EUROPEAN
COMMISSION

Strasbourg, 6.2.2024
SWD(2024) 63 final

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

{COM(2024) 63 final} - {SEC(2024) 64 final} - {SWD(2024) 64 final}

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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

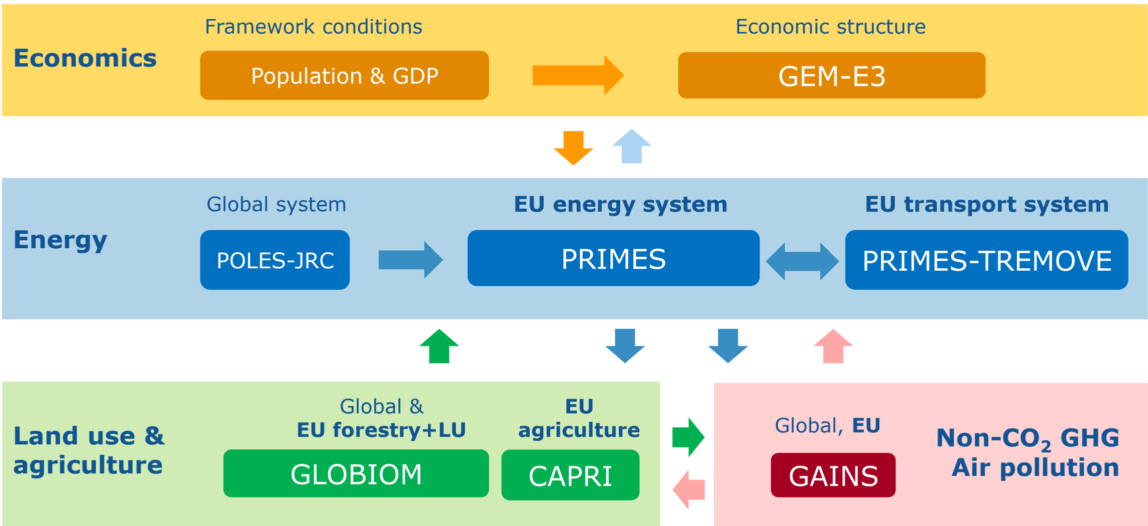
2.1 Models ([4])

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 prejudge 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

([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

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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 polices. 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

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([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., Koukoufikis, 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 assessement, 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

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([45]) ENGIE, *Trajectoires de décarbonation de l'Europe : le scenario 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 emissions[51]. 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 exogeneous 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.

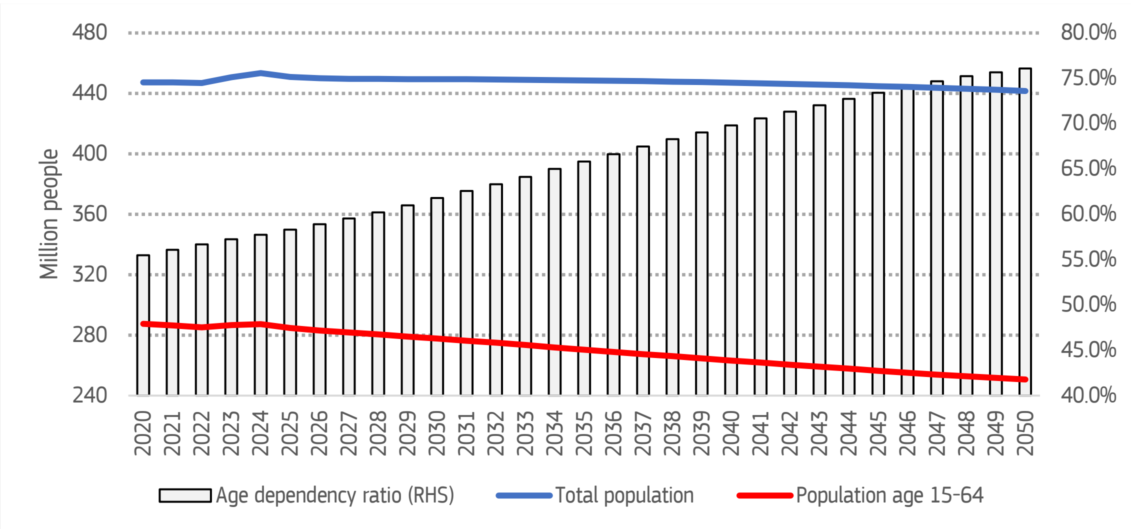
([50]) For overview and selected publications: https://forest.jrc.ec.europa.eu/en/activities/forestbioeconomy/modelling/

([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.

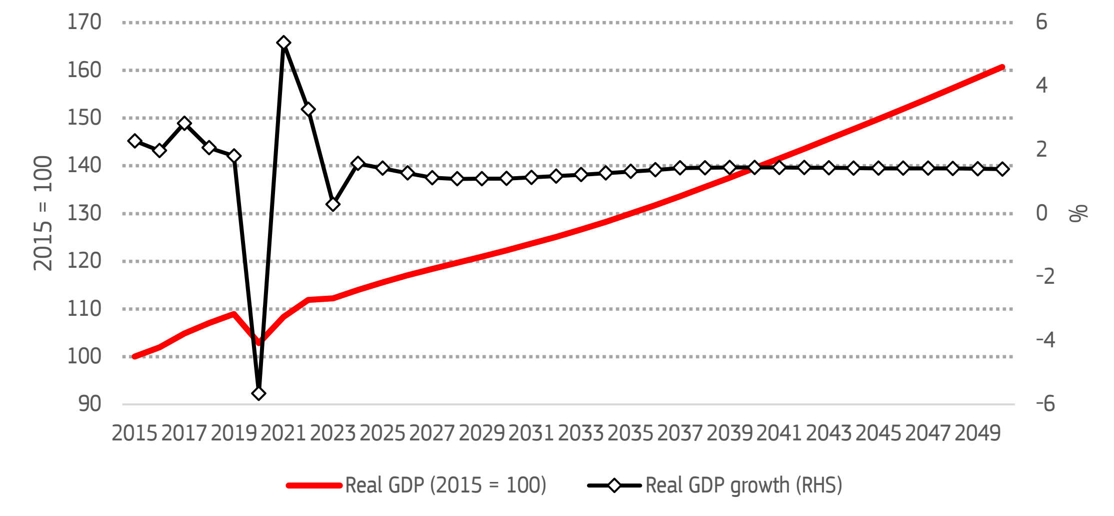
([53]) DG ECFIN. Autumn 2022 Economic Forecast: The EU economy at a turning point.

([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.

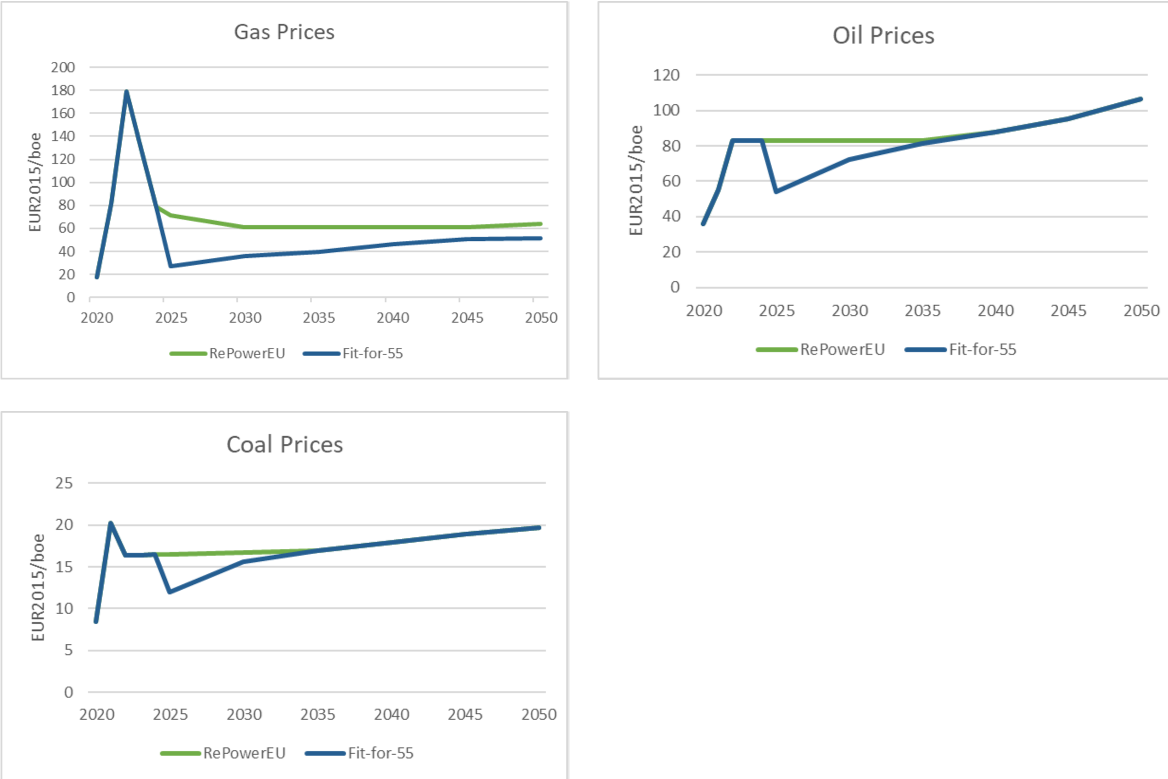
2.4.3 Energy Prices Trajectory between 2020 and 2050

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 pubication 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 Maintainenance 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 biogsases

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

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([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 CO_2 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 promotiong 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

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([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

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([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 im 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 and 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 Energétiques 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 Members 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 analised (see Annex 8). Current estimates suggest tnat 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. Consequentely, 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

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([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 anual GHG emissions from international shipping by atleast 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 $MtCO_2$ 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 $MtCO_2$ 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 MtCO_2 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-friendy 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 unerpinning 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 recyling 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. 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.
		Lower aviation demand and stronger shift to rail	
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 incuded 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 CO_2-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/tCO2-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/tCO2-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 witha 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 sectorial 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 prejudge the future design of the post-2030 policy framework.

([163]) For instance, the main modelling suite of Impact Assessement 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 Manuel, 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/macroeconomic-models/quest-macroeconomic-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.

