagship initiatives of the Farm to Fork Strategy ⁽¹⁶⁰⁾. It aims to accelerate and make the transition to sustainable food systems easier while mainstreaming sustainability in all food-related policies and strengthening the resilience of food systems. As a result of a more sustainable food system emissions in the agriculture sector as well as in food processing industry should decline. One important input to the proposal is the independent expert report ⁽¹⁶¹⁾, which highlights the need to decrease the environmental impacts from food production, reduce food waste and loss, and stimulate dietary changes towards healthier and less resource-intensive diets through a combination of various policy measures.

⁽¹⁶⁰⁾ COM(2020) 381 final

⁽¹⁶¹⁾ European Commission, Directorate-General for Research and Innovation, Group of Chief Scientific Advisors, Towards a sustainable food system – Moving from food as a commodity to food as more of a common good – Independent expert report, Publications Office, 2020, <https://data.europa.eu/doi/10.2777/282386>.

Carbon farming is a business model whereby land managers are rewarded for providing carbon sequestration. To enable this approach, the Commission has proposed an EU-wide voluntary framework for the certification of carbon removals, as a tool to reliably monitor, report, and verify (MRV) high-quality carbon removals that deliver unambiguous climate benefits and have the potential to also deliver on biodiversity and restoration of ecosystem services. The proposed framework can create innovative business opportunities for land managers, but only if the resulting carbon removals are credible and trustworthy, so that they can attract private and public financial support. Carbon farming will provide farmers, foresters, and other land managers with an additional source of income in exchange for storing carbon in the soil, trees, shrubs, wetlands, and peatlands. The proposal requires that carbon farming does not harm other environmental objectives and encourages the delivery of environmental co-benefits, such as on biodiversity and the provision of ecosystem services. Once the Regulation enters into force, the EU-level quality criteria and verification rules will be further operationalised through technical certification methodologies adopted by the Commission, in the forms of Delegated Acts, tailored to the different types of carbon removal activities. To this end, the Commission has established an Expert Group on Carbon Removals, which will assist the Commission to map out best practices on certification methodologies for carbon removals, ensuring full and close involvement of civil society.

4.2 Reducing GHG emissions from the land sector

4.2.1 Agricultural emissions

GHGs emitted from agricultural activities include non-CO₂ emissions such as methane (CH₄) and nitrous oxide (N₂O). Most of these non-CO₂ emissions come from the livestock digestion process, the management of manure, and the use of fertilisers. Over the last decade, the agricultural sector has not reduced its absolute GHG emissions, although increasing production efficiencies have led to reduced GHG emissions per unit produced. Practices to reduce methane emissions from enteric fermentation should focus on breeding to reduce methane intensity and improve animal health and fertility, optimising feed management and use of pastures/grazing, and using appropriate feed additives. The best way to reduce fertiliser emissions is to optimise the fertilisation process, mainly through a precise selection of the fertiliser dose in space and time (precision agriculture); other options include management practices beneficial for the nutrient cycle and soil, such as using legume crops or pastures in rotation instead of nitrogen fertiliser, catch and cover crops or practicing minimum tillage for cropping. Techniques to decrease manure-related emissions are cooling slurry, slurry acidification, covering manure and slurry stores, anaerobic digestion with biogas recovery for renewable energy, improvements in the housing of livestock.

4.2.2 Halt and reverse the loss of soil carbon

_ Besides creating non-CO₂ emissions, agricultural activities may cause a loss of carbon from soils due to the use of land as cropland and grassland. Overall, EU soils are losing carbon. In 2019, Member States reported net emissions of 108 MtCO₂ from organic soil and net removals of 44 MtCO₂ from mineral soil. The IPCC ⁽¹⁶²⁾ cites afforestation, enhanced

⁽¹⁶²⁾ IPCC AR6 WG III Full Report, 2022, Mitigation of Climate Change

sequestration in cropland and grasslands, use of biochar, peatland and coastal wetland restoration and agroforestry as mitigation options with a positive impact on soil carbon storage. These nature-based removals can provide important co-benefits such as better resilience to climate change (in particular, droughts and floods) improved soil quality, increased crop yields, improved biodiversity and reduced N₂O and CH₄ emissions, when implemented properly ⁽¹⁶³⁾. However, the solutions can also lead to increased competition for land and negative impacts on food production (with consequent risks for food security) and on biodiversity, as well as increase N₂O and CH₄ emissions and the risk of subsequent loss of sequestered carbon due to climate change and future disturbances ⁽¹⁶⁴⁾.

4.2.3 Increase forest carbon sinks

The capacity of EU forests to sequester carbon has been rapidly declining: EU forests only absorbed 256 MtCO₂ in 2020, down from 320 MtCO₂ in 2016 and 357 MtCO₂ in 2013. The decline in the forest sink can be attributed to an increase in wood demand, an increasing share of forests reaching harvest maturity, and an increase in natural disturbances ⁽¹⁶⁵⁾. To reverse this trend, it is important to consider mitigation options in the LULUCF sector such as improved forest management, afforestation, rewetting, and emission reduction on agricultural land, while ensuring that any new forest is composed of mixes of species that can be resilient in the face of climate change.

4.3 Preserve and restore biodiverse ecosystems

Climate change and biodiversity loss are two of the most pressing issues of the Anthropocene. The rapid decline of biodiversity and changes in climate are interdependent: they share underlying direct and indirect drivers, they interact and are mutually reinforcing. Furthermore, both can have cascading and complex effects that impact people's quality of life and compromise societal goals.

Climate change is one of the five main drivers of global biodiversity loss, with change of land and sea use, direct exploitation, pollution, and invasive alien species ⁽¹⁶⁶⁾. At the same time, biodiversity is an essential ally to fight climate change. Healthy ecosystems deliver services that are key for climate mitigation and adaptation (protection against floods, droughts, urban heat and desertification, water retention, air, and water purification). However, it should be noted that climate change is not the only factor threatening ecosystems. For instance, certain forestry practices may be beneficial to store carbon but can exacerbate the risks of extreme weather events, such as forest fires or plagues ⁽¹⁶⁷⁾. More biodiverse forests are more resilient,

⁽¹⁶³⁾ European Environment Agency, Briefing no. 14/2022, Soil carbon, 2022. doi: 10.2800/822511

⁽¹⁶⁴⁾ IPCC, 2022, IPCC 6 Assessment Report, WG3, Chapter 12

⁽¹⁶⁵⁾ SWD(2021) 609 final

⁽¹⁶⁶⁾ IPBES (2019). Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (Version 1). Zenodo. <https://doi.org/10.5281/zenodo.6417333>

⁽¹⁶⁷⁾ Robbie S.H. Johnson, Younes Alila (2023). Nonstationary stochastic paired watershed approach: Investigating forest harvesting effects on floods in two large, nested, and snow-dominated watersheds in British Columbia, Canada, Journal of Hydrology, Volume 625, Part A, 129970, ISSN 0022-1694, <https://doi.org/10.1016/j.jhydrol.2023.129970>.

multifunctional, productive, deliver more ecosystem services and even capture more carbon ⁽¹⁶⁸⁾ ⁽¹⁶⁹⁾.

Nature-based solutions are actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits ⁽¹⁷⁰⁾. In that sense, nature-based solutions not only help to mitigate climate change but also can directly provide additional benefits to biodiversity and people ⁽¹⁷¹⁾. Examples of concrete nature-based solutions are conserving forests and ecosystems, and ecosystem restoration, reforestation, and afforestation. The IPCC highlights that nature-based solutions have greater likelihood of being successful than other mitigation measures on agriculture, forestry and land-use, whose rapid deployment is essential to reach the 1.5°C target ⁽¹⁷²⁾. Biodiversity-friendly climate strategies, far from leading to additional costs, are often a more economical approach than mitigation that does not take environmental protection into account ⁽¹⁷³⁾, thanks to the synergies generated and the socio-economic costs avoided from degraded ecosystems ⁽¹⁷⁴⁾.

The EU has launched several initiatives to preserve and restore biodiverse ecosystems. The EU Biodiversity Strategy for 2030 ⁽¹⁷⁵⁾ is a part of the European Green Deal and focuses on halting biodiversity loss, protect areas at land and at sea, restoring degraded ecosystems, and introduce measures to enable the necessary transformative changes as well as to tackle the global biodiversity challenge. The EU Forest Strategy for 2030 ⁽¹⁷⁶⁾ builds on the EU biodiversity strategy for 2030 and sets a vision and concrete actions to improve the quantity and quality of EU forests and strengthen their protection, restoration, and resilience. It aims to restore and enlarge the EU's forests to combat climate change but also to reverse biodiversity loss and ensure resilient and multifunctional forest ecosystems. The strategy is designed to

⁽¹⁶⁸⁾ Lewis, S.L., Wheeler, Ch.E.; Mitchard, E.T.A. and Kock, A. (2019). "Restoring natural forests is the best way to remove atmospheric carbon, in *Nature*, 68, 25-28, <https://doi.org/10.1038/d41586-019-01026-8>.

⁽¹⁶⁹⁾ Pukkala, T. (2016). Which type of forest management provides most ecosystem services? *Forest Ecosystems* 3, 1-16.

⁽¹⁷⁰⁾ UNEA (2022). Nature-based solutions for supporting sustainable development. UNEP/EA.5/Res.5. Available at: <https://wedocs.unep.org/20.500.11822/39864>.

⁽¹⁷¹⁾ Seddon, N. et al. (2020). 'Global recognition of the importance of nature-based solutions to the impacts of climate change', *Global Sustainability*, 3, p. e15. Available at: <https://doi.org/10.1017/sus.2020.8>.

⁽¹⁷²⁾ IPCC (2022). Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Available at: <https://www.ipcc.ch/report/ar6/wg3/>.

⁽¹⁷³⁾ Strassburg, B.B.N. et al. (2018). 'Strategic approaches to restoring ecosystems can triple conservation gains and halve costs', *Nature Ecology & Evolution*, 3(1), pp. 62–70. Available at: <https://doi.org/10.1038/s41559-018-0743-8>.

⁽¹⁷⁴⁾ Pörtner, H.-O. et al. (2023) 'Overcoming the coupled climate and biodiversity crises and their societal impacts', *Science*, 380(6642), p. eabl4881. Available at: <https://doi.org/10.1126/science.abl4881>

⁽¹⁷⁵⁾ COM(2020) 380 final

⁽¹⁷⁶⁾ COM(2021) 572 final

address various challenges and opportunities related to forests, including environmental, economic, and social aspects. Part of the strategy therefore is to promote the sustainable forest bioeconomy for long-lived wood products, ensure the sustainable use of wood-based resources for bioenergy and the re- and afforestation of biodiverse forests.

The proposal for a Directive on Soil Monitoring and Resilience ⁽¹⁷⁷⁾ is also part of the EU Biodiversity Strategy for 2030 and was proposed to ensure a level playing field and a high level of environmental and health protection. More specifically, the proposed Soil Monitoring Law aims to address key soil threats in the EU, such as erosion, floods and landslides, loss of soil organic matter, salinisation, contamination, compaction, sealing, as well as loss of soil biodiversity.

4.4 Investment needs for biodiversity and a sustainable and circular bioeconomy

The Bioeconomy Strategy Progress Report 2022 ⁽¹⁷⁸⁾ which was delivered in response to the updated EU bioeconomy strategy ⁽¹⁷⁹⁾ emphasizes that EUR 2.7 billion of private investment has been unlocked to bio-based industries, which helped to develop new technologies for sustainable and circular bio-based value chains. However, pressure on ecosystems is increasing and more action is needed. Most importantly, future bioeconomy needs to develop solutions on how to better manage land and biomass demands ⁽¹⁸⁰⁾ and make consumption patterns more sustainable.

Annual financing need for biodiversity protection and restoration reaches up to EUR 48 billion per year to 2030, with a foreseen gap of around EUR 19 billion, with implications beyond 2030. As part of this, nature restoration investments of EUR 8-15 billion per year, need to be maintained up to 2050 ⁽¹⁸¹⁾. These investments are also necessary to increase the carbon removal capacity and the resilience of ecosystems.

4.4.1 Towards biodiversity credits and payment for ecosystem services (PES)

The Kunming-Montreal Global Biodiversity Framework (GBF) commits parties to increase financial resources for biodiversity ⁽¹⁸²⁾ for example through stimulating innovative schemes

⁽¹⁷⁷⁾ COM(2023) 416 final

⁽¹⁷⁸⁾ European Commission, Directorate-General for Research and Innovation, European bioeconomy policy – Stocktaking and future developments – Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Publications Office of the European Union, 2022, <https://data.europa.eu/doi/10.2777/997651>.

⁽¹⁷⁹⁾ COM/2018/673 final

⁽¹⁸⁰⁾ See for instance JRC, ‘Biomass production, supply, uses and flows in the European Union’, *JRC Science for policy report*, 2023.

⁽¹⁸¹⁾ European Commission, Directorate-General for Environment, Nesbit, M., Whiteoak, K., Underwood, E. et al., Biodiversity financing and tracking – Final report, Publications Office of the European Union, 2022, <https://data.europa.eu/doi/10.2779/950856>.

⁽¹⁸²⁾ GBF Target 19 ‘Financial resources increased to \$ 200 billion per year, including \$ 30 billion through international finance’; <https://www.cbd.int/gbf/targets/19/>.

such as payment for ecosystem services (PES), green bonds, biodiversity offsets and credits, and benefit-sharing mechanisms, with environmental and social safeguards.

Payment for ecosystem services (PES) ⁽¹⁸³⁾ represent a policy instrument and describe incentives provided to landowners, farmers, or communities in exchange for managing their land or natural resources in ways that benefit the natural ecosystems and its respective services. Ecosystem services are the various benefits that humans receive from natural ecosystems, including clean water, air purification, soil fertility, pollination, and climate regulation. PES has received wide attention among scientists, governments, and institutions, and have been implemented at local, national, and international levels ⁽¹⁸⁴⁾. PES programmes around the globe have already generated annual payments over US\$36 billion by 2018 ⁽¹⁸⁵⁾ financing services such as providing water quality and quantity, biodiversity and habitat conservation, pollination services, but as well climate change mitigation through forests and other ecosystems. In a PES scheme dedicated to climate mitigation, owners of land that hosts ecosystems such forests, grasslands, and wetlands but also agroecosystems would receive a premium for carbon sequestration and long-term carbon storage. The payments are either user-financed (direct beneficiaries of ecosystem services), government-financed, or compliance-based (parties facing regulatory obligations paying to satisfy their mitigation requirements such as the EU ETS).

Biodiversity credits is a more specific policy instrument designed specifically for biodiversity. The credits are tradeable units of biodiversity, which can be bought by companies to measure milestones towards becoming nature positive. They can be self-standing or complement voluntary carbon credits. Biodiversity credits represent improvements in biodiversity, while biodiversity offsets are measurable conservation outcomes designed to compensate for adverse impacts of projects. The credits may become an emerging instrument to mobilize financial resources toward nature-positive outcomes and are generating interest among many governments, financial entities, and stakeholders at both global and European level. While biodiversity credits are certainly not a panacea to close the biodiversity finance, they can provide a sizable contribution.

Work is ongoing internationally to define and develop instruments for resource mobilisation in favour of biodiversity. In this context, biodiversity credits and related tools could help to address the concerns raised by countries with high forest cover and low levels of deforestation, such as Gabon and Guiana, which are calling for more international funding earmarked for the conservation and protection of tropical forests. It is important to offer

⁽¹⁸³⁾ Sattler, Claudia, and Bettina Matzdorf. "PES in a nutshell: From definitions and origins to PES in practice—Approaches, design process and innovative aspects." *Ecosystem services* 6 (2013): 2-11.

⁽¹⁸⁴⁾ China has implemented large-scale PES programs, particularly for watershed protection, reducing erosion and reforestation. Mexico has established PES programs to protect forests and watersheds. The UN's Reducing Emissions from Deforestation and Forest Degradation (REDD+) program involves payments for conserving forests and reducing carbon emissions. The United States pay alndowners and farmers for watershed, biodiversity protection and the control of soil erosion.

⁽¹⁸⁵⁾ Salzman, J., Bennett, G., Carroll, N., Goldstein, A. and Jenkins, M. 'The global status and trends of Payments for Ecosystem Services', *Nature Sustainability*, 1(3), pp.136-144, 2018.

incentives to these countries to avoid deforestation and preserve their forests. At the same time biodiversity credits, self-standing or part of voluntary carbon removals credits, must be reliable, measurable and guarantee high-quality (including additionality, long-term duration and sustainability), avoiding greenwashing. At this stage, there are several voluntary schemes internationally, but without common methodologies and supervision. The Commission is reflecting on how to address this issue and exploit the potential of biodiversity credits.