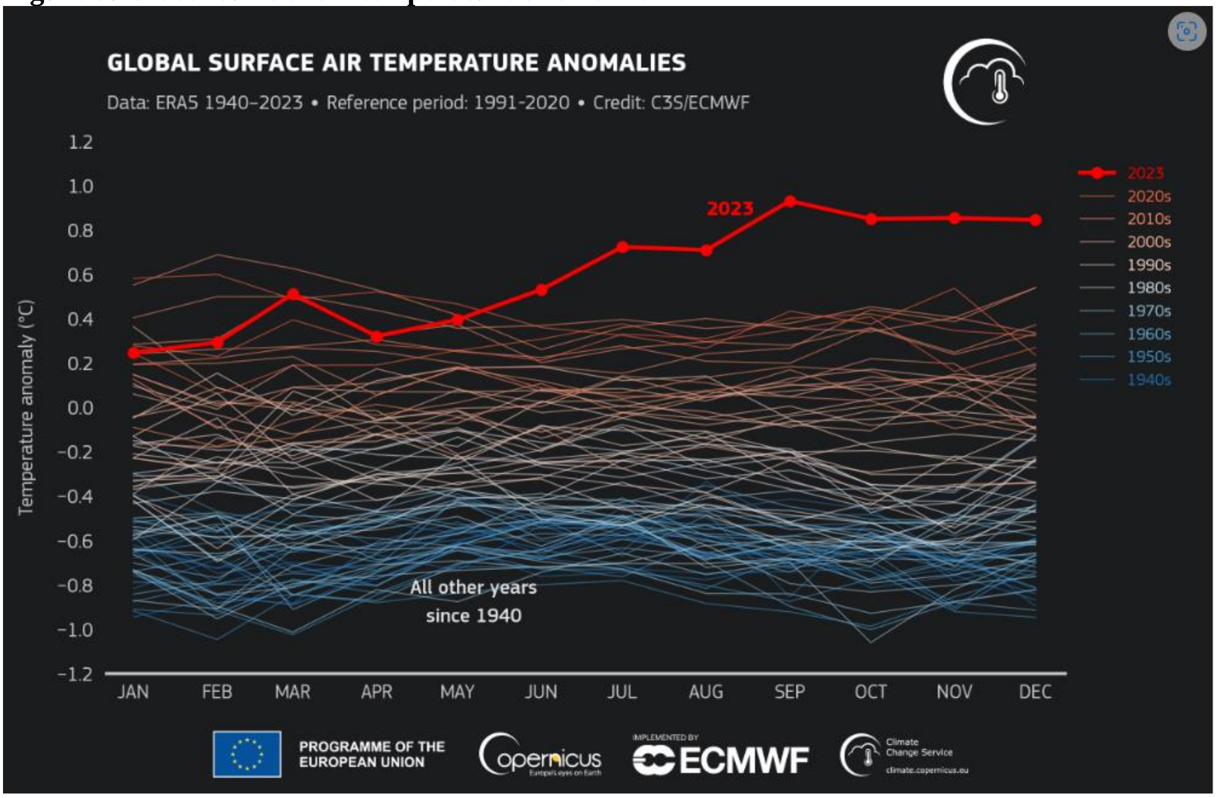
([172]) Crippa, Monica; Guizzardi, Diego; Pagani, Federico; Pisoni, Enrico; (2023): GHG Emissions at sub-national level (v1.0). European Commission, Joint Research Centre (JRC) [Dataset]

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^{o}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.

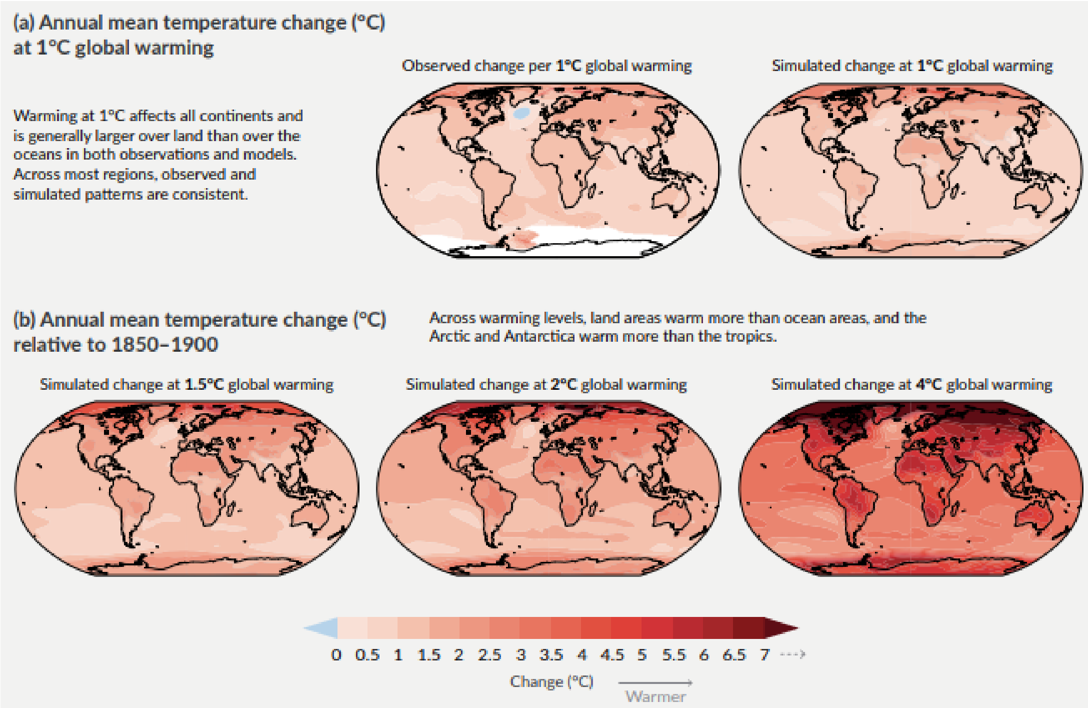
Source: based on IPCC AR6 WG I (2021), Table SPM.1

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

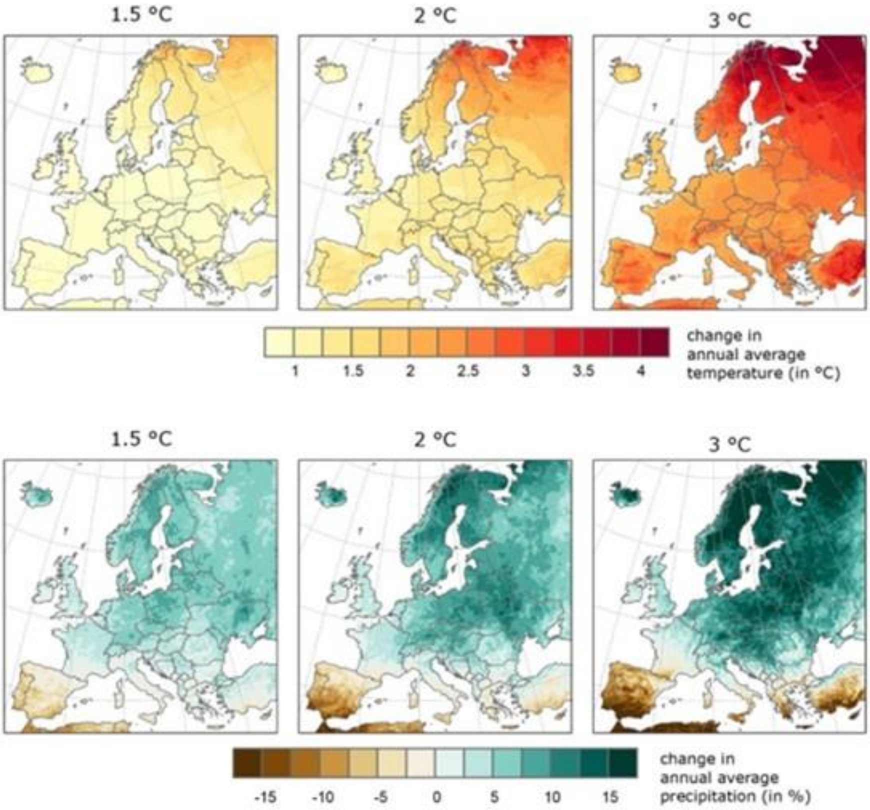
With increasing GHG emissions, global warming will increase in all regions, but the pace of change varies by region (Figure 6). Europe has been warming faster than any other continent, at more than twice the rate of the global average over the past 30 years, with temperatures increasing at an average 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

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([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.

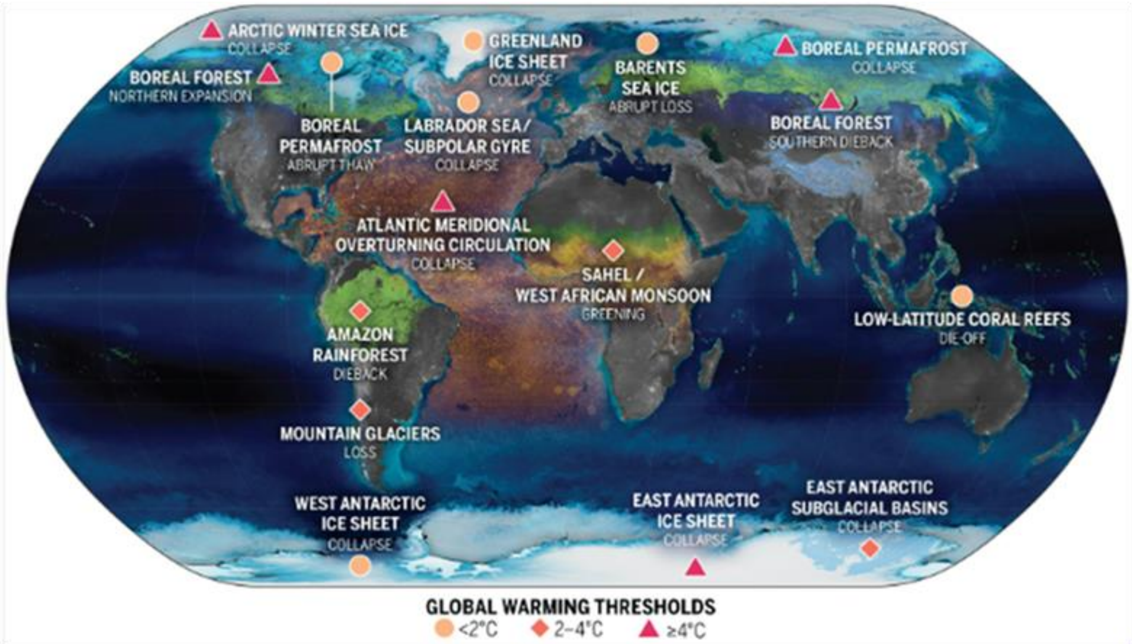
([181]) Cissé, G., R. McLeman, H. Adams, P. Aldunce, K. Bowen, D. Campbell-Lendrum, S. Clayton, K.L. Ebi, J. Hess, C. Huang, Q. Liu, G. McGregor, J. Semenza, and M.C. Tirado, 2022: Health, Wellbeing, and the Changing Structure of Communities. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. 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

Source: Lenton et al (2019) (190).

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. Talukdarr, 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 CO_2 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. Ghebrehiwet, 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

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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

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([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

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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.

([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 threats 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.

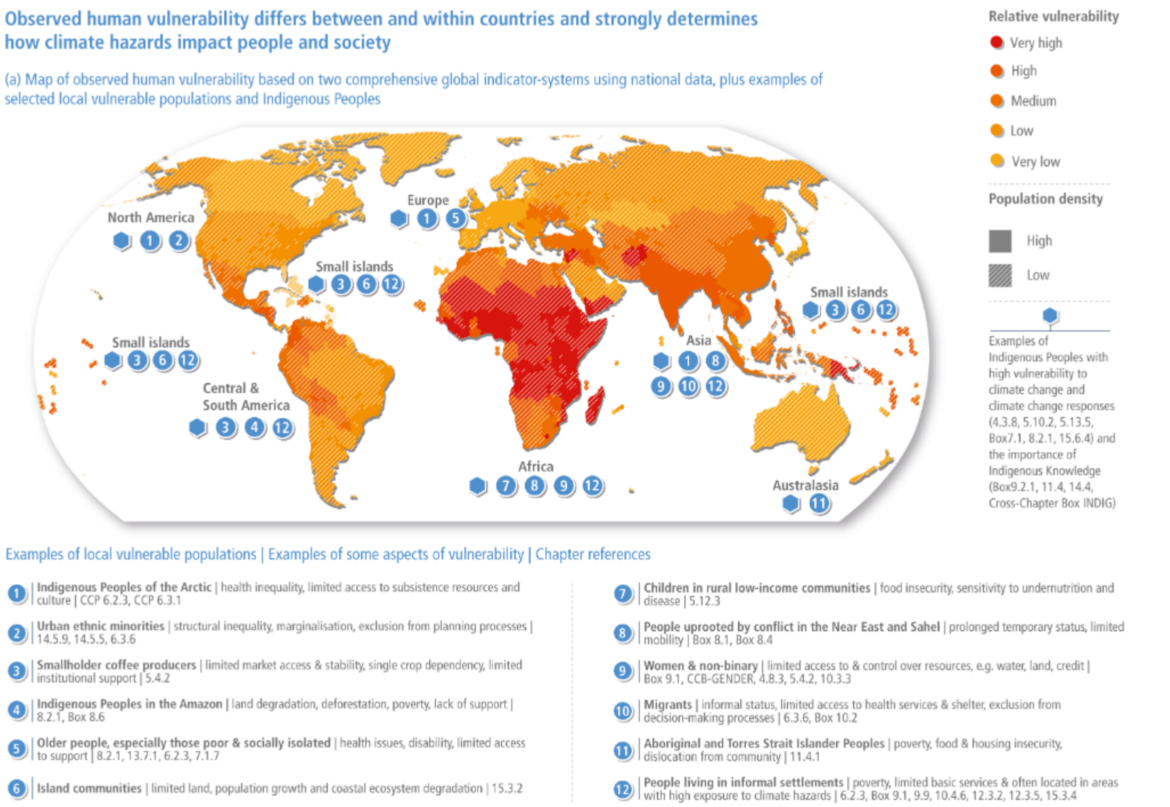
([227]) Abrahms, B. (2021). Human-wildlife conflict under climate change. Science, 373(6554), 484–485. https://doi.org/10.1126/science.abj4216

([228]) Salvatteci, 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.



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. Efitre, A. Gemeda, 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.

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 consequitive 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℃ global warming, all of the listed risks will transition to high, and some become very high at below 2℃ global warming. At 1.5℃ a 9% decline is 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℃ 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.

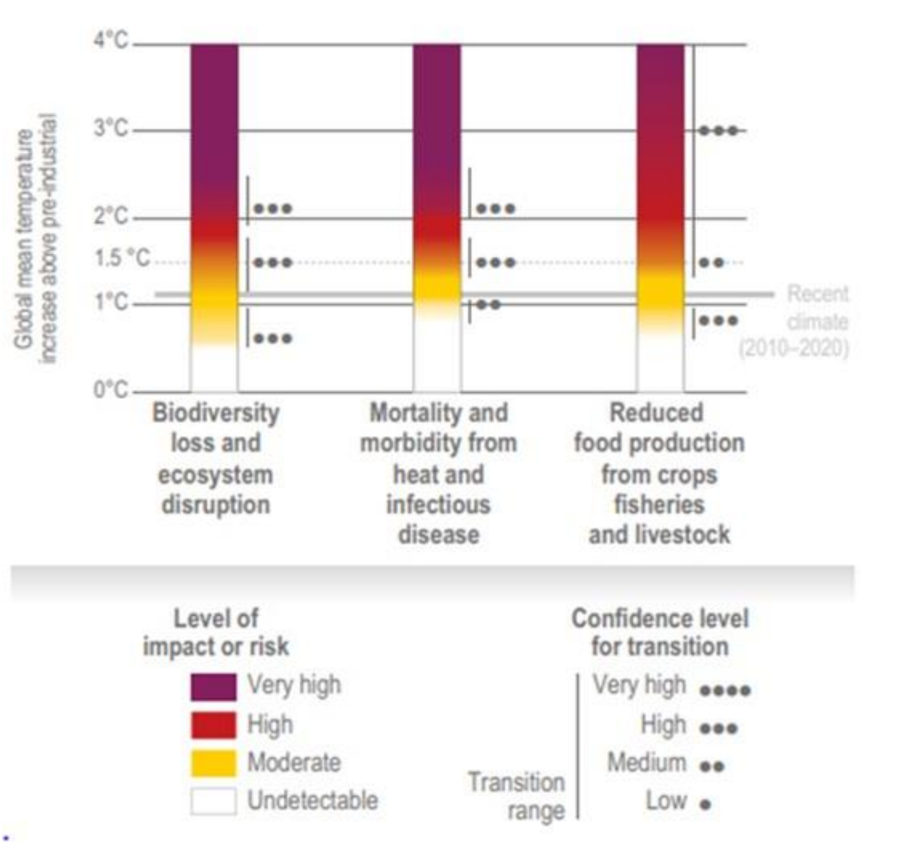
([232]) World Meteorological Organization: State of the Climate in Africa 2021 (WMO-No. 1300). 2022. Chair, Publications Board, WMO, Geneva, Switzerland, ISBN 978-92-63-11300-9

([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. Gemeda, 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℃ global warming 70-90% of reef building corals will be lost and at 2℃ 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). 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-climaxing 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 Sir 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). IBSN: 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., at 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

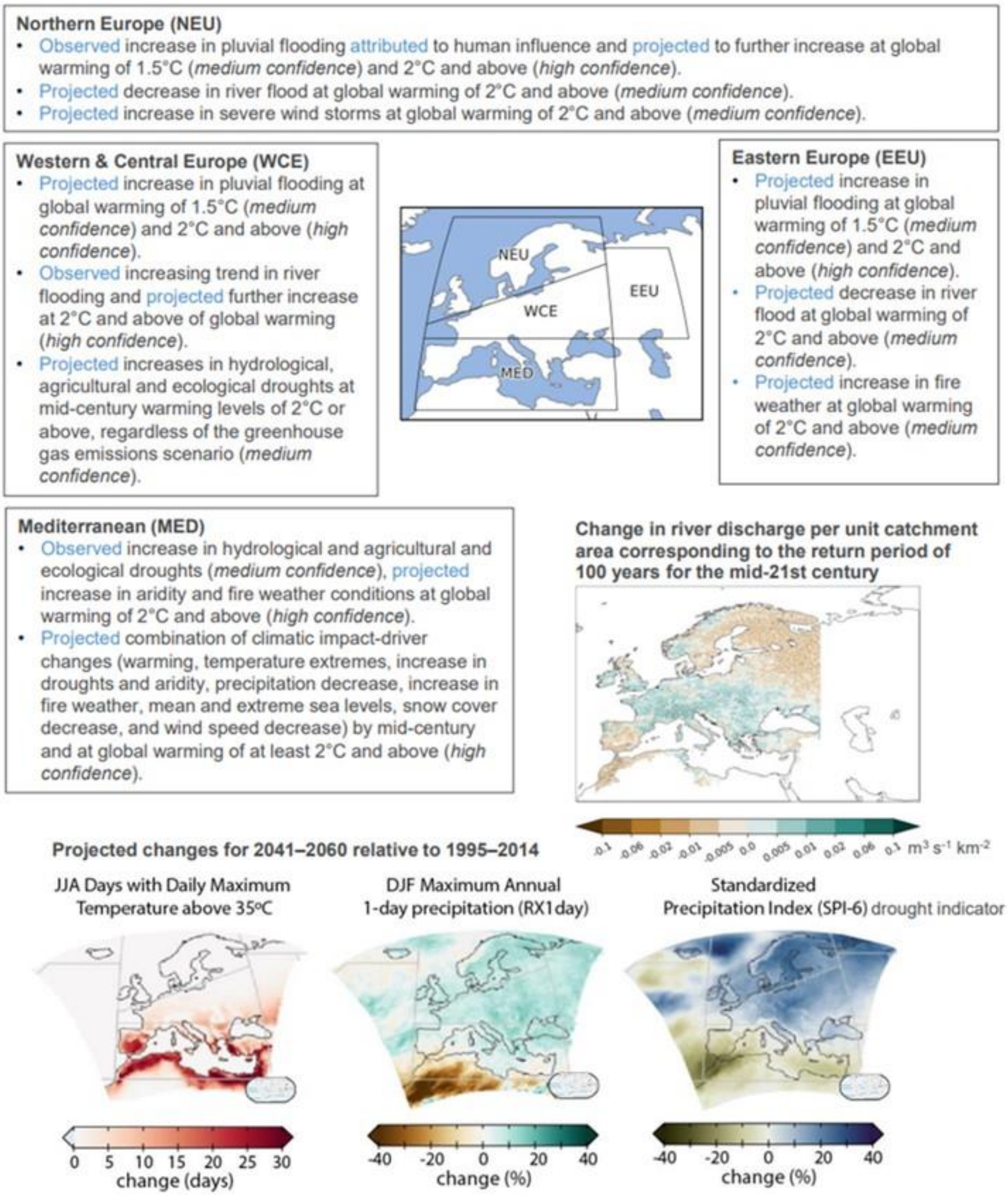
([250]) https://climate.copernicus.eu/global-climate-highlights-2023