There are however other market-based instruments to support biodiversity: taxation (based, for instance, on the “polluter pays principle”) and subsidies ⁽¹⁸⁶⁾. The advances in cost-benefit analysis methodologies, which increasingly include environment-related impacts and a long-term perspective, represent an opportunity for further biodiversity and climate friendly investments, such as nature-based solutions. The European Investment Bank (EIB) provides good examples about how these methodologies and approaches are already implemented ⁽¹⁸⁷⁾.

⁽¹⁸⁶⁾Romain Pirard, 2012, Market-based instruments for biodiversity and ecosystem services: A lexicon, Environmental Science & Policy, Volumes 19–20, Pages 59-68, ISSN 1462-9011, <https://doi.org/10.1016/j.envsci.2012.02.001>.

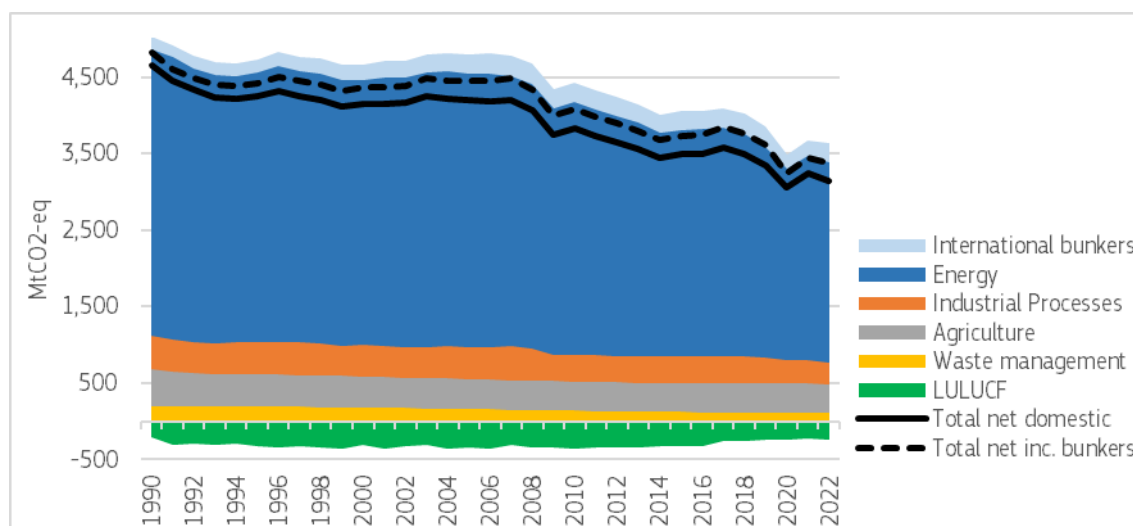
⁽¹⁸⁷⁾The EIB partnered with the NBI Global Resource Centre of IISD and provided funding for project preparation activities and will probably provide financing for implementation. The EIB used these results to understand the value of NBS compared to grey infrastructure, particularly regarding environmental impacts, such as reduced erosion, carbon storage, and improved habitat quality/biodiversity.

ANNEX 10: State of play of GHG emissions and the energy system

1 TOTAL GHG EMISSIONS IN THE EU

After the 2021 strong rebound in greenhouse gas (GHG) emissions following the unprecedented fall in 2020 due to the COVID-19 pandemic, EU emissions in 2022 are expected to be back in line with its 30-years descending trend. According to provisional data, total EU domestic GHG emissions (i.e., excluding LULUCF and international aviation) decreased by 2.4% in 2022 compared to 2021, whilst EU GDP grew by 3.5% in the same year. This translates into a reduction in GHG emissions of 30.4% compared to the 1990 base year (or 29% when international aviation is included). Over the same period, there is an approximated increase in reported GHG net removals from land use, land use change, and forestry (LULUCF) of 14 million tonnes of CO₂ equivalent compared to 2021¹⁸⁸. As a result, net GHG emissions for 2022 (i.e., including LULUCF) are expected to be 32.5% below the 1990 level (or 31.1% when international aviation is included).

Figure 12: Historical EU GHG emissions



Source: EEA GHG data viewer (extracted 20/6/2023).

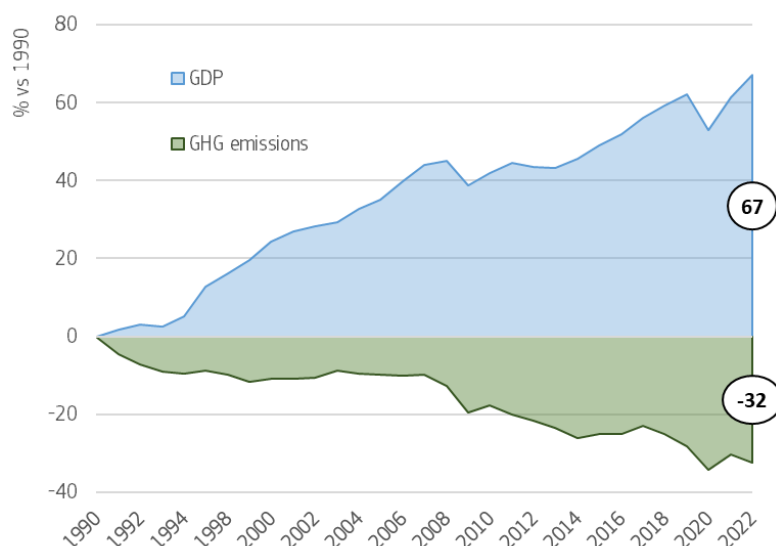
Emission reductions in the last three decades (1990-2021) were significant in the energy industry (e.g., electricity and heat production, -42%), in the manufacturing industry (e.g., iron and steel production, -48%) and in the industrial processes and product use industries (e.g., chemical industry, -65%; metal industry, -44%). Conversely, emissions in the transport sector have increased, especially in road transportation (+16%) although they have been slightly decreasing since 2010. While the agriculture sector has reduced emissions over 1990-2010 (by 22%), emissions since have stabilized or even very slightly increased. Finally, natural CO₂

¹⁸⁸ Approximated 2022 data could suggest a break to the declining trend in the LULUCF sink observed in recent years. However, the assessment takes into consideration the large uncertainty of these data and as it will possibly be subject to revisions.

sink role of land use, land use change, and forestry sector (LULUCF) has declined at a worrying speed in the last decade, getting back to close to the 1990 level.

Policies promoting more efficient energy use, a growing deployment of renewable energy supply and the use of less carbon intensive fossil fuels have played a key role in driving the decarbonisation process so far. This has allowed continued decoupling of emissions and economic growth, with the GHG emission intensity of GDP falling to 229 gCO₂-eq/EUR in 2022, less than half the 1990 level.

Figure 13: GHG emissions and GDP development in the EU (1990 = 100)



Source: 2023 GHG EEA inventory data, AMECO and WB ⁽¹⁸⁹⁾.

2 EMISSIONS UNDER THE EMISSION TRADING SYSTEM

By 2022, the EU ETS had helped drive down emissions from power and industry installations by 37.3% compared to 2005 levels.

Overall EU ETS emissions in 2022 decreased by 0.2% compared to the previous year. ⁽¹⁹⁰⁾ This reflects a slight decrease in emissions from power and industry installations and a continued rebound in emissions from aviation after the COVID-19 pandemic. Looking to before COVID-19, however, emissions have remained on the decline. In 2022, emissions were around 8% lower than in 2019.

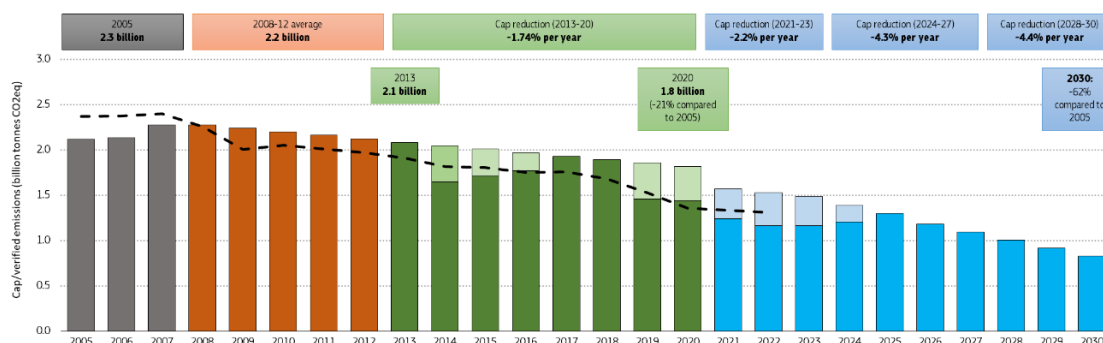
Emissions from the energy sector and manufacturing decreased slightly by 1.8% compared to 2021, partially as result of the energy crisis and its impacts. EU verified emissions from

⁽¹⁸⁹⁾ 2022 GHG data from approximated GHG EEA inventory estimates. 1995-2022 GDP from AMECO (6-DOMESTIC PRODUCT – 6.1 GROSS DOMESTIC PRODUCT – GDP, at constant prices (OVGD)) and 1990-1994 derived from WB (NY.GDP.MKTP.KD | GDP constant 2015 US\$) with growth rate applied to AMECO 1995.

⁽¹⁹⁰⁾ Based on data from the EU Registry as of 30 June 2023.

aircraft operators increased significantly, by 75% compared to 2021, reflecting a continued rebound of air traffic.

Figure 14: Historical evolution of ETS emissions



Note: Verified ETS emissions 2005-2022, Member States projections with existing measures 2021-2030, ETS cap phases 2, 3 and 4, and accumulated surplus of ETS allowances 2008-2021; including UK (Northern Ireland), Norway and Iceland; NB: adjusted for cap phase 4. ⁽¹⁹¹⁾ Legend: bars (cap), light shade bars in 2014-16 (allowances backloaded in phase 3), light shade bars since 2019 (feeds of allowances to the Market Stability Reserve), dash line (verified emissions).

Source: Climate Action Progress Report 2023.

3 EMISSIONS UNDER THE EFFORT SHARING LEGISLATION

The Effort Sharing legislation covers emissions from domestic transport (excluding CO₂ emissions from aviation), buildings, agriculture, small industry, and waste which account for around 60% of total domestic EU emissions. The Effort Sharing legislation sets binding national targets to reduce emissions in these sectors compared to 2005 levels, under the Effort Sharing Decision (ESD) ⁽¹⁹²⁾ for the period 2013-2020 and under the Effort Sharing Regulation (ESR) ⁽¹⁹³⁾ for the period 2021 to 2030.

In the period 2013 to 2020 all Member States met their effort sharing obligations under the ESD in every year. The EU overachieved its 2020 emission reductions target by more than six percentage points. EU-27 emissions covered by the ESD were 16.3% lower in 2020 than they were in 2005. Compared to 2013, the EU-27 emissions were 7.2% lower in 2020. 2020 was the last year covered by the ESD. Member States could not carry-over (bank) AEAs for use in future years under the ESR.

Based on approximated data, emissions from the effort sharing sectors in 2022 were 3% lower than in 2021. It followed the rebound of emissions in 2021, after the pandemic. The reduction

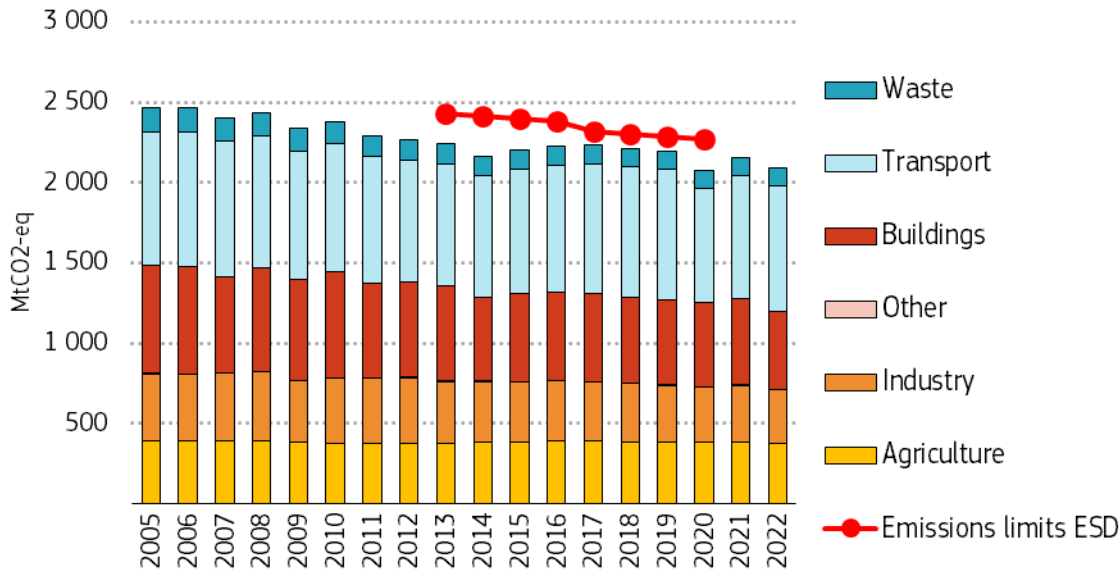
⁽¹⁹¹⁾ Emissions cap in the EU ETS (considering the 2023 revision of the ETS Directive, i.e. rebasing in 2024 and 2026, inclusion of the maritime transport sector in 2024, and the linear reduction factor of 4.3% in 2024-27 and of 4.4% from 2028), compared with verified emissions. Aviation is not included. Due to scope changes, 2005-7 figures are not directly comparable to the latest.

⁽¹⁹²⁾ Decision No 406/2009/EC of 23 April 2009

⁽¹⁹³⁾ Regulation (EU) 2018/842 of 30 May 2018, as amended by Regulation (EU) 2023/857 of 19 April 2023

in emissions resulted in particular from the buildings sector which showed an emission decrease of more than 9% compared to 2021. Small industry showed the second largest emission reduction with a decrease of almost 6% compared to 2021. The transport sector is the largest sector under the ESR, accounting for over one third of total effort sharing emissions, and the only one that saw its emissions increase, by over 2% from 2021 to 2022.

Figure 15: Historical evolution of GHG from ESR sectors



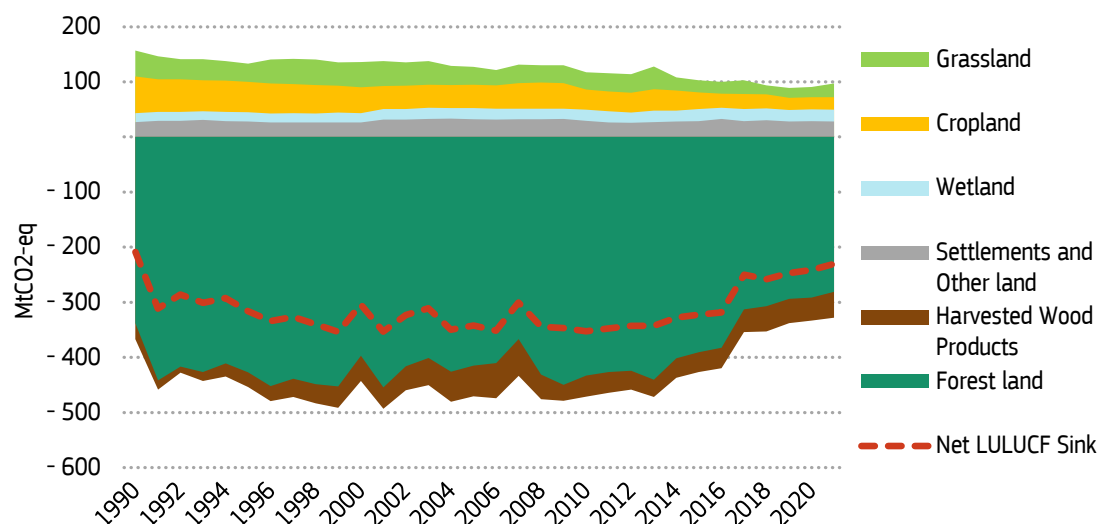
Note: From GHG inventory data (2005-2021) and approximated GHG inventory data (2022) as reported by Member States under Regulation (EU) 2018/1999, compiled and checked by the EEA. The ESD AEAs are expressed in GWP AR4, all other numbers are in GWP AR5. Figures include EU-27 only.

Source: EEA.

4 EMISSIONS UNDER THE LULUCF REGULATION

On EU level, the LULUCF sector absorbs more greenhouse gases than it emits, making it a net carbon sink and thereby contributing to achieving the commitment. Nevertheless, carbon removals have significantly decreased in recent years, and the land sink function declined at a worrying speed in the last decade. The decreasing trend is mainly due to a decrease in removals by an increase in harvest rates and to a limited extent, caused by reduced carbon sequestration in ageing forests across certain areas. The increasing frequency of natural disturbances such as windstorms, forest fires, and droughts introduces inter-annual variations and impacts long-term trends (see Figure 16).

Figure 16: Historical evolution of GHG from LULUCF



Note: Gridded line shows the net LULUCF net removals.

Source: UNFCCC 2023.

5 RENEWABLES DEPLOYMENT UNDER THE RENEWABLE ENERGY DIRECTIVE

The Renewable Energy Directive is the legal framework for the development of clean energy across all sectors of the EU economy, supporting cooperation between EU countries towards this goal. The Renewable Energy Directive (2009/28/EC) was adopted in 2009 and set an EU target of 20% renewables by 2020 and national binding targets.

Since that, the share of renewable energy sources in EU energy consumption has increased from 12.5% in 2010 to 21.8% in 2021.

Given the need to speed up the EU's clean energy transition, the Directive EU/2018/2001 was revised and entered into force in 2018. It sets an overall European renewable energy target of 32% by 2030 and includes rules to ensure the uptake of renewables in the transport sector and in heating and cooling. The directive sets common principles and rules for renewable energy support schemes, sustainability criteria for biomass and the right to produce and consume renewable energy and to establish renewable energy communities. It also establishes rules to remove barriers, stimulate investments and drive cost reductions in renewable energy technologies and empowers citizens and businesses to participate in the clean energy transformation.

In July 2021, the Commission proposed another revision of the directive, raising the 2030 target to 40% (up from 32%), as part of the 'Fit for 55' package.

Less than a year later, following Russia's military aggression against Ukraine and the need to accelerate the EU's independence from fossil fuels, the Commission proposed to further increase the target to 45% by 2030.

On 30 March 2023, a provisional agreement was reached for a binding target of at least 42.5% by 2030, but aiming for 45%. Building on the 2009 and 2018 directives, the current proposal introduces stronger measures to ensure that all possibilities for the further development and uptake of renewables are fully utilized. This will be key to achieving the EU's objective of

climate neutrality by 2050. To support renewables uptake in transport and heating and cooling, the proposal seeks to convert into EU law some of the concepts outlined in the energy system integration and hydrogen strategies, published in 2020. These concepts aim at creating an energy-efficient, circular, and renewable energy system that facilitates renewables-based electrification and promotes the use of renewable and low-carbon fuels, including hydrogen, in sectors like transport where electrification is not yet a feasible option.

This new legislation is likely to be formally adopted in October (vote in EP schedule on 12 September, and adoption at the Council on 9 October).

6 ENERGY EFFICIENCY DIRECTIVE

First adopted in 2012, the Energy Efficiency Directive (EED, Directive 2012/27/EU) ⁽¹⁹⁴⁾, setting rules and obligations for achieving the EU's ambitious energy efficiency targets, was updated in 2018 and 2023 to reflect the increased targets and to adapt the measures to deliver them.

The 2012 EED quantified the 20% energy efficiency target by 2020 and established a set of binding measures to help the EU reach it.

In 2018, the 'Clean energy for all Europeans package' ⁽¹⁹⁵⁾ introduced the revised EED (Directive 2018/2002) ⁽¹⁹⁶⁾ to update the policy framework to the 2030, having already in mind the 2050 decarbonisation objective. The central feature was the establishment of a prominent energy efficiency target for 2030, set at a minimum of 32.5% improvement compared to the 2007 projections for the same timeframe, which translated into indicative targets of 1,128 Mtoe of primary energy and 846 Mtoe for final energy consumption for the whole EU by 2030 ⁽¹⁹⁷⁾.

In 2021, primary energy consumption in the EU reached 1,309 Mtoe, a 5.9% increase compared with 2020, but still below the 2019 level (1,354 Mtoe). Data ⁽¹⁹⁸⁾ show that the EU had a distance to reach the 2030 target of 16.0% in 2021 (Figure 17).

⁽¹⁹⁴⁾ <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1399375464230&uri=CELEX:32012L0027>

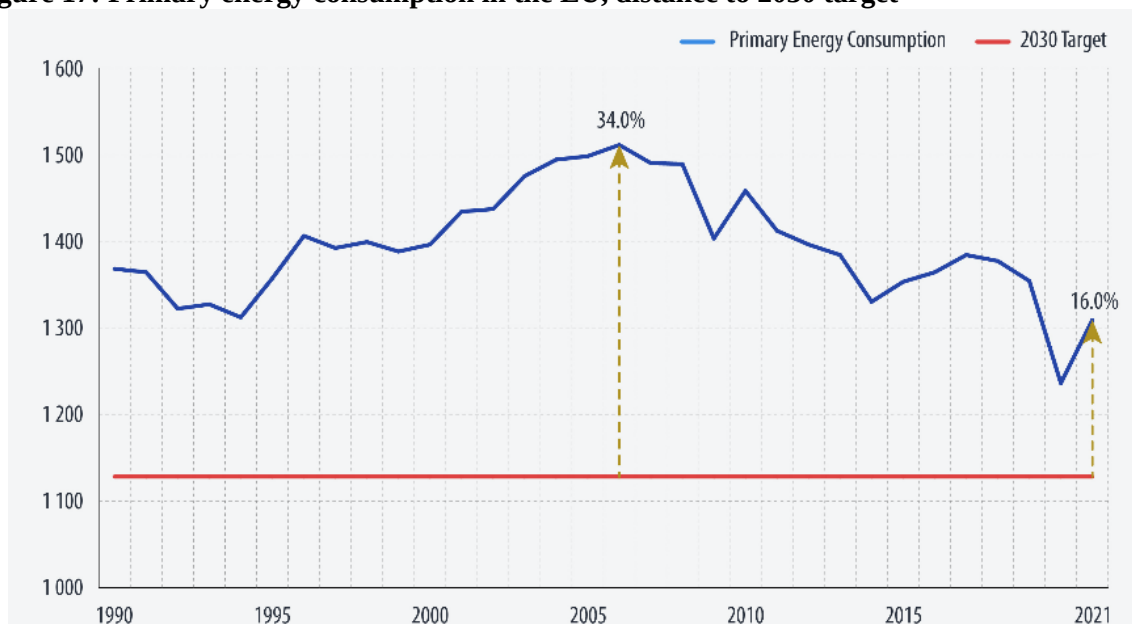
⁽¹⁹⁵⁾ https://energy.ec.europa.eu/topics/energy-strategy/clean-energy-all-europeans-package_en

⁽¹⁹⁶⁾ https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.328.01.0210.01.ENG

⁽¹⁹⁷⁾ Both targets refer to the post Brexit EU27. The initial EU28 targets were talking of 1,273 Mtoe of primary energy and 956 Mtoe of final energy consumption.

⁽¹⁹⁸⁾ <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20221219-4>

Figure 17: Primary energy consumption in the EU, distance to 2030 target

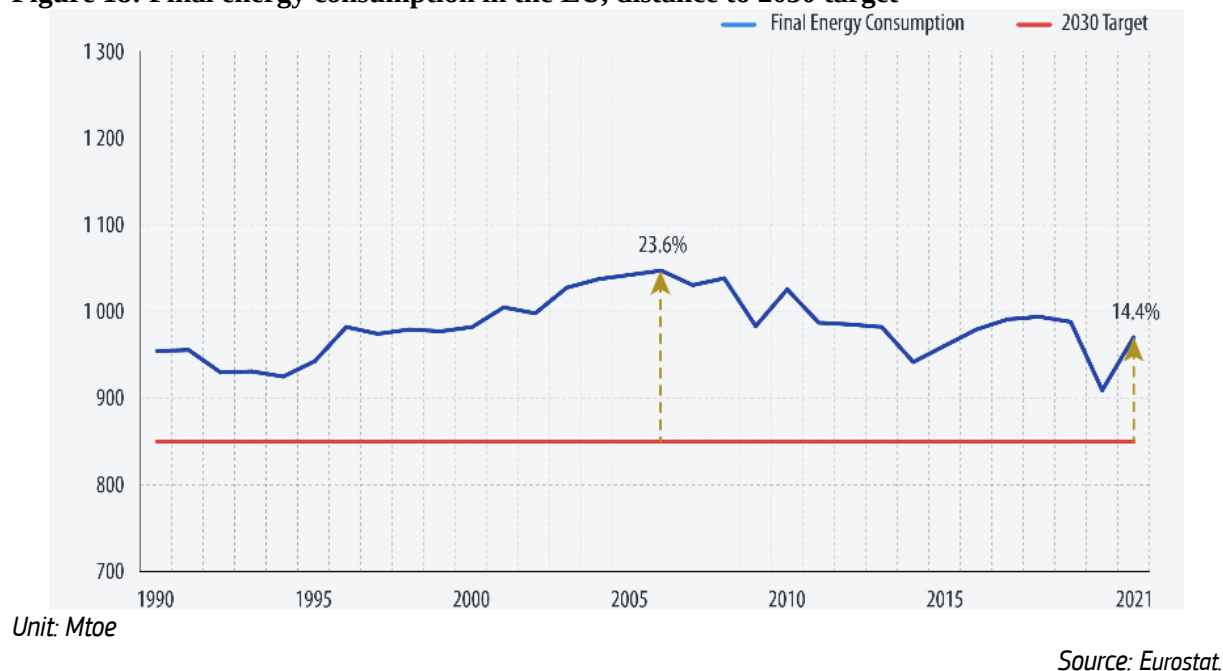


Unit: Mtoe

Source: Eurostat

Final energy consumption reached 968 Mtoe in 2021, a 6.8% increase compared with 2020 and a 1.8% decrease compared with 2019. In 2021, final energy consumption was 14.4% away from the 2030 target (Figure 18).

Figure 18: Final energy consumption in the EU, distance to 2030 target



To achieve the 2030 climate target, as set by the 2030 Climate Target Plan, and contribute to ensuring energy security within the EU, the EED recast formally agreed on 24 July 2023 ⁽¹⁹⁹⁾ significantly raises the EU's ambition, by making it binding for EU countries to collectively achieve an additional 11.7% reduction of final energy consumption by 2030, compared to the 2020 reference scenario projections ⁽²⁰⁰⁾. This translates into an indicative target of 992.5 Mtoe of primary energy and a binding target of 763 Mtoe for final energy consumption for the whole EU by 2030. Furthermore, the EED recast establishes 'energy efficiency first' as a fundamental principle of EU energy policy, recognising its vital role in practical policy applications and investment decision-making beyond the energy sector.

⁽¹⁹⁹⁾ https://energy.ec.europa.eu/news/european-green-deal-energy-efficiency-directive-adopted-helping-make-eu-fit-55-2023-07-25_en

⁽²⁰⁰⁾ https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-targets_en

Annex 11: The climate policy framework considered for the analysis

The list of EU policies considered is presented in the tables below, organised by sector. This list of EU policies is an updated version of the list of policies presented in Annex I of the EU Reference Scenario 2020 report ⁽²⁰¹⁾. Some of the most recent policies mentioned in the list have been proposed by the European Commission but have not been formally adopted (negotiations are underway).

1 ENERGY EFFICIENCY POLICIES

Energy Efficiency		
1	Ecodesign Framework Directive	Directive 2009/125/EC
	Stand-by Regulation	Commission Regulation (EC) No 1275/2008 as amended by Commission Regulation (EU) No 801/2013
	Office/street lighting Regulation	Commission Regulation (EC) No 347/2010
	Lighting Products in the domestic and Tertiary Sectors Regulations	Commission Regulation (EU) 2019/2020 Commission Regulation (EC) No 244/2009 Commission Regulation (EC) No 245/2009 Commission Regulation (EU) No 1194/2012
	External power supplies Regulation	Commission Regulation (EU) 2019/1782
	TVs Regulation (+labelling) Regulation	Commission Regulation (EU) 2019/2021
	Electric motors Regulation	Commission Regulation (EC) No 640/2009
	Freezers/refrigerators Regulation	Commission Regulation (EU) 2015/1095 Commission Regulation (EU) 2019/2019 Commission Regulation (EU) 2019/2024
	Household washing machines Regulation	Commission Regulation (EU) 2019/2023
	Household dishwashers Regulations	Commission Regulation (EU) 2019/2022
	Air conditioners	Commission Regulation (EU) No 206/2012 Commission Regulation (EU) Regulation No 327/2011 Commission Regulation (EU) No 1253/2014 Commission Regulation (EU) 2016/2281
	Circulators Regulation	Commission Regulation (EC) No 641/2009 as amended by Commission Regulation (EU) No 622/2012 and Commission Regulation (EU) 2019/1781
	Water pumps	Commission Regulation (EU) No 547/2012
	Tumble driers	Commission Regulation (EU) No 932/2012
	Computers and servers	Commission Regulation (EU) No 617/2013 Commission Regulation (EU) 2019/424
	Vacuum cleaners	Commission Regulation (EU) No 666/2013

⁽²⁰¹⁾ European Commission, DG for Climate Action, DG for Energy, DG for Mobility and Transport, De Vita, A., Capros, P., Paroussos, L., et al. (2021), EU Reference Scenario 2020: Energy, transport and GHG emissions - Trends to 2050.

	Cooking appliances	Commission Regulation (EU) No 66/2014
	Power transformers	Commission Regulation (EU) No 548/2014 Commission Regulation (EU) 2019/1783
	Heaters Regulation	Council Directive 92/42/EEC Commission Regulation (EU) No 813/2013 Commission Regulation (EU) No 814/2013 Commission Regulation (EU) 2015/1185 Commission Regulation (EU) 2015/1189 Commission Regulation (EU) 2016/2281
	Welding equipment	Commission Regulation (EU) 2019/1784
	Omnibus	Commission Regulation (EU) 2021/341
	Imaging equipment	Voluntary agreement – Report from the Commission to the European Parliament and the Council on the voluntary ecodesign scheme for imaging equipment COM/2013/023 final
	Game consoles	Voluntary agreement - Report from the Commission to the European Parliament and the Council on the voluntary ecodesign scheme for games consoles COM/2015/0178 final
2	Energy Labelling Directive and delegated Regulations covering: - lamps and luminaires, - air conditioners - Electronic displays - household washing machines - household refrigerating appliances - household dishwashers - household electric tumble-driers - Labelling of tyres Regulations - Cooking appliances Omnibus	Regulation (EU) 2017/1369 supplemented by Delegated Regulations and Commission Directives Commission Delegated Regulation (EU) No 874/2012 Commission Delegated Regulation (EU) No 626/2011 Commission Delegated Regulation (EU) No 1254/2014 Commission Delegated Regulation (EU) 2019/2013 Commission Delegated Regulation (EU) 2019/2014 Commission Delegated Regulation (EU) 2015/1094 Commission Delegated Regulation (EU) 2019/2016 Commission Delegated Regulation (EU) 2019/2018 Commission Delegated Regulation (EU) 2019/2017 Commission Delegated Regulation (EU) No 392/2012 Regulation (EU) 2020/740 Commission Delegated Regulation (EU) 2015/1186 Commission Delegated Regulation (EU) No 811/2013 Commission Delegated Regulation (EU) No 812/2013 Commission Delegated Regulation (EU) 2015/1187 Commission Delegated Regulation (EU) No 65/2014 Commission Delegated Regulation (EU) 2021/340 of 17 December 2020 amending Delegated Regulations (EU) 2019/2013, (EU) 2019/2014, (EU) 2019/2015, (EU) 2019/2016, (EU) 2019/2017 and (EU) 2019/2018
3	Energy Performance of Buildings Directive	Directive 2010/31/EU, as amended by Directive (EU) 2018/844, and Proposal for a revision of this directive (COM(2021) 802 final)
4	Energy Efficiency Directive	Directive (EU) 2023/1791

2 POWER GENERATION AND ENERGY MARKETS

Power generation and energy markets		
1	Completion of the internal energy market (including provisions of the 3rd package). Since March 2011, the Gas and Electricity Directives of the 3rd package for an internal EU gas and electricity market are transposed into national law by Members States and the three Regulations:	Directive 2009/73/EC Directive (EU) 2019/944

	- on conditions for access to the natural gas transmission networks	Regulation (EC) No 715/2009
	- on conditions for access to the network for cross-border exchange of electricity	Regulation (EU) 2019/943
	- on the establishment of the Agency for the Cooperation of Energy Regulators (ACER)	Regulation (EU) 2019/942
2	Energy Taxation Directive	Directive 2003/96/EC, and Proposal for recasting (COM(2021) 563 final)
3	Regulation on security of gas supply	Regulation (EU) 2017/1938
4	Regulation on market integrity and transparency (REMIT)	Regulation (EU) 1227/2011
5	Nuclear Safety Directive	Council Directive 2009/71/Euratom
6	Nuclear Waste Management Directive	Council Directive 2011/70/Euratom
7	Basic safety standards Directive	Council Directive 2013/59/Euratom
8	Directive on the promotion of the use of energy from renewable sources	Directive (EU) 2018/2001, as amended by Directive (EU) 2023/2413.
9	Guidelines on State aid for environmental protection and energy 2014-20	2014/C 200/01
	Guidelines on State aid for climate, environmental protection and energy 2022	C/2022/481
10	Hydrogen and decarbonised gas market package	Proposal for a directive (COM(2021) 803 final), and Proposal for a regulation (COM(2021) 804 final).
11	REPowerEU plan	Regulation (EU) 2023/435 amending Regulation (EU) 2021/241 as regards REPowerEU chapters in recovery and resilience plans and amending Regulations (EU) No 1303/2013, (EU) 2021/1060 and (EU) 2021/1755, and Directive 2003/87/EC.