([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



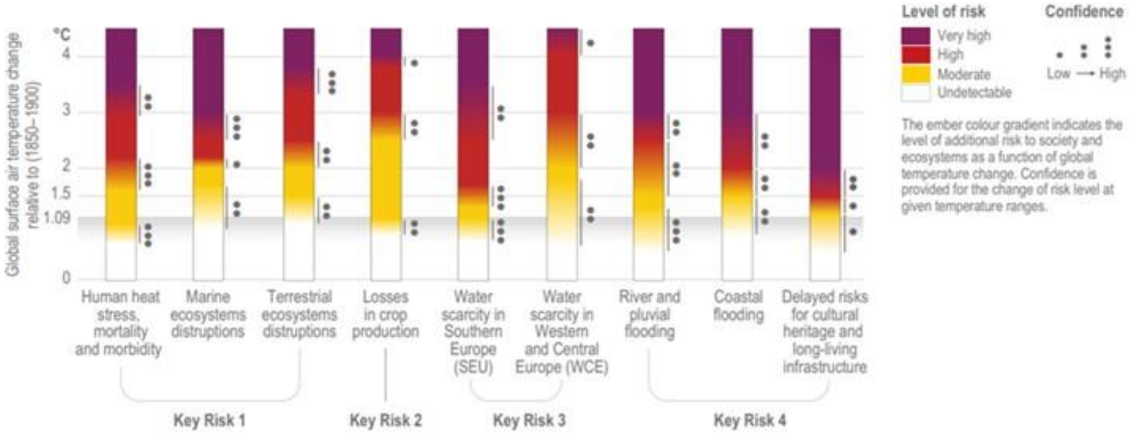
Source: IPCC AR6 WG I (2021): Regional Factsheet Europe

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. 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.

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

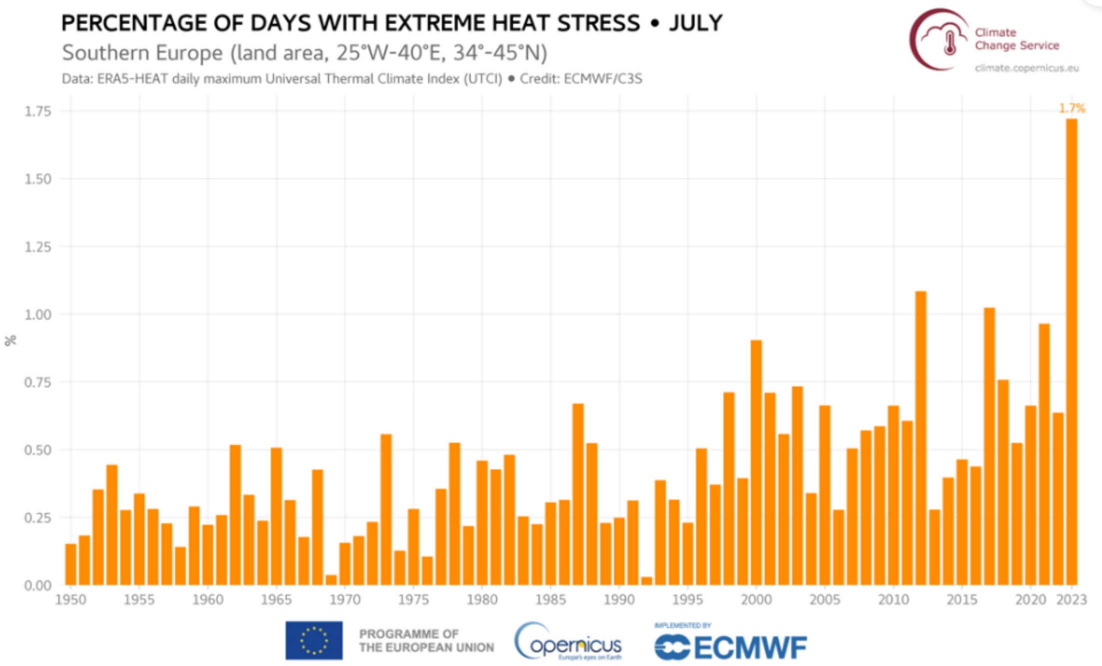
Climate change is already affecting the health and well-being of people in Europe. The record-breaking heatwave in the summer of 2022 resulted more than 60 000 ([255]) fatalities in Europe. The number of days with extreme heat stress has been increasing (Figure 15) and heatvawes are projected to further 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.

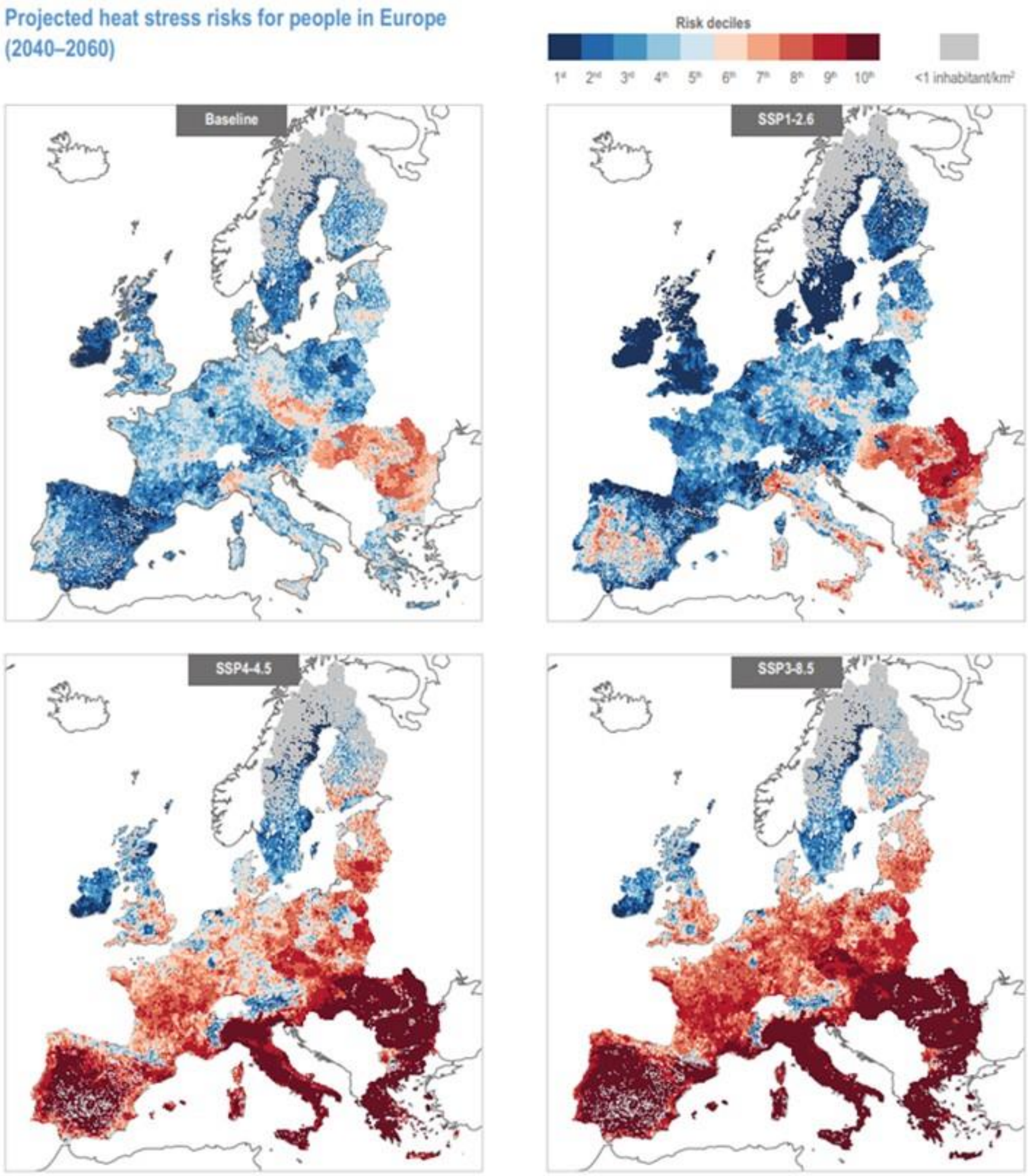
([258]) European Academies' Science Advisory Council, EASAC (2019) The imperative of climate action to protect human health in Europe. EASAC policy report 38.

([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

([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

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 pollutnts 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 PM2.5 ([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 PM2.5 are projected to increase by 73% at 2.5℃ 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. Thick-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

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([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 constrains 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 midlle 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

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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 scaricity ([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]) Khatoon, 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 Rietvels (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 Rietvels. 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.

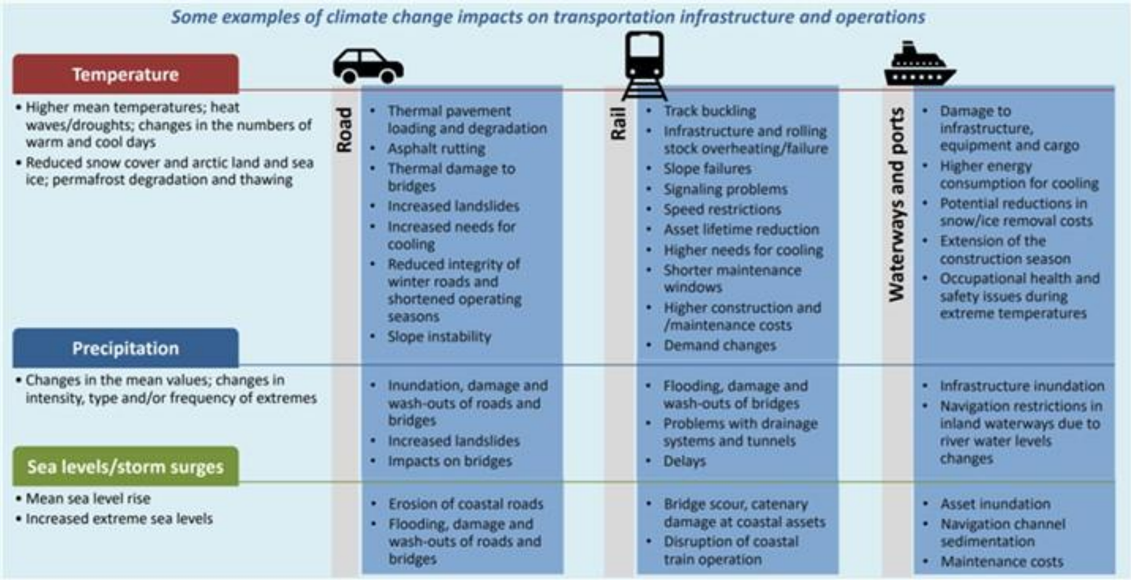
([306]) A. Christodoulou, P. Christidis, B. Bisselink. Forecasting the impacts of climate change on inland waterways. Transportation Research Part D: Transport and Environment; Volume 82, May 2020.

([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. 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

([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



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. 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

([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 CO_2 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, exceserbating 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

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([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. 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.

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 CO_2 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 Communicationn 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

([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 IPPC 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 inset 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.

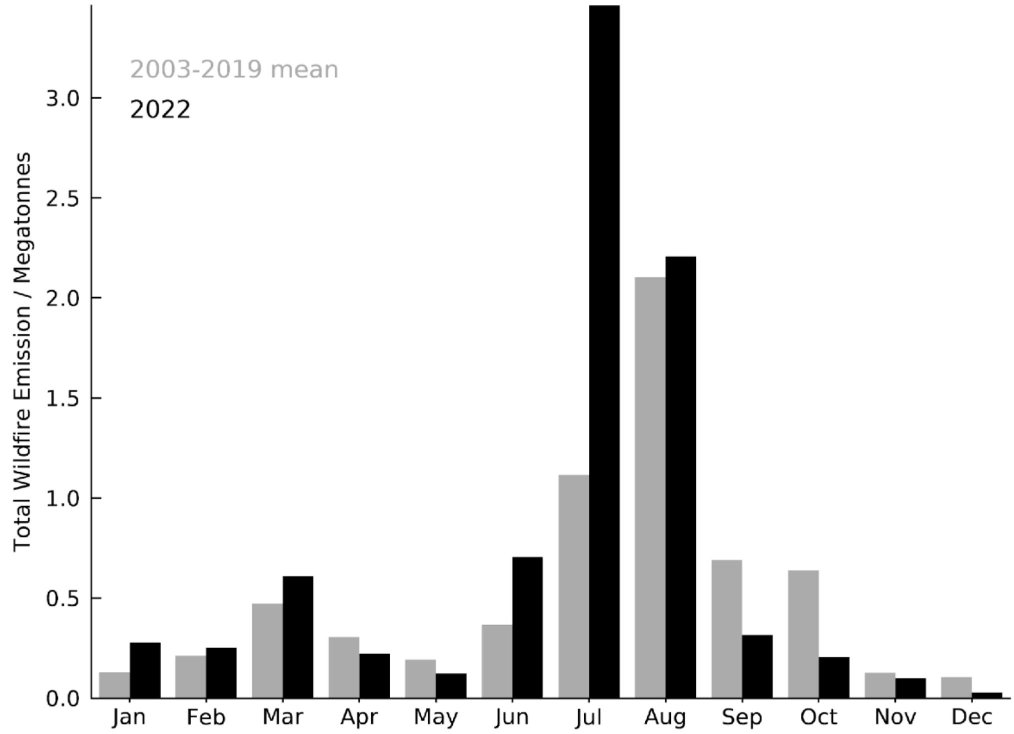
([332]) Sebald, J., Senf, C. and Seidl, R.: Human or natural? Landscape context improves the attribution of forest disturbances mapped from Landsat in Central Europe, Remote Sens. Environ., 262(May), 112502, doi:10.1016/j.rse.2021.112502, 2021.

([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]).

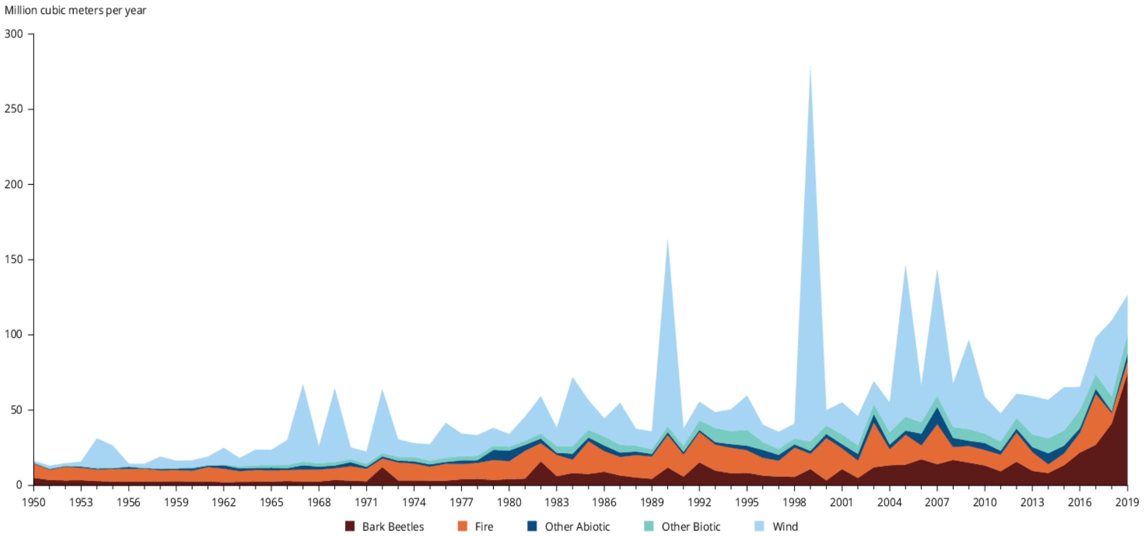
([335])Copernicus (2022) European State of the Climate 2022 https://climate.copernicus.eu/esotc/2022/wildfires

([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.

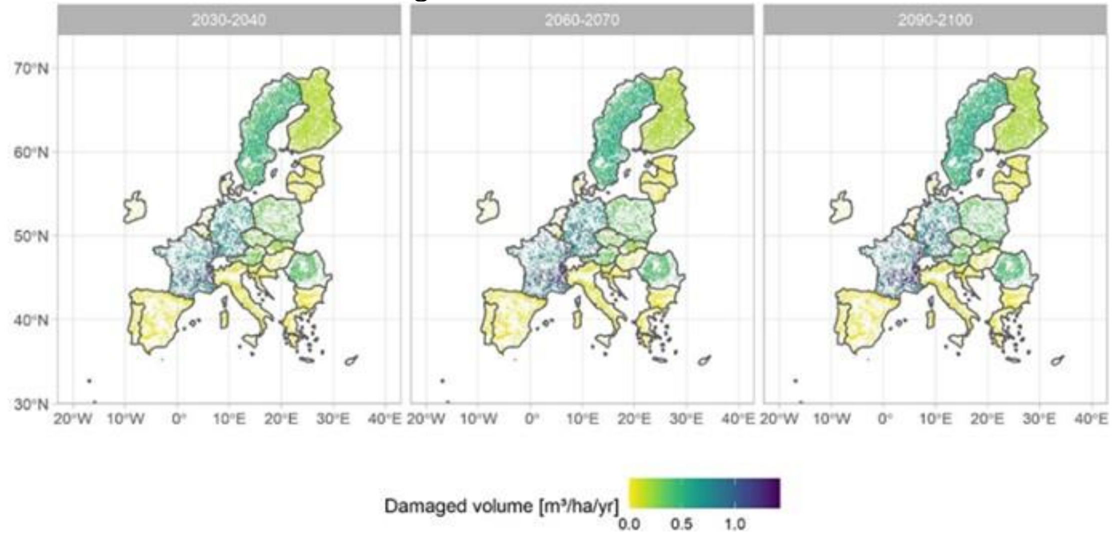
([343]) Martinez del Castillo, E., Zang, C.S., Buras, A. et al. Climate-change-driven growth decline of European beech forests. Commun Biol 5, 163 (2022). https://doi.org/10.1038/s42003-022-03107-3

([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).

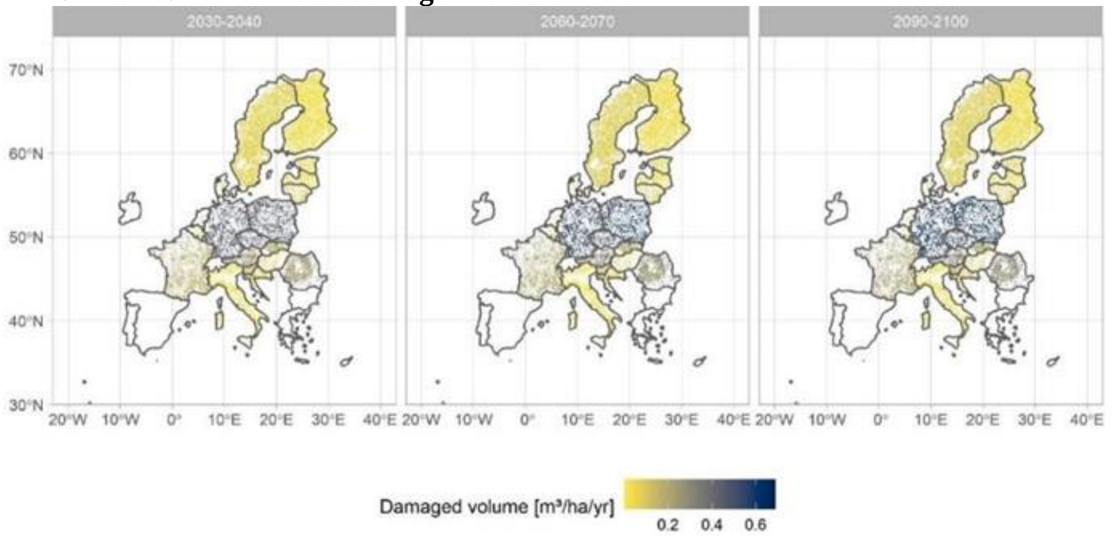
Source: GLOBIOM.

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

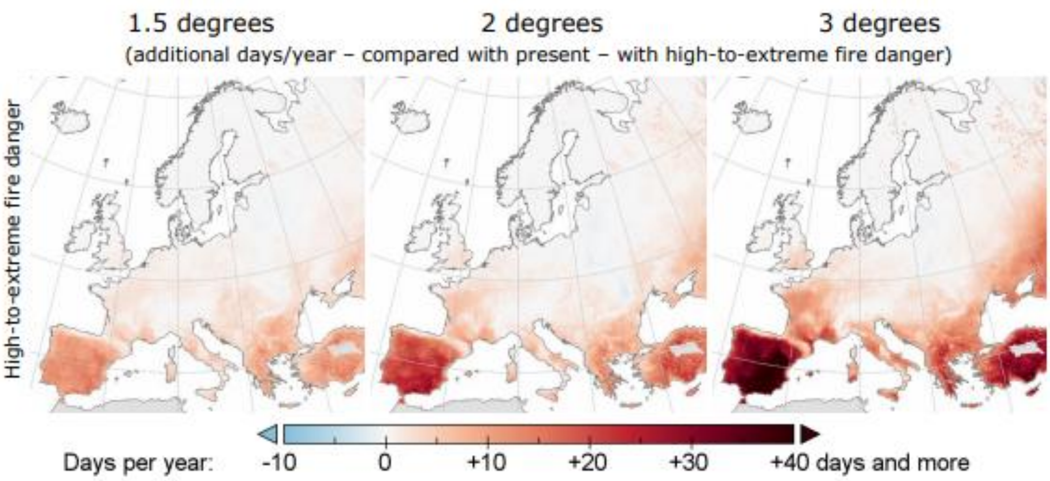


Note: The figure shows the yearly expected damage in m^3/ha/year, caused by insect outbreaks in the EU forest area, as an average over three periods (2030-2040, 2060-2070 and 2090-2100).