3 CLIMATE POLICIES

(Cross-sectorial) Climate policies		
1	EU ETS Directive	Directive 2003/87/EC, as amended notably by Directive 2008/101/EC (aviation), Decision (EU) 2015/1814 (Market Stability Reserve), Regulation (EU) 2017/2392 (aviation “stop the clock” derogation), Directive 2018/410 (revision for 2030 climate and energy framework), Regulation (EU) 2023/435 (REPowerEU), Directive (EU) 2023/958 (aviation) and Directive (EU) 2023/959.
2	Directive on the geological storage of CO ₂	Directive 2009/31/EC
3	GHG Effort Sharing Regulation	Regulation (EU) 2018/842, as amended by Regulation (EU) 2023/857.
4	European Commission proposal to revise the F-gas Regulation	Proposal COM (2022) 150 final, to amend Directive (EU) 2019/1937 and repeal Regulation (EU) No 517/2014 (provisionally agreed by co-legislators in October 2023).
5	LULUCF Regulation	Regulation (EU) 2018/841, as amended by Regulation (EU) 2023/839.
	Carbon Border Adjustment Mechanism (CBAM)	Regulation (EU) 2023/956.

6	Communication from the Commission Guidelines on certain State aid measures in the context of the system for greenhouse gas emission allowance trading post-2021.	2020/C 317/04

4 TRANSPORT-RELATED POLICIES

Transport-related policies		
1	CO2 emission performance standards for new passenger cars and light commercial vehicles	Regulation (EU) 2019/631, as amended by Regulation (EU) 2023/851.
2	CO2 emission performance standards for heavy-duty vehicles	Regulation (EU) 2019/1242, amending Regulations (EC) No 595/2009 and (EU) 2018/956. Proposal to amend Regulation (EU) 2019/1242 (COM (2023) 88 final)
3	Improving testing procedures - real driving conditions ('Real Driving Emissions' – RDE) and improved laboratory test ('World Harmonised Light Vehicle Test Procedure' – WLTP)	Commission Regulation (EU) 2018/1832 Commission Regulation (EU) 2017/1151 Commission Regulation (EU) 2017/1154 Commission Regulation (EU) 2016/646 Commission Regulation (EU) 2016/427
4	Regulation EURO 5 and 6, and EURO 7 standard proposal	Regulation (EC) No 715/2007, implemented by Commission Regulation (EU) 2017/1151 Commission Proposal COM(2022) 586
5	Directive on the promotion of the use of energy from renewable sources	Directive (EU) 2018/2001, as amended by Directive (EU) 2023/2413.
6	Fuel Quality Directive	Directive 98/70/EC, as amended by Directive (EU) 2015/1513
7	Regulation Euro VI for heavy duty vehicles	Regulation (EC) No 595/2009, implemented by Commission Regulation (EU) 582/2011
8	Eurovignette Directive on road infrastructure charging	Directive 1999/62/EC, as amended by Directives 2011/76/EU and (EU) 2022/362.
9	Directive on the Promotion of Clean and Energy Efficient Road Transport Vehicles (in public procurement)	Directive 2009/33/EC, as amended by Directive (EU) 2019/1161
10	Regulation on the deployment of alternative fuels infrastructure	Regulation (EU) 2023/1804, repealing Directive 2014/94/EU.
11	Directive on weights & dimensions	Council Directive 96/53/EC, as amended by Directive 2015/719/EU, Decision (EU) 2019/894 and Regulation (EU) 2019/1242.

Transport-related policies		
		Proposal to amend Council Directive 96/53/EC (COM(2023) 445 final)
12	End of Life Vehicles Directive	Directive 2000/53/EC, as amended by Directive (EU) 2018/849
13	Mobile Air Conditioning in motor vehicles Directive	Directive 2006/40/EC
14	Directive on the sound level of motor vehicles	Regulation (EU) No 540/2014 as amended by Regulation (EU) 2019/839
15	Roadworthiness Package	Directive 2014/45/EU, Directive 2014/46/EU, Directive 2014/47/EU
16	Road infrastructure safety management	Directive (EU) 2019/1936
17	General safety regulation	Regulation (EU) 2019/2144
18	Intelligent Transport Systems Directive	Directive 2010/40/EU, as amended by Directive (EU) 2023/2661
19	Regulation concerning type-approval requirements for the deployment of the eCall in-vehicle system	Regulation (EU) 2015/758
20	Fourth railway package	Directives (EU) 2016/798 on railway safety, Directive (EU) 2016/797 on railway interoperability and the Directive 2016/2370/EU regarding the opening of the market for domestic passenger transport services by rail and the governance of the railway infrastructure
21	Directive establishing a single European railway area (Recast)	Directive 2012/34/EU
22	European Rail Traffic Management System European deployment plan	Commission Implementing Regulation (EU) 2017/6
23	Regulation on electronic freight transport information	Regulation (EU) 2020/1056
24	Regulation on noise-related operating restrictions at Union airports	Regulation (EU) No 598/2014
25	Regulations governing the performance and charging schemes as well as the network functions of the Single European Sky	Commission Implementing Regulations (EU) No 390/2013, 391/2013 and 677/2011; later replaced by Regulations (EU) 2019/317 and 2019/123
26	Inland waterways and port services	Directive 2016/1629/EU on technical requirements for inland waterway vessels and the Regulation on non-road mobile machinery (NRMM) Regulation (EU) 2017/352 establishing a framework for the provision of port services
27	Provision of port services	Regulation (EU) 2017/352
28	European Maritime Single Window	Regulation (EU) 2019/1239

Transport-related policies		
29	Directive on the sulphur content of marine fuels	Directive 2012/33/EU
30	Monitoring, reporting and verification of greenhouse gas emissions from maritime transport	Regulation (EU) 2015/757
31	Regulation on ensuring a level playing field for sustainable air transport – ReFuelEU Aviation	Regulation (EU) 2023/2405
32	Regulation on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC – FuelEU Maritime	Regulation (EU) 2023/1805
33	Action Plan to boost long-distance and cross-border passenger rail	Commission Proposal COM(2021) 810
34	Proposal for a Regulation on the accounting of greenhouse gas emissions of transport services	Commission Proposal COM(2023) 441
35	Proposal for a Regulation on the use of railway infrastructure capacity in the single European railway area	Commission Proposal COM(2023) 443
36	Proposal for a revision of the Combined Transport Directive	Commission Proposal COM(2023)702

5 INFRASTRUCTURE, INNOVATION AND RTD FUNDING

Infrastructure, innovation and RTD funding		
1	TEN-E guidelines	Regulation (EU) 347/2013
2	Regulation establishing the Connecting Europe Facility	Regulation (EU) 1316/2013
3	EEPR (European Energy Programme for Recovery) and NER 300 (New entrants reserve) CCS and innovative renewables funding programme	Regulation (EC) No 663/2009, ETS Directive 2009/29/EC Article 10a (8), further developed through Commission Decision 2010/670/EU and implementing decisions, e.g. EC(2014) 4493 and C(2015) 6882
4	Horizon 2020 support to energy research and innovation	Energy research under H2020: info available here: http://ec.europa.eu/programmes/horizon2020/en/area/energy
5	European Structural and Investment Funds ⁽²⁰²⁾ : European Regional Development Fund (ERDF) European Social Fund (ESF) Cohesion Fund (CF) European Agricultural Fund for Rural Development (EAFRD) European Maritime & Fisheries Fund (EMFF)	Regulation (EU) No 1303/2013 Regulation (EU) No 1301/2013 Regulation (EU) No 1304/2013 Regulation (EU) No 1305/2013 Regulation (EU) No 508/2014

⁽²⁰²⁾ As of May 2021, a revision of the regulations of the European Structural and Investment Funds has been agreed and is planned for publication.

Infrastructure, innovation and RTD funding		
	Social Climate Fund	Regulation (EU) 2023/955
6	TEN-T guidelines	Commission Proposal COM(2021) 812 final.

6 ENVIRONMENTAL POLICIES

Environment and other related policies		
1	General block exemption Regulation	Commission Regulation (EU) 2014/651, Commission Regulation (EU) 2017/1084, Commission Regulation (EU) 2023/1315
2	Landfill Directive	Directive 99/31/EC
3	Urban Wastewater Treatment Directive	Directive 91/271/EEC, Directive 98/15/EEC, Implementing Decision 2014/431/EU, Revision proposal COM(2022) 541 final
4	Waste Management Framework Directive	Directive 2008/98/EC
5	Nitrate Directive	Directive 91/676/EEC
6	Common Agricultural Policy (CAP)	e.g. Council Regulations (EC) No 1290/2005, No 1698/2005, No 1234/2007, No. 73/2009, Regulations (EU) No 1305-1308/2013, Regulation (EU) 2020/2220
7	Industrial emissions (Recast of Integrated Pollution and Prevention Control Directive 2008/1/EC and Large Combustion Plant Directive 2001/80/EC)	Directive 2010/75/EU, and revision proposal COM/2022/156 final/3
8	Directive on national emissions' ceilings for certain pollutants	Directive 2001/81/EC, Directive (EU) 2016/2284
9	Water Framework Directive	Directive 2000/60/EC
10	Substances that deplete the ozone layer	Relevant EU legislation implementing the Montreal protocol, e.g., Regulation (EC) No 1005/2009 as amended by Commission Regulation (EU) 744/2010, Regulation (EU) No 517/2014, Council Decision (EU) 2017/1541. Commission proposal to revise the Ozone Depleting Substances (ODS) Regulation (COM(2022) 151 final), provisionally agreed by co-legislators in October 2023.
11	Nature Restoration Law	Proposal COM/2022/304 final.

7 INTERNATIONAL POLICIES

Other policies at international level		
1	International Maritime Organisation (IMO) International convention for the prevention of pollution from ships (MARPOL), Annex VI	2008 amendments - revised Annex VI (Prevention of Air Pollution from ships) Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), IMO Resolution MEPC.203(62) GHG emission reduction targets agreed on in July 2023 as per MEPC 80/WP.12.

Other policies at international level		
2	Voluntary agreement to reduce PFC (perfluorocarbons, potent GHG) emissions in the semiconductor industry	
3	International Civil Aviation Organisation (ICAO), Convention on International Civil Aviation, Annex 16, Volume II (Aircraft engine emissions) and Volume III (CO ₂ emissions standard for aircraft)	

8 IMPLEMENTATION OF POLICIES TO REDUCE NON-CO₂ GHG EMISSIONS

Sector	Gas	Policy	Regional coverage	Policy description and implementation in GAINS
Agriculture	CH ₄	Feed-in tariffs or other subsidies to stimulate co-digestion of manure on farms	Italy, Netherlands, Latvia, Sweden, Cyprus, Austria, Croatia, Germany	Reflected via assumptions on uptake of farm-scale biogas technology consistent with information from EurObserv'ER (2020) on installed capacity. Future uptake follows trend in biogas production from anaerobic digestion as projected in the PRIMES model Reference scenario.
	CH ₄ & N ₂ O	EU Common Agricultural Policy (CAP) and EU Nitrate Directive (EEC/676/1991) with revisions	EU-wide	Reflected in GAINS through input of CAPRI model data on trends in livestock numbers, milk yield and fertilizer use.
	CH ₄	Ban on burning of crop residues	EU-wide	Assumed not fully enforced. GAINS uses information derived from satellite images (e.g., MODIS) as approximate estimates of the mass of crop burned on fields.
Waste & wastewater	CH ₄	EU Landfill Directive (EC/31/1999) with amendment (EC/850/2018) and EU Waste and Packaging Directives (EC/851/2018, EC/852/2018)	EU-wide	Biodegradable waste diverted away from landfills (relative 1990 by -25% in 2006, -50% in 2009 and -65% in 2016). All landfill sites equipped with gas recovery by 2009. By 2035, countries must not landfill more than 10% of MSW generated. Member states that landfill more than 60% of MSW in 2013 are given a 5 years grace period but must not landfill more than 25% in 2035. GAINS Reference scenario assumes future targets will be met.
	CH ₄	EU Waste Management Framework Directive (EC/98/2008)	EU-wide	The following hierarchy is to be respected in waste treatment: recycling and composting preferred to incineration/energy recovery, which in turn is preferred to landfill disposal. Considered in GAINS when simulating pathway for compliance with the Landfill Directive target.
	CH ₄	Decree on waste landfill	Slovenia	Decree on landfill of waste beyond EU Landfill Directive. Includes partial ban on landfill of biodegradable waste.
	CH ₄ & N ₂ O	Legislation to replace current composting with anaerobic digestion of food waste	Germany	In GAINS, the current composting of organic waste is phased-out linearly and replaced with anaerobic digestion between 2020 and 2050.
	CH ₄	Ban on landfill of biodegradable waste.	Austria, Belgium, Denmark, Germany, Netherlands, Sweden	Complete ban on landfill of untreated biodegradable waste. Reflected in GAINS.

	CH ₄	EU urban wastewater treatment directive (EEC/271/1991)	EU-wide	GAINS reflects an "appropriate treatment" of wastewater from urban households (all agglomerations > 2000 people) and food industry must be in place latest by end of 2005. This means discharge must ensure receiving waters meet relevant quality objectives.
Industry	N ₂ O, PFCs	EU ETS Directive (EC/29/2009): Primary aluminum production and production of nitric acid, adipic acid, glyoxal and glyoxylic acid.	EU-wide	Industry needs to acquire tradable emission permits under the EU emission trading system (EU-ETS).
	PFCs	Voluntary agreement in semiconductor industry	EU-wide	Semiconductor producers to reduce PFC emissions by 2010 to a level at 10 percent of 1995 emissions. Accounted for in GAINS to the extent it is reflected in national emission inventories to the UNFCCC.
F-gases	HFCs, PFCs, SF ₆	EU F-gas regulation (EC 517/2014)	EU-wide	Phase-down of F-gas sold on the market, banning of use in applications where alternatives to F-gases are readily available, and preventing emissions from existing use of F-gases through leakage control and end-of-life recovery.
	HFCs	EU MAC Directive (EC 40/2006)	EU-wide	Mobile air conditioners: replacing the use of high GWP HFCs with cooling agents GWP100 < 150 in all new vehicle models placed on the market.
	HFCs	EU Directive on end-of-life vehicles (EC 53/2000)	EU-wide	Scrapped mobile air conditioners: recovery and proper handling
	HFCs, PFCs, SF ₆	National F-gas regulations more stringent than EU regulation	Austria ("HFKW-FKW-SF6-Verordnung"), Belgium (end-of-life regulation from 2005 for large-scale refrigeration), Denmark (deposit-refund scheme since 1992, tax since 2001 and ban on import, sale and use since 2002), Germany ("Chemikalien-Klimaschutzverordnung" specify maximum leakage rates), Netherlands ("STEK" since 1992), Sweden (environmental fees since 1998, specific regulation since 2007)	
Energy	CH ₄	European Commission Proposal COM(2021) 805 final, for a Regulation on methane emissions reduction in the energy sector, amending Regulation (EU) 2019/942	EU-wide	Improved measurement, reporting and verification of energy sector methane emissions. Leak detection and repair and a ban on venting and flaring practices. A methane transparency requirement on imports.

Annex 12: Non-CO2 climate impacts of the navigation and aviation sectors

1 AVIATION

1.1 Scientific evidence

In its 1999 special report on aviation, IPCC ⁽²⁰³⁾ explored the sector's impacts on climate. Since then, updated assessments and studies ⁽²⁰⁴⁾ have been regularly published, improving the understanding of non-CO2 aviation effects.

In the scientific literature, those effects are mostly expressed in terms of “Effective Radiative Forcing” (ERF) ⁽²⁰⁵⁾ (Figure 19). The ERF from the sum of non-CO2 aviation impacts yields a net positive (warming) that is at least as large as those of CO2 alone. Despite uncertainties regarding the scientific knowledge on non-CO2 aviation effects, its contribution to global warming is clear.