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 compare dot pre-industrial times.

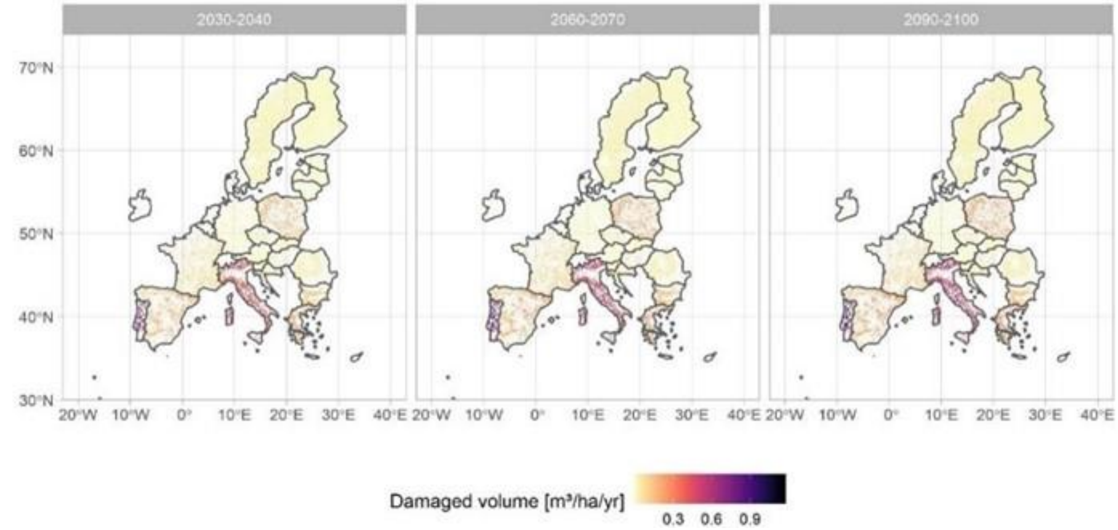
Source: JRC PESETA IV (350)

(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. Lluch-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 CO_2 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 CO_2 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^{o}C global temperature increase, maize yield would decrease by 3% in Northern Europe and 7% in Southern Europe, and under 2.0C 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

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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.

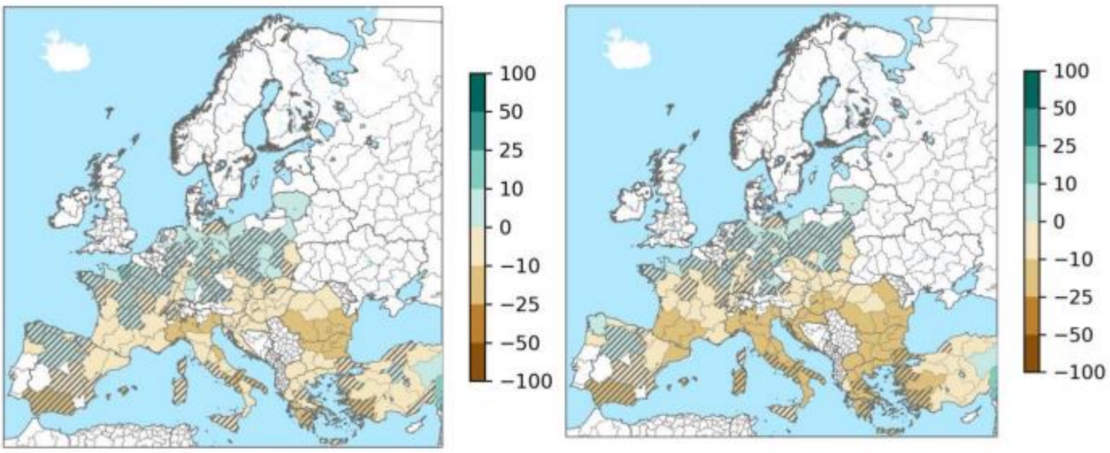
([360]) Stahl et al. 2016

([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., Toreti, 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.

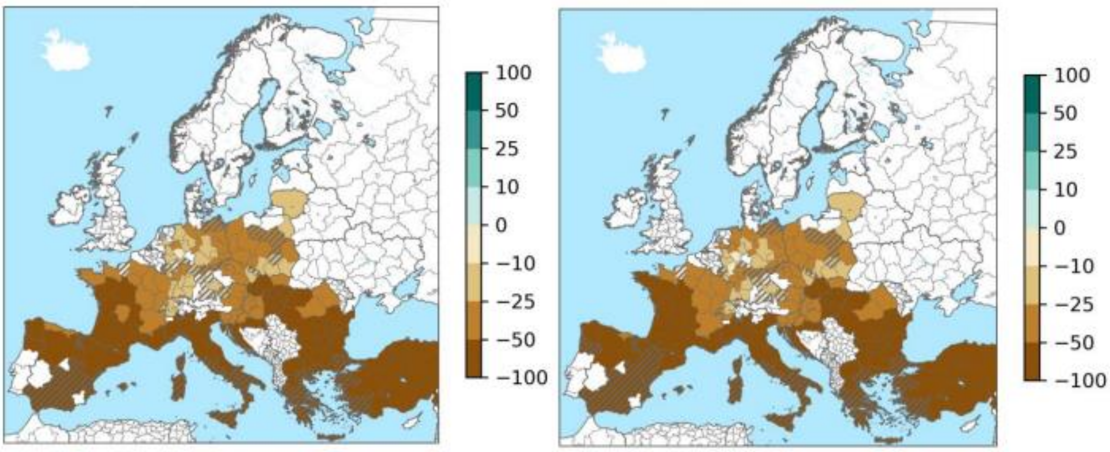
Figure 24: Changes in grain maize yield from Climate Change impacts with irrigation



Note: Graph shows impacts under RCP8.5 for 1.5oC (left panel) and 2oC (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)

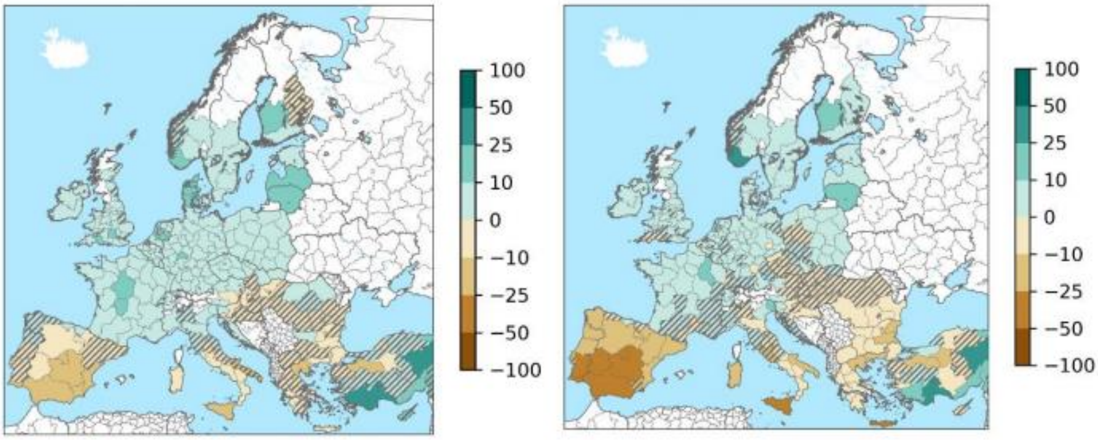
Source: JRC PESETA IV

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 1.5ºC (left panel) and 2ºC (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 1.5ºC global warming, wheat yields could increase by 5% in Northern Europe and decrease by 7% in Southern Europe. At 2ºC 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. 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.

([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 CO_2 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. 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.

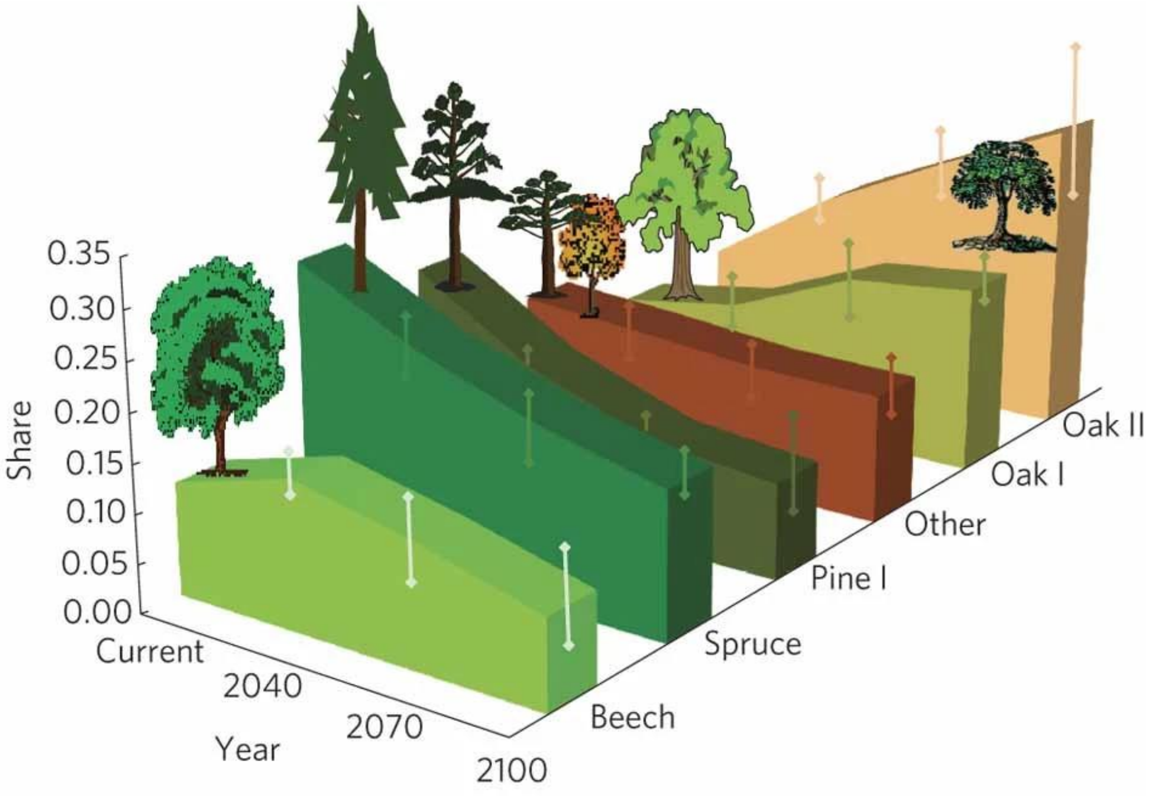
([372]) COPERNICUS, European State of the Climate 2022. European State of the Climate 2022 Summary | Copernicus

([373]) https://wmo.int/files/provisional-state-of-global-climate-2023

([374]) Bednar-Friedl, B., R. Biesbroek, D.N. Schmidt, P. Alexander, K.Y. 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.