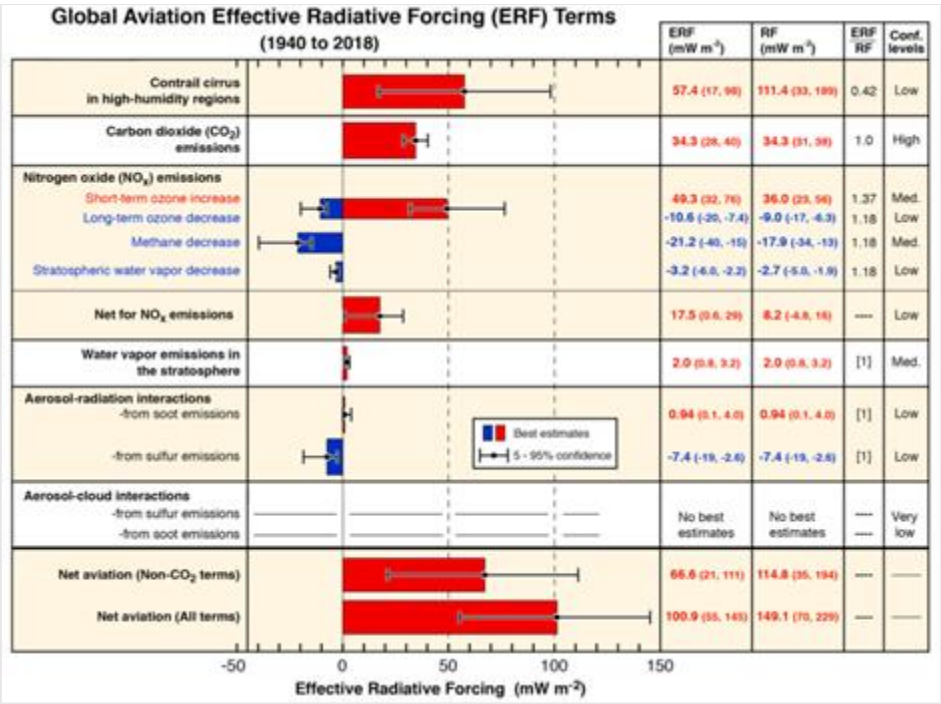
It must also be noted that the non-CO2 ERF ratios in Figure 19 are not fixed in time and the non-CO2 forcing from aviation is sensitive to the rate of growth of CO2, such that it grows faster under a scenario of increasing CO2 emissions, but equally, falls more quickly if CO2 emissions are reduced (Figure 20). Therefore, the growth of the sector in coming years and the fuels used will be determinant to the warming caused by the non-CO2 emissions.

⁽²⁰³⁾ IPCC (1999), Special Report Aviation and the global atmosphere

⁽²⁰⁴⁾ Sausen et al (2005), Aviation radiative forcing in 2000: An update on IPCC (1999); D.S. Lee et al (2009), Aviation and global climate change in the 21st century; D.S. Lee et al (2020), The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018; Klower et al (2021), Quantifying aviation's contribution to global warming.

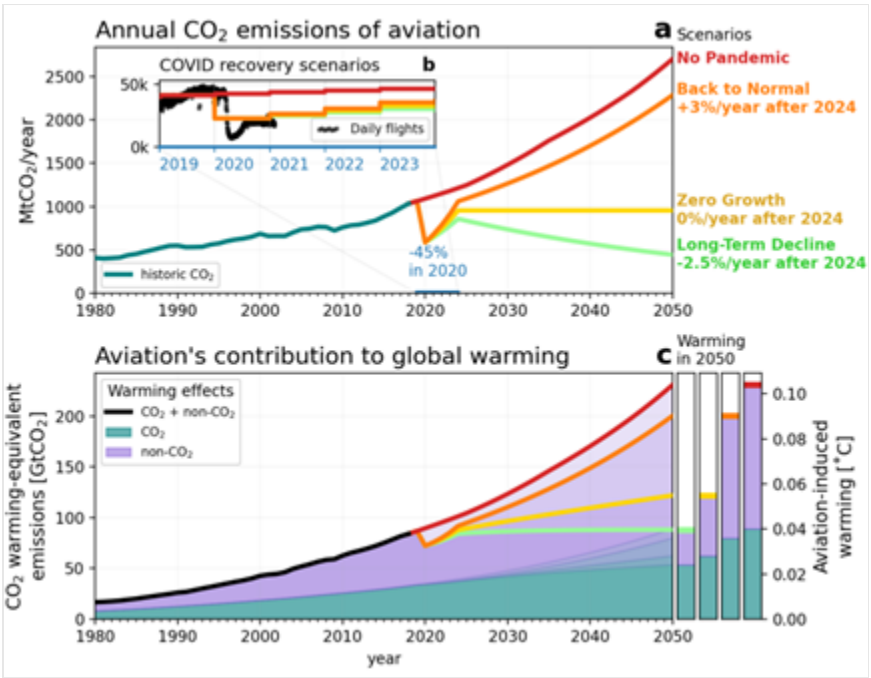
⁽²⁰⁵⁾ The “Radiative Forcing” (RF) metric stands for stratosphere-adjusted radiative forcing and it has been used as a proxy for predicting global mean surface temperature change. It represents the instantaneous change in total irradiation due to incoming short wave solar radiation minus the outgoing long wave terrestrial radiation (difference between sunlight energy received by the Earth and the energy Earth radiates back to space). In the Fifth Assessment Report (2013), in order to better take into account the complexities of heterogeneous distribution of certain forcing agents, the IPCC introduced the “Effective Radiative Forcing” (ERF) metric. ERF is considered to be a good predictor of the long-term change in global surface temperature caused through rapid adjustments in the atmosphere (e.g., thermal structure of the atmosphere, clouds, aerosols, etc.), while maintaining sea surface temperatures constant.

Figure 19: Global aviation contribution to anthropogenic climate forcing for 2000 to 2018



Source: Lee et al., 2020.

Figure 20: Quantifying aviation's contribution to global warming



Source: Klöwer et al., 2021.

The main aviation non-CO₂ climate agents are water vapour (H₂O), nitrogen oxides (NO_x), sulphur dioxide (SO₂), and soot particles, as well as the atmospheric processes caused by such emissions, for example the formation of ozone (O₃) and contrail cirrus.

As shown in Figure 19 the best estimates about the largest aviation non-CO₂ impacts are those from NO_x and contrails. The effects on climate of NO_x emissions (“net-NO_x effect”) depends largely on their interaction with background emissions⁽²⁰⁶⁾ and the location of the emissions. NO_x contributes to the production of ozone (O₃) and at the same time to the destruction of methane (CH₄). This results generally in a net warming effect. Minimizing NO_x can increase CO₂ (decreased fuel efficiency *via* increased fuel burn), while optimising engines could lead to higher combustion temperatures and to more NO_x emissions, which implies finding a balance between CO₂ and NO_x emissions.

Water vapour emissions resulting from hydrocarbon combustion have small direct climate effect for subsonic aircrafts at current cruise altitudes (up to 12-13 km), but they contribute to the formation of contrails (condensation trails). Contrail cirrus clouds are artificial clouds composed of ice crystals that form behind jet engines when the relative humidity in the engine plume increases reaching saturation. They occur at cold ambient temperatures between -35°C and -60°C. Water vapour condenses on condensation nuclei, with soot particles⁽²⁰⁷⁾ being the effective nuclei. The water droplets freeze and grow as ice crystals until the humidity with respect to ice drops below saturation. Contrails generally cool during the day and always warm at night⁽²⁰⁸⁾.

When it comes to hydrogen-powered aircrafts, the climate effect of water vapour (main exhaust product) needs to be further investigated and the warming effect will increase in the case of higher altitudes (e.g., supersonic) where water vapour is emitted into the drier stratosphere.

⁽²⁰⁶⁾ Background emissions refer to the levels of NO_x and other emissions that already exist in the atmosphere from various sources unrelated to aviation.

⁽²⁰⁷⁾ The non-volatile particulate matter (nvPM) often referred to as “soot” (or “black carbon”), represents the inorganic and organic carbon in engine exhaust and plume. Soot emissions from aircraft engines contribute to contrail formation, where the number and size of ice crystals depend on soot concentration. The aromatic, and more precisely naphthalene content of jet fuel is associated with the production of soot particles. When it comes to vPM, sulphate particles originate from sulphur (S) in aviation kerosene fuel, which is oxidised to sulphur dioxide (SO₂) during the combustion process and then to sulphuric acid to a minor extent in the combustor and to a major part, in the ambient atmosphere. Sulphuric acid can form, or coat pre-existing particles. These particles reflect solar radiation back to space as a “direct effect” and thus have a negative radiative forcing (cooling). This effect is small but needs to be noted as hydrotreatment (treating with hydrogen) of fuels to remove the impurities, and clean further the fuels, implies reduction of sulphur as well (sulphur particles, particularly those generated from combustion processes, can have detrimental effects on human health).

⁽²⁰⁸⁾ During the day, contrails clouds mostly reflect sunlight back into space, exerting a cooling effect. However, at night, the Earth's surface emits thermal radiation, and contrails act as a barrier, trapping some of this radiation within the atmosphere.

1.2 Policy context at global and EU level

At global level, in 2022 the IPCC ⁽²⁰⁹⁾ stated that current sectoral levels of ambition vary, with emission reduction aspirations in international aviation and shipping lower than in many other sectors.

At the same time, the IPCC report noted that between 2010 and 2019, aviation grew particularly quickly (on average, 3.3% per annum). With the end of the COVID-related travel restrictions this trend is returning quickly ⁽²¹⁰⁾.

In October 2022, the 41st ICAO Assembly adopted a long-term global aspirational goal (LTAG) for international aviation of net-zero carbon emissions by 2050 in support of the UNFCCC Paris Agreement's temperature goal ⁽²¹¹⁾. The ICAO LTAG does not cover non-CO₂ aviation effects.

At EU level, the 2006 Commission's Impact Assessment ⁽²¹²⁾ on the inclusion of aviation in the EU greenhouse gas Emissions Trading System (EU ETS), as well as Directive 2008/101/EC recognised that aviation has an impact on the global climate through the release of non-CO₂ emissions.

Article 30(4) of Directive 2003/87/EC, as amended by Directive (EU) 2018/410, required the Commission to present an updated analysis of the non-CO₂ effects of aviation, accompanied, where appropriate, by a proposal on how to best address those effects. To fulfil that requirement, the European Union Aviation Safety Agency (EASA) conducted an updated analysis of the non-CO₂ effects of aviation on climate change and published its study ⁽²¹³⁾ in November 2020. The findings confirmed what had been previously estimated, namely that the non-CO₂ climate impacts of aviation activities are, in total, at least as significant as those of CO₂ alone.

The revised EU ETS Directive ⁽²¹⁴⁾, which concerns aviation's contribution to the Union's economy-wide emission reduction target and implementing a global market-based measure, concludes that non-CO₂ aviation effects can no longer be ignored in line with the precautionary principle. Regulatory measures are thus needed to achieve reductions of non-CO₂ emissions in line with the Paris Agreement.

⁽²⁰⁹⁾ IPCC (2022), Special Report Global Warming of 1.5°C

⁽²¹⁰⁾ [ICAO forecasts complete and sustainable recovery and growth of air passenger demand in 2023](#)

⁽²¹¹⁾ By applying the goal to hold the increase in the global average temperature to well below 2 degrees Celsius above pre-industrial levels, and to pursue efforts to limit the temperature increase to 1.5 degrees Celsius, the Paris Agreement encompasses *de facto* all anthropogenic activities contributing to the warming of climate, aviation included.

⁽²¹²⁾ COM(2006) 818 final

⁽²¹³⁾ SWD(2020) 277 final

⁽²¹⁴⁾ Directive (EU) 2023/958

Accordingly, from 1 January 2025, Member States shall ensure that each aircraft operator monitors and reports the non-CO₂ effects from each aircraft that it operates during each calendar year to the competent authority after the end of each year. For this purpose, the EU ETS aviation revised Directive instructs the Commission to adopt, by 31 August 2024, an implementing act based on the principles for monitoring and reporting set out in Annex IV to the EU ETS revised Directive, to include non-CO₂ effects in a monitoring, reporting and verification (hereinafter, MRV) framework. This MRV framework must contain, at a minimum, the three-dimensional aircraft trajectory data available, ambient humidity, and temperature to enable CO₂ equivalents per flight to be produced. The EU ETS revised Directive requires the Commission to ensure, subject to available resources, that tools are available to facilitate and, to the extent possible, automatise the monitoring, reporting and verification tasks in order to minimise any administrative burden. From 2026, the Commission will publish the results from the MRV framework once a year. By 31 December 2027, based on the results of the application of the EU ETS MRV framework of non-CO₂ aviation effects (i.e., monitoring, reporting and verifying CO₂ equivalents from non-CO₂ aviation effects), the Commission will submit a report and, where appropriate, a legislative proposal after having first carried out an impact assessment to mitigate such effects by expanding the scope of the EU ETS to include non-CO₂ aviation effects.

In addition, additional financial support is available to reduce aviation's non-CO₂ climate impacts from the EU ETS-funded Innovation Fund, which specifically provides for support for electrification and to reduce the overall climate impacts from aviation ⁽²¹⁵⁾.

The provisional political agreement reached in April 2023 for sustainable aviation fuel mandates for aviation (ReFuelEU Aviation) is another milestone in the direction of reducing the GHG impact of aviation. This measure will reduce the CO₂ impact of aviation. If the characteristics of the fossil fuel share of aviation fuels are not modified, the measure will also reduce the non-CO₂ impacts of the sector. The agreement also requires monitoring and reporting of aromatics, naphthalene and sulphur content of the aviation fuels supplied, by EASA.

In its “Fly the Green Deal” report published in June 2022, the Advisory Council for Aviation Research and innovation in Europe (ACARE) European Technology Platform, defines quantitative targets for aviation non-CO₂ effects in Europe:

- By 2035 new technologies, fuels and operational procedures in service result in a 30% reduction in non-CO₂ climate effects of all intra-EU flights and those departing the EU relative to the 1990 baseline.
- By 2050 new technologies and operational procedures in service result in a 90% reduction in NO_x and non-volatile particulate matter (nvPM) emissions, and warming contrail cirrus, from all intra-EU flights and those departing the EU relative to the year 2000.

⁽²¹⁵⁾ Innovation Fund (INNOVFUND) Methodology for GHG Emission Avoidance Calculation Version 3.0 01 November 2023.

1.3 Mitigation technologies

A possible mitigation option for mitigation of non-CO₂, as a co-benefit of reducing CO₂ is the use of sustainable aviation fuels. Nevertheless, their potential to address the climate problem is currently uncertain. As shown by Becken et al ⁽²¹⁶⁾, further analysis is needed on the level of effectiveness of SAFs in terms of reduced GHG footprint on a life-cycle analysis (LCA) basis and displacement of emissions.

Other more immediate options to reduce non-CO₂ effects relate to operational measures to seek a climate-optimised flights (as the climate impact of non-CO₂ emissions depends not only on the amount, but also on the location and time of emission) and the use of lower emissions, alternative kerosene. On the latter, research publications under Horizon 2020 projects ⁽²¹⁷⁾ demonstrated that the use of low-sulphur, low-aromatics and low-naphthalene kerosene would have significant social benefits, as the climate benefits (and also the fuel cost savings and air pollution benefits) exceed the additional production costs and the external effects of emissions from fuel production.

Additionally, technical measures like improving the design of aircrafts (reducing weight and optimising aerodynamics) and the efficiency and combustion characteristics of aircraft engines, are promising as well, but subject to longer time spans compared to the two previous options.

1.4 Non-CO₂ effects in the context of the 2040 climate target

While the 2030 Climate Target Plan did not cover aviation non-CO₂ effects, the 2040 Climate Target Plan needs to explore those, in line with the latest scientific findings and agreement on the EU ETS Directive. A qualitative approach is complimentary to a quantitative one when it comes to reducing the non-CO₂ effects from aviation. In this regard, identifying cost-effective mitigation actions ⁽²¹⁸⁾ that reduce the overall climate impact from both CO₂ and non-CO₂ aviation emissions, whilst also accounting for the uncertainties surrounding non-CO₂ effects, will be required. Qualitative and quantitative considerations for reducing aviation non-CO₂ effects will be further informed by the deliverables under the EU ETS Directive (see above), expected on 31 December 2027.

Modelling tools supporting the definition of the current EU climate targets do not refer to aviation non-CO₂ effects. Nevertheless, a number of already existing modelling tools demonstrate functions for producing figures on CO₂ equivalence of aviation non-CO₂ effects (e.g., AirClim model assesses the climate impact of aircraft emissions (i.e., altitude, longitude, and latitude of emissions) for a variety of previously calculated aviation scenarios over short- and long-time horizons, including different routings and technological options. Other models

⁽²¹⁶⁾Becken et al (2023), Implications of preferential access to land and clean energy for Sustainable Aviation Fuels, *Science of The Total Environment* 886, 163883. <https://doi.org/10.1016/j.scitotenv.2023.163883>

⁽²¹⁷⁾JET Fuel SCREENing and Optimization

⁽²¹⁸⁾Such actions need to take into account the uncertainties in non-CO₂ effects as part of a risk-based assessment in order to ensure confidence in robust mitigation gains.

exist as well (CoCIP, LinClim, OSCAR, etc.) and further analysis and eventual intercomparison of those would inform the work on mitigation of aviation non-CO₂ effects.

2 NAVIGATION

2.1 Scientific evidence

Maritime transport remains today heavily reliant on fossil fuels⁽²¹⁹⁾, which, once combusted, produce emissions of various greenhouse gases (GHG), including carbon dioxide (CO₂) but also methane (CH₄) and nitrous oxide (N₂O) which have global warming potentials much higher than CO₂⁽²²⁰⁾. The amount of emissions produced is primarily a function of the amount of fuel consumed, the characteristics of the fuel, the engine technology employed and its operation, and any post-combustion emission controls in place⁽²²¹⁾.

Other GHGs which might be associated to maritime transport activities, as fugitive emissions, include Hydro Fluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulphur Hexafluoride (SF₆) and Nitrogen trifluoride (NF₃). These are mostly used on-board ships as refrigerants in various types of machinery, including for air conditioning and cargo cooling processes⁽²²²⁾.

Furthermore, maritime transport activities produce other air pollutants such as carbon monoxide (CO), oxides of nitrogen (NO_x), non-methane volatile organic compounds (NMVOCs), particulate matter (PM₁₀ and PM_{2.5}, commonly known as “black carbon”), and sulphur dioxide (SO₂). Although these latter pollutants are not direct greenhouse gases, some of them (CO, NO_x, NMVOCs, PM_{2.5}) do contribute to climate change.

Methane

Small quantities of methane (CH₄) are emitted to the atmosphere as a result of the combustion of marine hydrocarbons fuels, as by-product of their incomplete combustion. Additional amounts of methane can be released into the atmosphere as fugitive and slipped emissions, when certain fuels and technologies are used on-board. This might occur when gas or dual fuel engines are on-board or from the cargo tanks in Liquefied Natural Gas (LNG) carriers.

Nitrous oxide

Nitrous oxide (N₂O) is produced in small quantities during fossil fuel combustion when nitrogen in the air or fuel is oxidized in the high temperature environment of the engine. N₂O is also produced as a by-product of the combustion of ammonia in ammonia-fuelled vessels.

⁽²¹⁹⁾The use of alternative, renewable fuels, remains today extremely low, see IMO Report of fuel oil consumption data submitted to the IMO Ship Fuel Oil Consumption Database in GISIS (Reporting year: 2021), MEPC 79/6/1.

⁽²²⁰⁾IPCC AR5 reports the global warming potential of methane as 28 and of nitrous oxide of 265.

⁽²²¹⁾CO₂, CH₄, and N₂O emissions from transportation water borne navigation, in Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories.

⁽²²²⁾The impact of such other GHGs is not accounted for in the figures reported above (IMO, 2020) as deemed negligible.

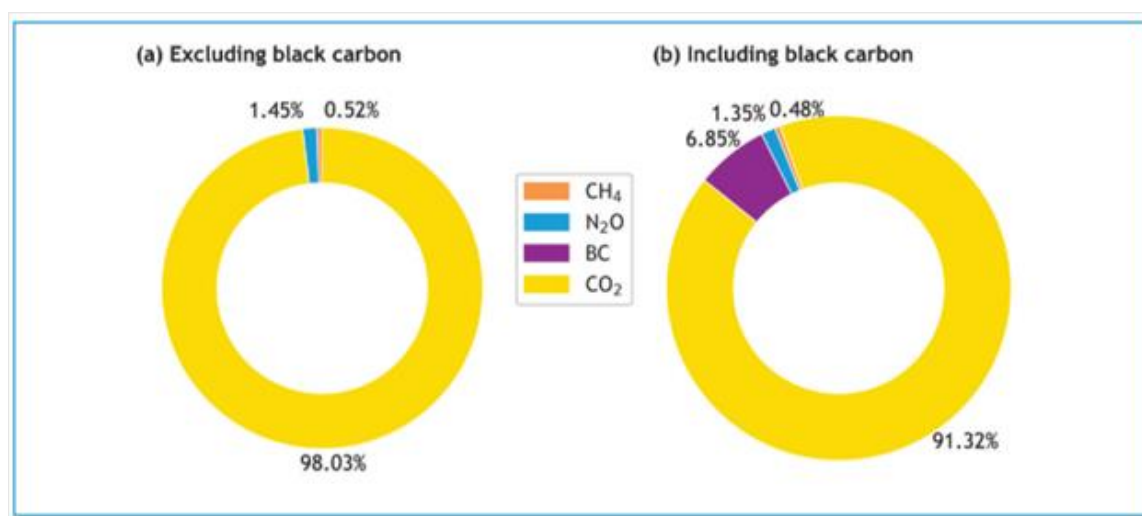
Black Carbon

As one component of fine particulate matter (PM_{2.5}), black carbon is a small, strongly light-absorbing dark particle which deteriorates air quality and causes health and environmental issues. At global level, black carbon is the second largest cause of climate impacts from the maritime sector and is contributing to the rapid decline in Arctic Sea ice ⁽²²³⁾. Black carbon emissions are mostly associated with the incomplete combustion of residual fuel oil, which leads to higher black carbon emissions compared to distillate fuels. As a result of its dark colour, black carbon absorbs a high proportion of incoming solar radiation and directly warms the atmosphere. Black carbon has a relatively short atmospheric lifetime, depositing on the Earth's surface a few days up to a few weeks after emission. However, when black carbon deposits onto light-covered surfaces, such as snow or ice, it reduces the albedo of the surface leading to a warming effect. The largest sources of black carbon emissions from maritime transport are from fossil fuel, biomass and biofuel combustion and its release by ships is mainly influenced by the type of fuel used, engine characteristics and load. ⁽²²⁴⁾

Emissions trends

While the bulk of greenhouse gases (GHGs) emissions from maritime transport are CO₂, when black carbon is included in the calculation of CO₂-equivalents ⁽²²⁵⁾, black carbon becomes the second most significant contributor at 6.85%, while the share of CO₂, CH₄ and N₂O go down to 91.32%, 0.48% and 1.35%, respectively ⁽²²⁶⁾.

Figure 21: Composition of non-CO2 GHG gases in the maritime sector



⁽²²³⁾ Comer, B., Olmer, N., Mao, X., Roy, B. & Rutherford, D., 'Black carbon emissions and fuel use in global shipping', *International Council on Clean Transportation*, 2015

⁽²²⁴⁾ The European Maritime Transport Environmental Report (EMTER).

⁽²²⁵⁾ Using a 100- year GWP of 900.

⁽²²⁶⁾ Fourth IMO GHG Study, 2020. The impact of other GHGs is not accounted for in the figures reported as deemed negligible.

Over the period 2012-2018, CO₂ emissions from international shipping increased by 5.6%. Methane emissions increased by 150%, far more than the 28-30% increase in the use of LNG as a marine fuel. This occurred as the LNG carrier fleet shifted from mostly using LNG as a fuel in steam turbine combustion engines to a larger share of the fleet using LNG-powered injection engines, which emit more unburnt methane. Black carbon emissions increased by 11.6% for total shipping (i.e., from 59 to 62 kilo tonnes) ⁽²²⁷⁾. An increase in the emissions of methane and nitrous oxide might be driven in the coming years by the deployment of dual fuel and Liquified-Natural-Gas-powered ships (for methane) and by the growing use of new fuels such as ammonia (for nitrous oxide) ⁽²²⁸⁾.

2.2 Policy context at EU and global level

The “Fit for 55” Package included several proposals to address maritime transport’s climate impact, thus ensuring that the sector would contribute to the EU overall climate ambition. In this context, amendments to the EU Maritime MRV Regulation have been adopted in May 2023 ⁽²²⁹⁾, parallel to the inclusion of the maritime sector in the European Emission Trading System. The amended EU Maritime MRV Regulation recognises the increasing importance of climate impacts from non-CO₂ emissions by updating monitoring and reporting rules to allow the inclusion of methane and nitrous oxide emissions already from the year 2024, in a tank-to-wake logic (which accounts for emissions from both combustion and tank-to-wake slippage). This will allow for an extension of the scope to methane and nitrous oxides (in addition to CO₂) under the ETS Directive as applied to the maritime sector from 2026 onwards. Furthermore, the Commission will continue to assess every two years the overall impact of shipping activities on the global climate, including through non-CO₂ emissions or effects and now also particulate matter with a global warming potential, not covered by the regulation.

Additional support to the decarbonisation of the maritime sector will be provided by the EU ETS-funded Innovation Fund, where the Commission has stated that 20 million allowances (i.e., about €1.6 billion with a price of €80 per allowance) should be used to reduce climate impacts from maritime up to 2030. Special attention is given in the Innovation Fund to addressing the maritime sector’s full climate impact, including from black carbon emissions. In addition, the FuelEU Maritime Regulation, ⁽²³⁰⁾ aims at boosting demand for renewable and low-carbon fuels by setting targets for the annual GHG intensity of the energy used on board ships (using a well-to-wake logic and accounting for the methane and nitrous oxides emissions), and by encouraging zero-emission technology when ships are at berth in ports.

⁽²²⁷⁾ Fourth IMO GHG Study, 2020.

⁽²²⁸⁾ Study on EU ETS for maritime transport and possible alternative options of combinations to reduce greenhouse gas emissions.

⁽²²⁹⁾ Regulation (EU) 2023/957 amending Regulation (EU) 2015/757 in order to provide for the inclusion of maritime transport activities in the EU Emissions Trading System and for the monitoring, reporting and verification of emissions of additional greenhouse gases and emissions from additional ship types.

⁽²³⁰⁾ Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport.

At the UN level, the EU is supporting the work at the International Maritime Organisation (IMO) for the development of guidelines on life cycle GHG intensity of marine fuels, which will allow for the calculation of emissions default values for fuels in a well-to-wake logic, including methane and nitrous oxide emissions in addition to carbon dioxide. Furthermore, the EU is supporting the work for the development of the IMO's mid-term decarbonisation measures, which will take the form of a global fuel standard and a global economic measure and are to be adopted by 2025 and enter into force by 2027. Those measures should deliver on the GHG reduction objectives of the 2023 IMO GHG Strategy (notably to reach net-zero well-to-wake GHG emissions by or around 2050). The EU is also supporting the revision of the IMO's short-term decarbonisation measures, which should also support the attainment of the 2023 IMO GHG Strategy goals.

Black carbon emissions are currently not directly regulated at international level. However, both the Arctic Council and the IMO are considering the impacts of black carbon in the Arctic. As part of these activities, the IMO agreed a reporting protocol and measurement methods for black carbon emissions with a view to investigating policy options. In 2021, the IMO approved a ban (with waivers) on the use of Heavy Fuel Oil and its carriage for use by ships in Arctic waters after 1 July 2024 ⁽²³¹⁾ and adopted a resolution which urges Member States and ship operators to voluntarily use distillate or other cleaner alternative fuels or methods of propulsion that could contribute to the reduction of black carbon emissions from ships when operating in or near the Arctic.

2.3 Mitigation options and technologies

The reduction of non-CO₂ emissions from maritime transport can be pursued through technologies already available in the market, while additional ones are currently under development.

The application of currently available high-pressure dual-fuel injection engines could reduce methane emissions compared to low pressure engines, as thanks to the resulting combustion being nearly complete, methane slip is reduced to nearly zero ⁽²³²⁾. Additional methane emissions reduction technologies applied to the engine include exhaust gas recirculation (EGR), engine tuning and control software, and engine component design optimization. ⁽²³³⁾

Nitrous oxide emissions can be reduced by using catalytic emission treatment technologies that are well-known and commercially available. A wide range of different catalysts can be used, in different temperature and gas conditions, with or without reducing agents. ⁽²³⁴⁾ Plasma reduction systems (PRS) are currently being developed and could potentially be applied to reduce both methane and ammonia slip emissions. PRS systems, still in the early

⁽²³¹⁾ See <https://www.reuters.com/article/shipping-arctic-imo-idUKL8N2HY5IS>.

⁽²³²⁾ Decarbonizing Maritime Transport: The Importance of Engine Technology and Regulations for LNG to Serve as a Transition Fuel, Lindstad, 2020.

⁽²³³⁾ Reducing methane emissions onboard vessels, The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, October, 2022.

⁽²³⁴⁾ Managing emissions from ammonia-fueled vessels, The Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, March, 2023.

stages of development, consist of a catalyst and an absorbent-free after-treatment technology aimed at producing a non-thermal plasma. The processing of the exhaust gas by means of plasma results in the conversion of pollutants in harmless molecules via a chain of chemical-kinetic reactions.

As black carbon emissions are largely influenced by the type of fuel used and engine characteristics, key available abatement technologies include fuel type selection (e.g., low-sulphur distillate fuels) and fuel treatment, better engine maintenance, better fuel combustion, and exhaust treatment systems. Operational practices aiming at improving fuel efficiency such as slow-steaming and de-rating can further contribute to black carbon emissions reduction ⁽²³⁵⁾.

2.4 Non-CO₂ effects in the context of the 2040 climate target

Modelling tools supporting the definition of the current EU climate targets refer to non-CO₂ emissions from the maritime sector only in relation to N₂O and CH₄.

Black carbon from international maritime transport is estimated to account for about 2% of total global black carbon emissions ⁽²³⁶⁾ and between 8% to 13% of all black carbon diesel emissions. ⁽²³⁷⁾ Projections on the future impact of maritime black carbon emissions are subject to considerable uncertainty but suggest the marine sector will maintain and even increase (up to 35%) its share in total diesel black carbon emissions by 2030 compared to 2010 level ⁽²³⁸⁾.

While maritime transport has traditionally relied on the use of conventional fossil fuels, today several alternative fuels and energy technologies have the potential to decarbonise shipping, including biofuels and biogas, e-fuels and e-gas, ethyl and methyl alcohols, hydrogen, ammonia, and electricity. At present it remains unclear which of these will play the biggest share in the energy transition of the sector but the composition of the future fuel mix of the global fleet will affect the relative impact of the different greenhouse gases on total emissions from maritime. Overall, the uptake of alternative fuels will reduce CO₂ emissions and, to a certain extent, non-CO₂ emissions as well. In parallel, the decrease of CO₂ emissions from fossil fuel combustion will also increase the relative importance of non-CO₂ emissions, such as N₂O emissions from ammonia combustion, CH₄ from incomplete hydrocarbons combustion (irrespective of their origin), or black carbon from biofuels. Wind assist technology also has a significant potential to reduce GHG emissions from shipping.

The further reduction of non-CO₂ emissions will be possible both through the deployment of existing abatement technologies but also through regulatory measures incentivising the

⁽²³⁵⁾ Comer, B., et al., 2017, Black carbon emissions and fuel use in global shipping, 2015, International Council on Clean Transportation.

⁽²³⁶⁾ Bounding the role of black carbon in the climate system: A scientific assessment, Bond et al., 2013, Journal of Geophysical Research: Atmospheres, 118(11).

⁽²³⁷⁾ This share refers to the year 2010.

⁽²³⁸⁾ Azzara et al., 2015. Needs and opportunities to reduce black carbon emissions from maritime shipping. The International Council on Clean Transportation. Working Paper 2015-2.

reductions. The upcoming inclusion of CH₄ and N₂O emissions into the ETS for the maritime sector will create an incentive for their reduction, while regulatory developments on black carbon are ongoing and further action may need to be considered.

Annex 13: Literature review of 2040 net GHG reductions

This annex provides a review of recent analyses (published or in preprint in 2023) of GHG pathways to climate neutrality looking at the level of emissions in 2040.

Table 1 shows a range of reductions of net GHGs in 2040 compared to 1990 of around 85-95%. To be noticed that the scope considered in the analyses varies from “domestic” to “including international bunker fuels”.

The different analyses highlight how achieving 90% or more requires managing scale-up challenges, such as the sustainable use of biomass for bioenergy, the large-scale development of carbon capture or the supply of raw materials, but still lies within the feasibility limits of fast technological development ⁽²³⁹⁾. More sustainable lifestyles can contribute positively to overcoming such challenges.

⁽²³⁹⁾ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405.

Table 1. 2040 GHG level in recent analyses of 2040 climate targets for the EU

Projections	Approach	Level of net GHGs 2040 vs 1990	Scope
ESABCC ⁽²⁴⁰⁾	Analysis of IPCC AR6 + more recent scenarios	88-92% considering environmental risk and technological challenge	Intra-EU
		88-95% if technological challenge by 2030 can be overcome	
PBL ⁽²⁴¹⁾	Analysis of IPCC AR6 scenarios	86% for climate category C1 92% if selecting only trajectories meeting climate neutrality by 2050	Intra-EU
ECEMF ^{(242)*}	Multi-model analysis based on integrated assessment models	84-89%	Including international bunker fuels
		86-92%	Intra-EU
PIK ^{(243)*}	Integrated assessment model, under different assumptions	87-91%	Including intra-EU aviation
Strategic Perspectives ⁽²⁴⁴⁾	CLIMACT “2050 Pathways Explorer”	85-95%	Including international bunker fuels
CLEVER ⁽²⁴⁵⁾	Sufficiency scenario, sectoral approach	93%	Domestic
Agora Energiewende ⁽²⁴⁶⁾	Sectoral modelling	89%	Domestic

Note: *These publications are undergoing a scientific peer-review process.