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℃ global warming level, while in the Scandes and Alps it would shrink by around 87% and 75%, respectively. At 1.5℃ and 2℃ 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℃ and above 90% at 2℃. 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

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([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, MJ. 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℃ per decade, which is faster than the global rate of 0.23℃ 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℃ and 1℃ 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℃, and reached more than 4℃ 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]).

Iin 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

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([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. Alegría, 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. 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.

([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).

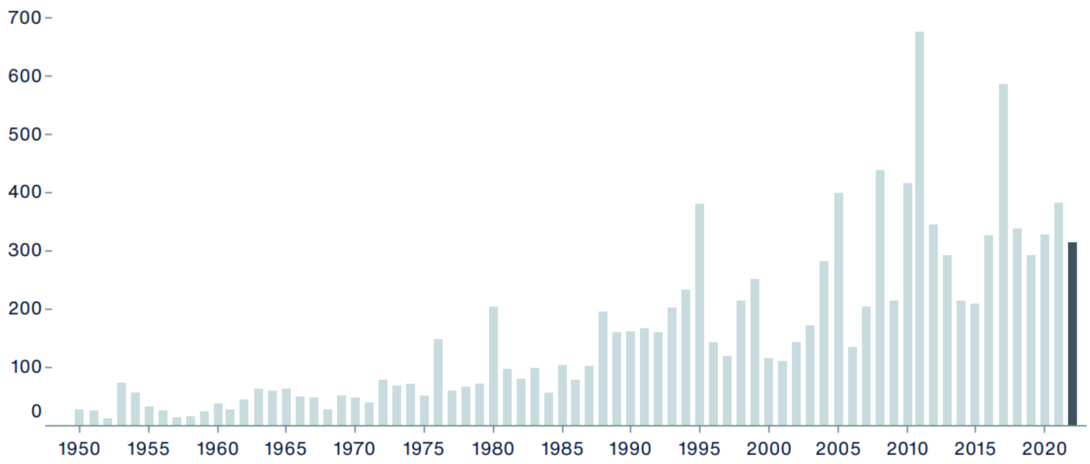
([383]) Costello, M.J., M.M. Vale, W. Kiessling, S. Maharaj, J. Price, and G.H. Talukdar, 2022: Cross-Chapter Paper 1: Biodiversity Hotspots. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel 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

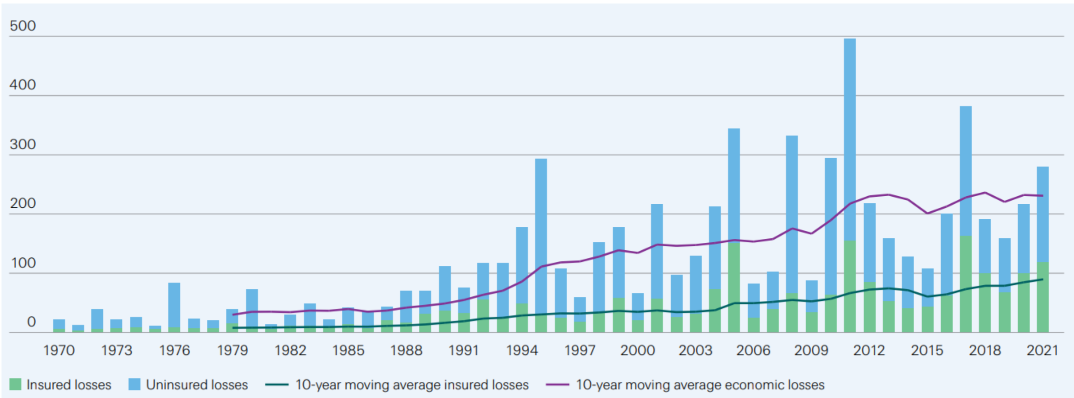


Note: Losses shown in billion US$ 2021

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).

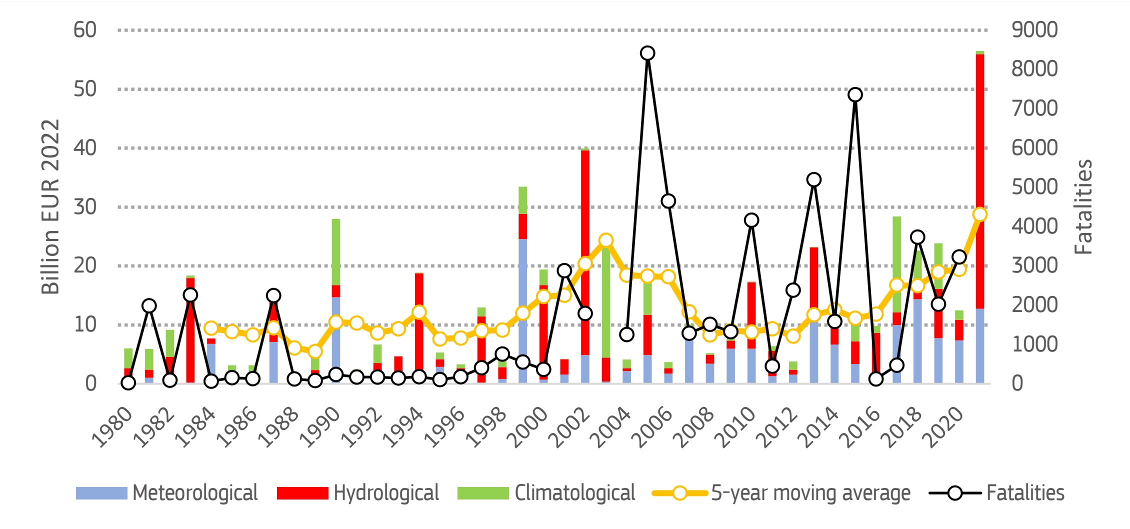
A rising trend in direct economic losses from climate-related events is also observed in the EU, particularly since the beginning of the 2010s. EEA reports that weather- and climate-related extremes caused economic losses estimated at EUR 560 billion in the EU between 1980 and 2021, of which only EUR 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 1.5ºC 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℃ global warming scenario, and 2% of GDP under a well below 2℃ 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).

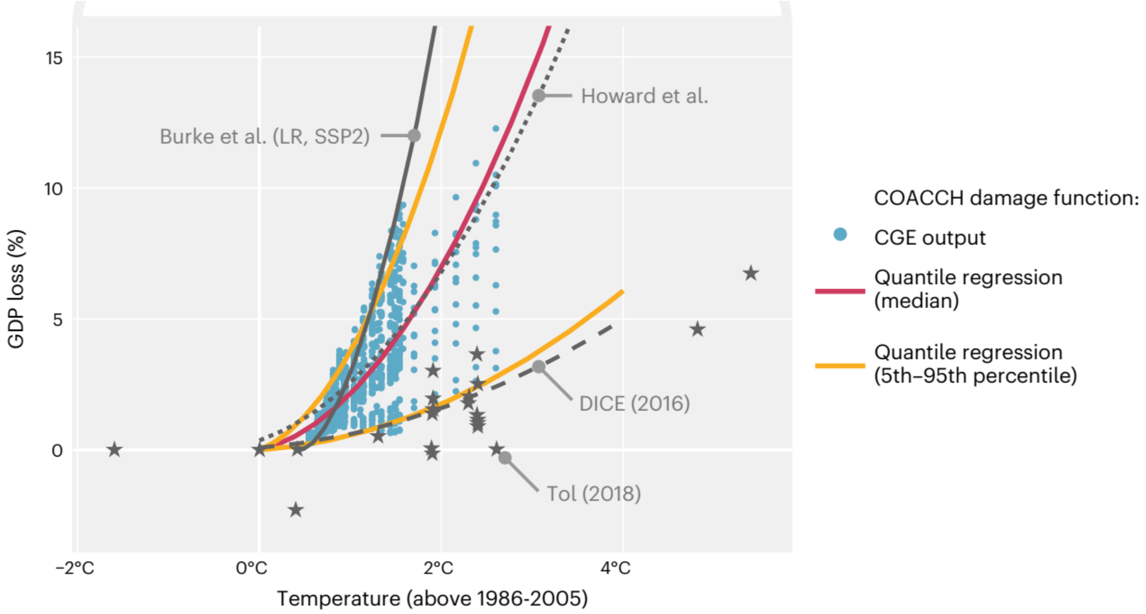
the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T.Maycock, M.Tignor, 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

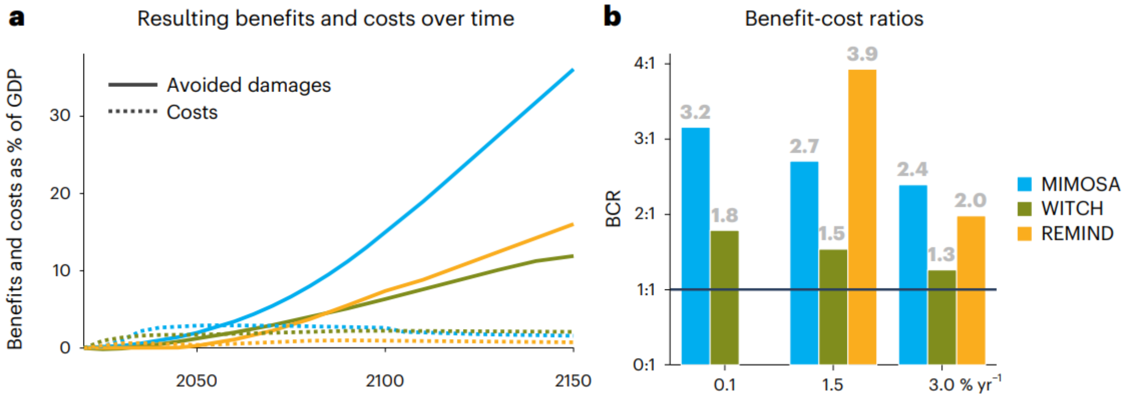
Figure 31: Example of damage functions as used in Integrated Assessment Models