The ESABCC analyses a large number of scenarios and excludes a vast majority of them on the basis of concerns on data quality and plausibility, consistency with EU and global climate goal and geophysical, technological and sociocultural feasibility criteria. 36 “filtered” scenarios projecting a wide range of emission reduction outcomes are selected and further assessed according to their environmental risk and technological deployment challenges. The

⁽²⁴⁰⁾ ESABCC (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. DOI: 10.2800/609405. Scenario database: <https://data.ece.iiasa.ac.at/eu-climate-advisory-board/#/login?redirect=%2Fworkspaces>

⁽²⁴¹⁾ Hooijschuur, E, den Elzen, M.G.J., Dafnomilis, I. and van Vuuren, D.P. (2023), Analysis of cost-effective reduction pathways for major emitting countries to achieve the Paris Agreement climate goal, The Hague: PBL Netherlands Environmental Assessment Agency.

⁽²⁴²⁾ ECEMF, *ECEMF Policy Brief: Insights on EU2040 targets based on a model intercomparison exercise of EU Climate Neutrality Pathways*, 2023. DOI 10.5281/zenodo.8337667 <https://zenodo.org/record/8337668>

⁽²⁴³⁾ Rodrigues et al: “2040 greenhouse gas reduction targets and energy transitions in line with the EU Green Deal”, *Nature Communication*, 2023. Under Review.

⁽²⁴⁴⁾ Kalcher, L. et al., (2023). The post-2030 climate target debate starts now, *Strategic Perspectives and Climact*. <https://strategicperspectives.eu/the-post-2030-climate-target-debate-starts-now/>

⁽²⁴⁵⁾ CLEVER, *Climate neutrality, Energy security and Sustainability: A pathway to bridge the gap through Sufficiency, Efficiency and Renewables – Final Report*, 2023. https://clever-energy-scenario.eu/wp-content/uploads/2023/08/CLEVER_final-report.pdf

⁽²⁴⁶⁾ Graf, A., et al. (2023). Breaking free from fossil gas. A new path to a climate-neutral Europe. Agora Energiewende. [A-EW_292_Breaking_free_WEB.pdf \(agora-energiewende.de\)](https://www.agora-energiewende.de/en/publications/292-breaking-free-from-fossil-gas)

environmental risk considers the extent to which scenarios count on large-scale uses of carbon capture (including removals) and bioenergy. Technological deployment challenges consider the implication of conservative estimates for the deployment potential of PV and wind energy, and hydrogen technologies. In the document, the levels at which the use or deployment of certain mitigation options can represent an environmental risk or a technological challenges are not defined as “hard” values, therefore examples from the literature are used. Out of the 36 filtered scenarios, 5 stays within the environmental risk and technological deployment challenge levels, leading to a range of 88-92% emission reductions in 2040 (vs 1990). If the challenges of deploying renewable energy can be overcome⁽²⁴⁷⁾, while still remaining within the environmental risk boundaries, the numbers of possible scenarios increases to 7, leading to a range of 88-95% emission reductions in 2040.

PBL shows a range of 76%-96% of domestic emission reductions for the EU for 2040 for climate category C1 ⁽²⁴⁸⁾, with a median value of 86%. The analysis follows a very similar approach to the one taken by the ESABCC, since the values are based on all IAM scenarios used in the IPCC AR6 report and its chapter on mitigation pathways compatible with long-term temperature goal and following least-cost consideration. The PBL study complements the ESABCC study since it also includes projections that do not reach net-zero in EU by 2050. Considering only scenarios in line with the EU climate target, hence reaching net-zero in 2050, the range of net GHG emission reductions in 2040 is 84-97%.

PIK provides a range of emission reduction of 87-91% (including intra-EU aviation), depending on emission levels and energy efficiency attained in 2030, availability of biomass and development of CCS in the long run. The study indicates the challenges related to the achievement of a highly electrified energy systems, including the need to invest significantly on grid infrastructure, to implement a large amount of flexibility solutions, and to address the strong contraction of gas network usage. It also mentions the requirements to limit the use of bioenergy according to sustainability constraints and the uncertainty on the development of carbon capture and carbon removal related to the creation of a robust regulatory framework that covers permits, monitoring, cross-border collaboration, local storage acceptance, remuneration and long-term liability across different EU countries.

ECEMF performs a multi-model intercomparison using 9 different models and provides a range of 84-89% (including international bunker fuels) and 86-92% (including only intra-EU

⁽²⁴⁷⁾ ESABCC, Table 6, defines such technological challenges as installed capacities in 2030 of solar (900 GW), wind (623 GW) and hydrogen (50 GW). In 2022, the total installed capacity of PV and wind in the EU were both close to 200 GW, including newly installed capacity that year of about 40 GW for PV and 15 GW for wind (source: Eurostat, Solar Power Europe, WindEurope).

⁽²⁴⁸⁾ Limit 1.5 °C with at least 50% probability, with limited or no overshoot. As per in Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren, 2022: Mitigation pathways compatible with long-term goals. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005. Table 3.2. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C-0.3°C, in both cases for up to several decades.

emissions). According to the paper, achieving such a level of ambitions requires a large effort to scale up carbon capture up by 2040 up to an average of 305 MtCO₂, and a fast scale up of wind, solar, electric vehicles, and heat pumps.

Strategic Perspective analyses a 2040 net reduction between 85% and 95% (including international bunkers). This is achieved with a strong contribution of nature-based removals (i.e., around 470 MtCO₂-eq of LULUCF in the case of a 95% reduction, i.e., above the environmental risk threshold of 400 MtCO₂ identified by the ESABCC and above the levels considered in this impact assessment) and complemented by industrial based removals (between 35 and 60 MtCO₂), mostly from BECCS. The scenarios discussed also project behavioural change trends: demand reduction plays a major role in decarbonisation of the industry and is responsible for 15% of the sectoral emissions reductions in 2040; a shift to other modes of transport, with public transport and “mobility as a service” reduces the car fleet by 20% while increasing mobility options, and a switch to a healthier and plant-based diet can contribute to reducing food demand by 12%.

The CLEVER scenario projects a reduction of 93% of emissions in 2040 vs 1990, implementing a modelling approach based almost exclusively on sufficiency, efficiency, and renewable energies. In the scenario, sufficiency alone can be responsible for reducing final energy consumption (FEC) by 20-30%, through a reduction of total passenger traffic by around 21% in 2050 compared to 2019 through a mobility switch from road and air to active and rail, and a reduction of industrial demand for energy intensive materials such as steel (-15%) and cement (-38%). Additional efficiency measures, an increasing share of renewables in the energy mix to above 50% and reduced meat (-40%) and milk (-20%) consumption, complete a picture that reaches reductions above 90% with very limited carbon capture, and no strong enhancement of the LULUCF net sink. The pathway prioritising these three specific aspects is considered capable to limit the possible challenges and risks associated to the ambitious target, such as: technical feasibility for deep renovation, material and metal resource depletion, sustainability of bioenergy production, adaptation of electricity networks, and timely delivery of large-scale new technologies (e.g., nature-based, and industrial carbon removals, e-fuels and new nuclear).

Agora Energiewende suggests a domestic 2040 target of 89%, and its analysis focuses on possible pathways to replace existing consumption of fossil gas. They describe uncertainties related to a correct estimation of sustainable and affordable biomethane potential, as well as the need to carefully manage the transition from gas (including LNG) to alternative sources (electricity, hydrogen, and e-fuels) to adapt the corresponding infrastructure and avoid the risk of stranded assets.

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COMMISSION STAFF WORKING DOCUMENT

IMPACT ASSESSMENT REPORT

Part 5

Accompanying the document

**COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN
PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL
COMMITTEE AND THE COMMITTEE OF THE REGIONS**

**Securing our future
Europe's 2040 climate target and path to climate neutrality by 2050 building a
sustainable, just and prosperous society**

{COM(2024) 63 final} - {SEC(2024) 64 final} - {SWD(2024) 64 final}

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Annex 14: GHG budget

This Annex looks at an indicative “GHG budget” for the EU with the geographical scope of 1st February 2021 (“EU27”). This “budget” is defined according to the emission scope of the European Climate Law and consistently with the proposed 2040 climate target.

1 EU COMMITMENT TO THE PARIS AGREEMENT

The Paris Agreement aims at limiting “the increase in the global average temperature to well below 2°C above pre-industrial levels” and pursue efforts “to limit the temperature increase to 1.5°C above pre-industrial levels.” In recent decisions taken in the UNFCCC, Parties have reinforced the need to deliver emissions reductions in line with the IPCC recommendations, in order to keep the 1.5°C within reach.

Under the Paris Agreement, Parties have agreed to prepare, communicate and maintain successive nationally determined contributions and pursue domestic measures, with the aim of achieving the objectives of such contributions. Article 4.3 states that each Party's successive nationally determined contribution will represent a progression beyond the Party's then current nationally determined contribution and reflect its highest possible ambition, reflecting its common but differentiated responsibilities and respective capabilities, in the light of different national circumstances. Article 4.4 of the Paris Agreement states that developed countries should continue taking the lead by undertaking economy-wide absolute emission reduction targets and developing countries should continue enhancing their efforts and are encouraged to move towards economy-wide targets over time. The Paris Agreement also requests all Parties to strive to formulate and communicate long-term low greenhouse gas emissions development strategies. The European Union has committed to the goals of the Paris Agreement and has been faithful to its provisions:

- In 2020, the EU committed to climate neutrality by 2050 in its long-term strategy to the UNFCCC and submitted an ambitious Nationally Determined Contribution with a 2030 climate target of at least 55% reduction of net emissions of greenhouse gases as compared to 1990. The 2030 and the 2050 targets are mutually supportive, are enshrined in the EU Climate Law and are legally binding. Setting these targets, the EU has set itself on a path of domestic GHG mitigation aiming at limiting the temperature increase to 1.5°C above pre-industrial levels, in line with the most ambitious interpretation of the Paris Agreement and reinforcing the EU's commitment towards its implementation.
- According to the Climate Law, the EU will undertake a review of its progress towards climate neutrality target every five years, in line with the global stocktake exercise under the Paris Agreement.
- The EU has substantially exceeded its 2020 targets, and, in 2022, the EU greenhouse emissions reduced to 32.5% below 1990 levels, while global emissions have risen by over 50% worldwide. During that period, the EU and its Member States' emissions reductions outpaced those of any other major developed or developing economy.
- Currently, the EU contributes 7% to global emissions and cannot solve the climate crisis on its own: international cooperation remains at the heart of the EU's

contribution to global climate action and the EU will continue to call on the countries with the largest share of emissions to commit to the highest possible ambition.

Internationally, the EU has been fully engaged as a positive actor to support the mitigation of GHG emissions globally in line with the Paris Agreement, aiming at keeping 1.5°C in reach. On a per capita basis, EU emissions are also among the lowest of any major high-income economy and lower than several emerging economies. The EU research and innovation and industrial policies have for decades incentivised and supported the development of innovative, state-of-the-art low carbon technologies and corresponding markets. For instance, between early 2000 and 2015, the EU has consistently deployed the largest share of the solar and wind energy capacity installed worldwide, reaching a 74% share at the beginning of the 2000s for wind and around 2010 for solar. In this way, the EU contributed to driving global learning and reducing costs for these two technologies that benefitted all countries: world average wind and solar Levelised Cost of Electricity (LCOE) reduced drastically in this period by around 50% ⁽¹⁾ and 80% ⁽²⁾ respectively. More than two decades of experience in designing, agreeing and implementing climate and energy policies, have provided a wealth of lessons, that the EU has been sharing for more than a decade through multilateral initiatives and bilateral policy dialogues and projects. Thereby, it continues to contribute to the creation of global value chains that, through technology dissemination and cost decrease, now drive the required transformations towards zero carbon economies and societies.

The EU and its MS are collectively the largest contributor to international public climate finance. Since the launch of the “USD 100 billion by 2020 goal” in 2009 the EU and its 27 Member States have been strongly committed to helping achieve it. In 2022, the European Union and its 27 member states contributed EUR 28.5 billion in climate finance from public sources and mobilised an additional amount of EUR 11.9 billion of private finance, including more than €12 billion per year for climate adaptation or actions combining adaptation and mitigation. Thanks to this contribution and to a significant increase in international climate finance in 2023, OECD Secretary General stated that the 100 billion USD will likely have been reached in 2022 based on preliminary data ⁽³⁾.

The EU will continue to stand by its commitment to deliver its fair share of the USD 100 billion USD mobilisation goal and the doubling of adaptation finance by 2025, making support for adaptation a priority of its global action. In 2024, the EU will also push for an agreement in 2024 on the New Collective Quantified Goal for climate finance under the Paris agreement including leveraging an increasing private sector contribution to global climate finance and reform of Multilateral Development Banks.

⁽¹⁾ Data extrapolated from Ourworldindata.org for the period 2008-2018. Original data source from IRENA (2022), Renewable Power Generation Costs in 2021, International Renewable Energy Agency, Abu Dhabi.

⁽²⁾ European Commission, Directorate-General for Energy, Rademaekers, K., Smith, M., Gorenstein Dedecca, J. et al., *Energy costs, taxes and the impact of government interventions on investments – Final report, summary*, Publications Office, 2020, <https://data.europa.eu/doi/10.2833/827631>

⁽³⁾ OECD, 2023. Climate Finance Provided and Mobilised by Developed Countries in 2013-2021: Aggregate trends and opportunities for scaling up adaptation and mobilised private finance, OECD Publishing

The EU aims to target and tailor support where it is needed the most, with a prime focus on most vulnerable countries, small island developing states and fragile countries. While developed countries shall continue to take the lead, moving the needle on climate finance should compel the EU to reach the largest possible donor base and go beyond the developed/developing countries split.

2 THE GHG BUDGET IN THE EUROPEAN CLIMATE LAW

Article 4(4) of the EU Climate Law mandates the Commission, when making the proposal for the Union 2040 climate target, ‘to publish in a separate report the projected indicative Union greenhouse gas budget for the 2030-2050 period’, taking into account the advice of the European Scientific Advisory Board on Climate Change (ESABCC). This GHG budget approach was an innovation for the EU introduced by the Climate Law, aiming to increase the transparency and accountability of climate policies. It also makes it easier to compare action at EU level with international efforts and the global emissions budget. The Climate Law also defines the indicative Union GHG budget as “the indicative total volume of net greenhouse gas emissions (expressed as CO₂ equivalent and providing separate information on emissions and removals) that are expected to be emitted in that period without putting at risk the Union’s commitments under the Paris Agreement’.

The 2030-2050 GHG budget is expressed in tonnes of CO₂ equivalent (tCO₂-eq) and covers all GHGs ⁽⁴⁾ under the scope of the European Climate Law ⁽⁵⁾ from 2030 (included) to 2050 (included). It combines a “carbon” budget (cumulative CO₂ emissions) with cumulative emissions of non-CO₂ GHGs ⁽⁶⁾ and including the contribution of carbon removals.

The notion of “emissions budget” refers to the carbon budget at global level that is defined in the IPCC AR6 as the maximum quantity of CO₂ emissions that can be released to the atmosphere over that period while keeping global warming below a given level of temperature. Non-CO₂ GHG emissions are not typically expressed as budget.

The differentiation between the role of CO₂ and non-CO₂ in the definition of the budget relates to the dominant contribution of CO₂ to global surface temperature increase: most warming to date has been caused by CO₂, which has the most permanent impact on the climate system ⁽⁷⁾. The IPCC indicates that the maximum temperature reached is determined with high confidence by cumulative net global anthropogenic CO₂ emissions up to the time of

⁽⁴⁾ See part 2 of Annex V to Regulation (EU) 2018/1999

⁽⁵⁾ The scope is the same as the ones for the Union 2040 climate target and is defined as all Union-wide GHG emissions regulated in Union law, which include: domestic EU emissions, international intra-EU aviation, international intra-EU maritime, and 50% of international extra-EU maritime under the MRV.

⁽⁶⁾ Non-CO₂ GHG emissions are converted into “CO₂ equivalent” using the global warming potential for a 100-year time horizon from the IPCC Fifth Assessment Report (“AR5”).

⁽⁷⁾ Jenkins, S., Cain, M., Friedlingstein, P., Gillett, N., Walsh, T., & Allen, M. R. (2021). Quantifying non-CO₂ contributions to remaining carbon budgets. *npj climate and atmospheric science*, 4(1), 47.

net zero CO₂ emissions and with medium confidence by the level of non-CO₂ radiative forcing in the decades prior to the time that maximum temperatures are reached ⁽⁸⁾.

3 THE REMAINING GLOBAL CARBON BUDGET

The IPCC AR6 report reaffirms with high confidence that there is a near-linear relationship between cumulative anthropogenic CO₂ emissions and the global warming they cause, estimating a global surface temperature increase of 0.45°C per each 1000 GtCO₂ of cumulative CO₂ emissions, and highlighting that limiting global temperature increase to a specific level, for example as defined in the Paris Agreement would imply limiting cumulative CO₂ emissions to a set carbon budget ⁽⁹⁾.

The IPCC AR6 ⁽¹⁰⁾ estimates that from the beginning of 2020, the remaining global carbon budget is 500 GtCO₂ for limiting global warming to 1.5°C with 50% likelihood, 850 GtCO₂ for limiting global warming to 1.7°C with 50% likelihood, and 1150 GtCO₂ for limiting global warming to 2°C with 67% likelihood (see Table 1).

⁽⁸⁾ IPCC, 2018: Summary for Policymakers. In: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-24. <https://doi.org/10.1017/9781009157940.001>.

⁽⁹⁾ IPCC, 2021: Summary for Policymakers. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32, doi:10.1017/9781009157896.001. Figure SPM.10

⁽¹⁰⁾ Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007

Table 1: IPCC estimates of the global carbon budget.

Table SPM.2 | Estimates of historical carbon dioxide (CO₂) emissions and remaining carbon budgets. Estimated remaining carbon budgets are calculated from the beginning of 2020 and extend until global net zero CO₂ emissions are reached. They refer to CO₂ emissions, while accounting for the global warming effect of non-CO₂ emissions. Global warming in this table refers to human-induced global surface temperature increase, which excludes the impact of natural variability on global temperatures in individual years.
[Table 3.1, 5.5.1, 5.5.2, Box 5.2, Table 5.1, Table 5.7, Table 5.8, Table TS.3]

Global Warming Between 1850–1900 and 2010–2019 (°C)		Historical Cumulative CO ₂ Emissions from 1850 to 2019 (GtCO ₂)				
1.07 (0.8–1.3; likely range)		2390 (± 240; likely range)				
Approximate global warming relative to 1850–1900 until temperature limit (°C) ^a	Additional global warming relative to 2010–2019 until temperature limit (°C)	Estimated remaining carbon budgets from the beginning of 2020 (GtCO ₂)				
		Likelihood of limiting global warming to temperature limit ^b				
		17%	33%	50%	67%	83%
1.5	0.43	900	650	500	400	300
1.7	0.63	1450	1050	850	700	550
2.0	0.93	2300	1700	1350	1150	900

^a Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.

^b This likelihood is based on the uncertainty in transient climate response to cumulative CO₂ emissions (TCRE) and additional Earth system feedbacks and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 GtCO₂) and non-CO₂ forcing and response (±220 GtCO₂) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 GtCO₂) and the climate response after net zero CO₂ emissions are reached (±420 GtCO₂) are separate.

^c Remaining carbon budget estimates consider the warming from non-CO₂ drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO₂ emissions.

Source: IPCC (2021). AR6. WG1, summary for policy makers, Table SPM.2

More recent estimates ⁽¹¹⁾ assess that these remaining carbon budgets have decreased, to 250 GtCO₂ as of beginning of 2023 for a 1.5°C global warming threshold (with a 50% likelihood), to 600 GtCO₂ for 1.7°C and 1150 GtCO₂ for 2°C (with a 50% likelihood) – see Table 2.

⁽¹¹⁾ Forster, P. M., Smith, C. J., Walsh, T., Lamb, W. F., Lamboll, R., Hauser, M., Ribes, A., Rosen, D., Gillett, N., Palmer, M. D., Rogelj, J., von Schuckmann, K., Seneviratne, S. I., Trewin, B., Zhang, X., Allen, M., Andrew, R., Birt, A., Borger, A., Boyer, T., Broersma, J. A., Cheng, L., Dentener, F., Friedlingstein, P., Gutiérrez, J. M., Gütschow, J., Hall, B., Ishii, M., Jenkins, S., Lan, X., Lee, J.-Y., Morice, C., Kadow, C., Kennedy, J., Killick, R., Minx, J. C., Naik, V., Peters, G. P., Pirani, A., Pongratz, J., Schleussner, C.-F., Szopa, S., Thorne, P., Rohde, R., Rojas Corradi, M., Schumacher, D., Vose, R., Zickfeld, K., Masson-Delmotte, V., and Zhai, P.: Indicators of Global Climate Change 2022: annual update of large-scale indicators of the state of the climate system and human influence, Earth Syst. Sci. Data, 15, 2295–2327, <https://doi.org/10.5194/essd-15-2295-2023>, 2023. Table 7.

Table 2: Updated estimates of the remaining carbon budget

Historical cumulative CO ₂ emissions (1850–2019) AR6 WGI Table SPM.2	2390 (±240; <i>likely</i> (66 %–100 % probability) range)					
Remaining carbon budgets Case/update	Base year	Estimated remaining carbon budgets from the beginning of base year (GtCO ₂)				
Likelihood of limiting global warming to temperature limit.		17 %	33 %	50 %	67 %	83 %
1.5 °C from AR6 WGI	2020	900	650	500	400	300
+ AR6 emulator update	2020	750	500	400	300	200
+ as above with AR6 scenario update	2020	750	500	400	300	200
+ as above with warming update (2013–2022) (best estimate)	2023	500	300	250	150	100
1.7 °C from AR6 WGI	2020	1450	1050	850	700	550
+ AR6 emulator update	2020	1250	900	700	600	450
+ as above with AR6 scenario update	2020	1300	950	750	600	500
+ as above with warming update (2013–2022) (best estimate)	2023	1100	800	600	500	350
2 °C from AR6 WGI	2020	2300	1700	1350	1150	900
+ AR6 emulator update	2020	2050	1500	1200	1000	800
+ as above with AR6 scenario update	2020	2200	1650	1300	1100	900
+ as above with warming update (2013–2022) (best estimate)	2023	2000	1450	1150	950	800

Source: Forster et al., See also (7)

Comparing these carbon budgets with current annual global CO₂ emissions shows that a significant global reduction of CO₂ emissions within this critical decade is imperative to keep the 1.5 °C in reach. The EDGAR report 2023 ⁽¹²⁾ estimates that the global CO₂ emissions in 2022 amounted to around 38.5 GtCO₂⁽¹³⁾, more than 15% of the remaining global CO₂ budget as of 2023.

⁽¹²⁾ Crippa, M., Guizzardi, D., Pagani, F., Banja, M., Muntean, M., Schaaf E., Becker, W., Monforti-Ferrario, F., Quadrelli, R., Riskey Martin, A., Taghavi-Moharamli, P., Köykkä, J., Grassi, G., Rossi, S., Brandao De Melo, J., Oom, D., Branco, A., San-Miguel, J., Vignati, E., GHG emissions of all world countries, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/953322, JRC134504. The choice of the database is motivated by the limited available data in the UNFCCC Inventory, which for the year 2021 reports only CO₂ emissions (including LULUCF) from 43 countries.

⁽¹³⁾ representing about 71.6% of the global GHG emissions estimated at 53.8 GtCO₂-eq in 2022

4 INDICATIVE EUROPEAN UNION NET GHG BUDGET FOR THE 2030-2050 PERIOD

4.1 GHG budget estimates

4.1.1 Advice by the ESABCC

In its advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050 ⁽¹⁴⁾, the ESABCC indicates a feasible domestic EU ⁽¹⁵⁾ net GHG budget for 2030–2050 of 13–16 GtCO₂-eq and recommends a range of 11–14 GtCO₂eq. These values assume a global warming limited to 1.5°C by the end of the century with no or limited overshoot with at least 50% chance.

The range presented by the ESABCC is calculated from existing modelled scenarios that are selected as described briefly below. The report proceeds with a multiple-step filtering process excluding many scenarios for the EU on “high feasibility concern” grounds (related to the role of CCUS, bioenergy, LULUCF net removals), and eventually selects seven scenarios ⁽¹⁶⁾. These seven scenarios are all compatible with the Paris Agreement, and more specifically with the long-term temperature goal of limiting global average temperature to 1.5°C. They serve to build the analysed range for the GHG budget within environmental risk levels (7 scenarios, 11–16 GtCO₂-eq), the analysed range within environmental risk levels and the technological deployment challenge (5 scenarios, 13–16 GtCO₂-eq), and the recommended range (6 scenarios, 11–14 GtCO₂-eq). The recommended range discards the scenario showing 2040 reductions lower than 90% compared to 1990 and includes two scenarios showing very ambitious 2040 reduction levels overcoming one or more of the technological deployment challenges defined by the report ⁽¹⁷⁾.

In terms of GHG profile, the six scenarios building the recommended range all show net negative GHGs in 2050 ⁽¹⁸⁾, implying a stronger effort than what is required under the Climate Law, which states that the European Union shall reduce emissions to net zero by 2050 and shall aim to achieve negative emission thereafter.

⁽¹⁴⁾ European Scientific Advisory Board on Climate Change. 2023. Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. URL: <https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040>

⁽¹⁵⁾ The scope of the recommended GHG Budget by the ESABCC is “intra-EU”, i.e. domestic as per the inventories and including intra-EU aviation and intra-EU maritime transport. It does not consider 50% of international extra-EU maritime under the MRV, which are included in the scope of the EU Climate Law. The difference in terms of cumulative emissions over 2030–2050 between the ESABCC “intra-EU” scope and EU Climate Law scope is estimated at around 0.5 GtCO₂-eq.

⁽¹⁶⁾ See the “European Climate Advisory Board Scenario Explorer”, for details on the different scenarios: <https://data.ece.iiasa.ac.at/eu-climate-advisory-board>.

⁽¹⁷⁾ The technological deployment challenges are defined as total installed capacity in 2030 of PV (900 GW), wind (630 GW) and hydrogen (50 GW).

⁽¹⁸⁾ The scenarios reach net GHGs in 2045 ranging from +141 MtCO₂-eq to -63 MtCO₂-eq, and are all net negative in 2050 from -46 to -176 MtCO₂-eq. Excluding the scenario meeting 88% in 2040 that has not been retained by the ESABCC in its recommended ranges for a 2040 target and the GHG budget, 2045 net emissions reach +73 to -63 MtCO₂-eq in 2045 (reductions between -98% and -101% compared to 1990) and -94 to -176 MtCO₂-eq in 2050 (-102% to -104%).

The above discussed numbers thus represent the most ambitious approach that can be taken by the EU.

4.1.2 Other estimates

A report by PBL ⁽¹⁹⁾ provides an analysis of GHG budgets for major emitting countries to achieve the Paris Agreement temperature goals. It looks at the global cumulative GHG emissions over 2030-2050 ⁽²⁰⁾ of scenarios in the IPCC AR6 database for different climate categories⁽²¹⁾:

- C1: limit warming to 1.5°C with no or limited overshoot and with a probability higher than 50%,
- C1a: subcategory of C1 including only scenarios reaching global net-zero greenhouse emissions in the second half of this century,
- C2: return warming to 1.5°C with a probability higher than 50% after a high overshoot
- C3: limit warming to 2°C with a probability higher than 67%.

The distribution of these global carbon budgets to regional carbon budgets (Table 3) focuses on five major economies (China, India, EU, United State and Japan). The analysis gives for the EU a 2030-2050 GHG budget of 15 GtCO₂-eq (ranging 7-24) for climate category C1, 17 GtCO₂-eq (12-25) for category C1a, 23 GtCO₂-eq (15-36) for category C2, and 26 GtCO₂-eq (18-40) for category C3.

⁽¹⁹⁾ Hooijschuur, E, den Elzen, M.G.J., Dafnomilis, I. and van Vuuren, D.P. (2023), Analysis of cost-effective reduction pathways for major emitting countries to achieve the Paris Agreement climate goal, The Hague: PBL Netherlands Environmental Assessment Agency.

⁽²⁰⁾ Including the year 2030, but excluding the year 2050.

⁽²¹⁾ Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, E. Kriegler, R. Matthews, G.P. Peters, A. Rao, S. Robertson, A.M. Sebbit, J. Steinberger, M. Tavoni, D.P. van Vuuren, 2022: Mitigation pathways compatible with long-term goals. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.005. Table 3.2. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C, high overshoot by 0.1°C-0.3°C, in both cases for up to several decades.

Table 3: GHG budget for 2030-2050 per climate category and per country or region.

			China	EU-27	India	Japan	US	World
Total cumulative net GHGs 2030-2050*	C1	Median	67	15	34	5	22	308
		Range	56-85	7-24	15-39	3-7	10-36	171-355
	C1a	Median	72	17	35	5	23	316
		Range	57-84	12-25	26-40	3-7	14-38	238-363
	C2	Median	98	23	39	7	41	414
		Range	77-116	15-36	27-50	5-12	23-61	311-492
	C3	Median	110	26	49	9	48	505
		Range	90-140	18-40	32-64	6-14	31-72	398-611

Note: *Includes the year 2030 and excludes the year 2050.

Source: Hooijschuur et al. (2023).

Other recent estimates for EU CO₂ and GHG budgets are reported:

- The German Advisory Council on the Environment calculates a CO₂ budget for the period 2022-2050 of 23.1 for 1.5°C with 50% probability and 39.5 GtCO₂ for 1.75°C with 67% probability ⁽²²⁾.
- Agora Energiewende suggests a domestic ⁽²³⁾ EU GHG budget of 14.3 GtCO₂-eq for the period 2030-2050 to achieve net-zero emissions by 2050 ⁽²⁴⁾.

4.2 Cumulative 2030-2050 GHG emissions associated to target options

The Impact Assessment looks at a broad range of options for the 2040 GHG emission reduction target, ranging from below 75% up to 95% in comparison with 1990 emission levels. The analysis focuses on three target levels:

- Option 1: a reduction of consistent with a linear trajectory between 2030 and climate neutrality by 2050,
- Option 2: a reduction of at least 85% up to 90%,
- Option 3: a reduction of at least 90% up to 95%.

For each target option, the “GHG budget” is calculated as the cumulative net GHG emissions of 2030-2050, assuming net GHG emissions reaching zero in 2050 and linear trajectories of net GHGs between 2030 and 2040, and between 2040 and 2050. The EU-wide net domestic GHG emissions cut by 2030 is estimated at 57% compared to 1990 under the Fit-for-55 legislation as adopted.

⁽²²⁾ German Advisory Council on the Environment (2022). A justified ceiling to Germany’s CO₂ emissions: Questions and answers on its CO₂ budget. German Advisory Council on the Environment. The upper limit for CO₂ for domestic budget in the period 2022-2050 is defined as of 23.1 GtCO₂.

⁽²³⁾ The difference in scope between the indicative budget (European Climate Law scope) and a domestic budget (excluding emissions for international aviation and maritime transport) is quantified to around 1.2 GtCO₂-eq.

⁽²⁴⁾ Graf, A., et al. (2023). Breaking free from fossil gas. A new path to a climate-neutral Europe. Agora Energiewende.

The resulting GHG budget ranges from above 23 GtCO₂-eq for a 2040 reduction lower than 75%, 21 GtCO₂-eq for target option 1, up to 18 GtCO₂-eq for option 2 and up to 16 GtCO₂-eq for option 3.

Table 4: EU GHG budget over 2030-2050 associated to each target option.

GHG reductions in 2040 compared to 1990	Below 75%	Target option 1 (linear 2040, 78%)	Target option 2 (85-90%)	Target option 3 (90-95%)
Corresponding GHG budget over 2030-2050 (GtCO₂-eq)	More than 23	21	Up to 18	Up to 16

4.3 Cumulative 2030-2050 GHG emissions associated to the proposed EU 2040 climate target

Consistently with the EU 2030 climate target of at least 55% reduction of net GHGs and its associated policy framework, with climate neutrality in 2050 and with the proposed 2040 target of -90%, the resulting indicative “GHG budget” for the EU over the 2030-2050 period is estimated at 16 GtCO₂-eq.

The scope of the indicative GHG budget is consistent with the European Climate Law: it includes domestic EU emissions, international intra-EU aviation, international intra-EU maritime, and 50% of international extra-EU maritime under the MRV. It is calculated considering linear reductions in the 2030-2040 decade to achieve -90% and in the 2040-2050 decade to achieve net-zero in 2050.

The indicative GHG budget consists of cumulative gross GHG emissions of around 21-24 GtCO₂-eq, and of cumulative net removals of around 5-8 GtCO₂-eq over the 2030-2050 period, depending on the contribution of LULUCF net removals and industrial carbon removals. The carbon budget (including the contribution of the LULUCF net removals and of industrial carbon removals) and the cumulative non-CO₂ emissions represent each about half of the indicative GHG budget.

It falls within the range analysed by the ESABCC from feasible scenarios compatible with a 1.5°C global warming ⁽²⁵⁾ and is in the middle of the range of AR6 scenarios analysed by PBL between climate category C1 and C1a, both compatible with the same global warming level.

This indicative 2030-2050 GHG budget is fully compatible with the Paris Agreement long term temperature goals of well below 2°C and pursuing effort to limit it to 1.5°C, and thus does not put at risk the EU’s commitment to contribute to achieving the Paris Agreement.

⁽²⁵⁾ The difference in scope between the indicative budget (European Climate Law scope) and the ESABCC budget (intra-EU emissions) is quantified to around 0.5 GtCO₂-eq

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