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

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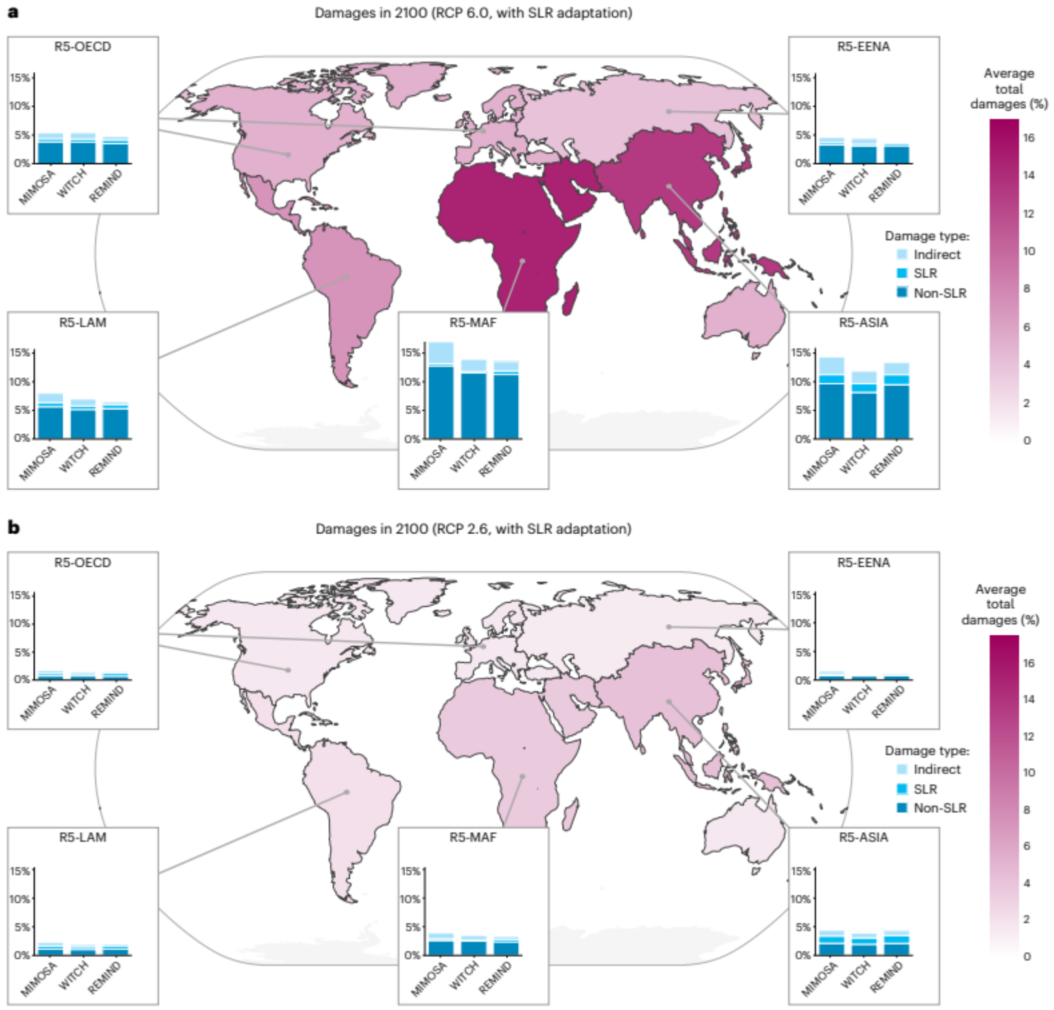
([401]) van der Wijst, KI., Bosello, F., Dasgupta, S. *et al.* New damage curves and multimodel analysis suggest lower optimal temperature. *Nature Climate Change*, **13**, 434–441 (2023). https://doi.org/10.1038/s41558-023-01636-1 impacts on poorer countries and households account for a smaller share 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 3ºC 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 3ºC 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/

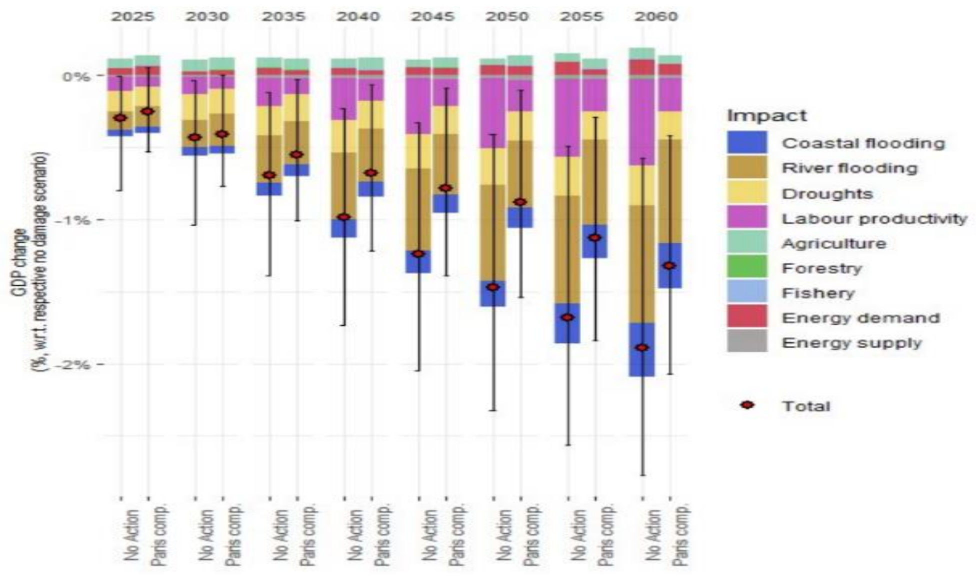
The “climate damage” scenarios assess the 9 types of hazards / sectoral impacts individually and combined. The macro-economic impacts are evaluated in comparison with a baseline where no climate hazards are taken into account. Two damage scenarios were modelled, each with its respective baseline: (1) 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

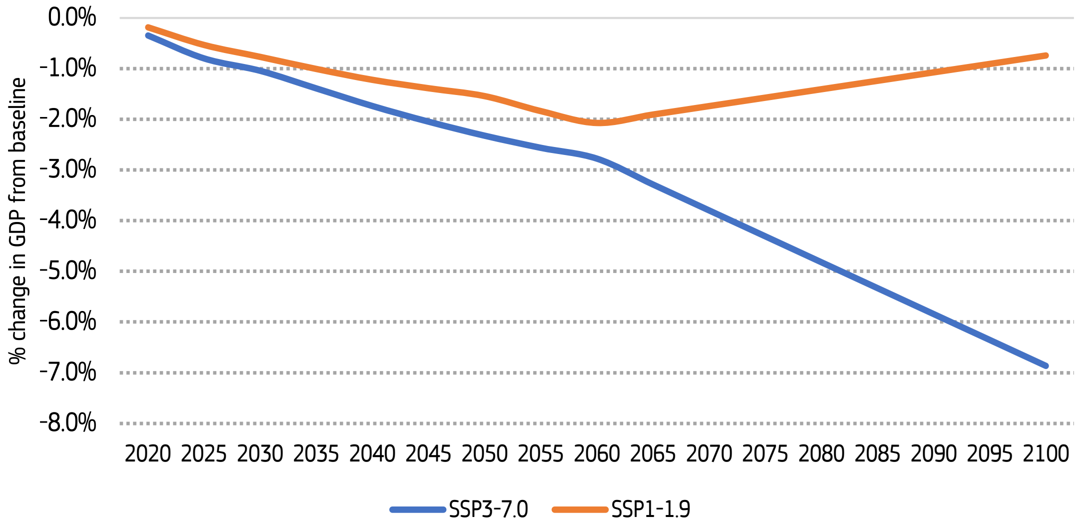
The difference in temperatures between the RCP1.9 and RCP7.0 become stark in the second half of the century: by around 2050, the global temperature increase of the two explored pathways differs only by 0.5°C, while in the subsequent decades that gap significantly increases to about 2.2°C before the end of the century (see Table 6 in this Annex).

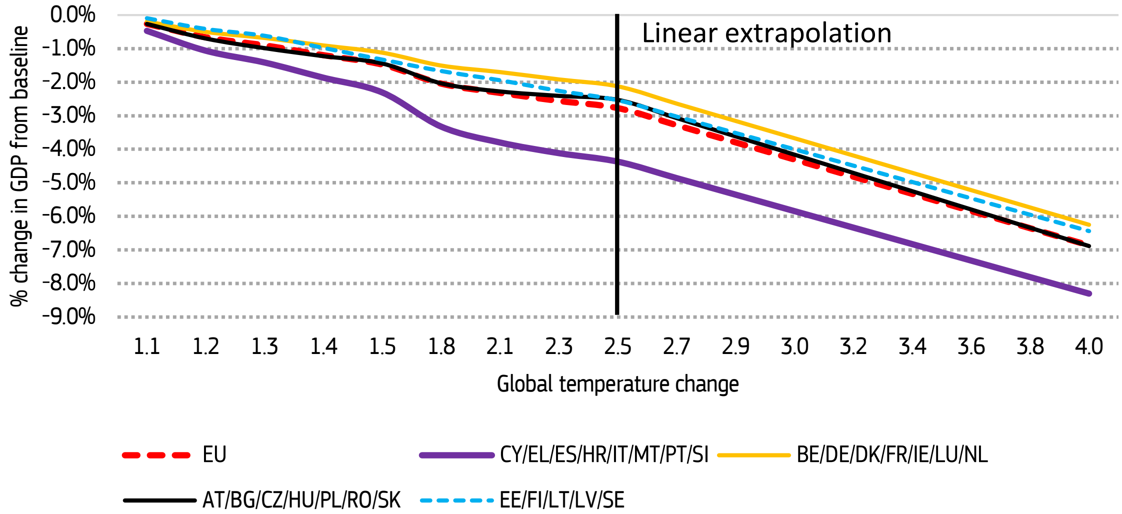
The impact on GDP of such temperature difference was therefore estimated with a simple linear extrapolation of the full modelling results between 2020 and 2060, building on the estimated impacts for given temperature increases between these two points of time in the explored SSPs. This approach thus 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





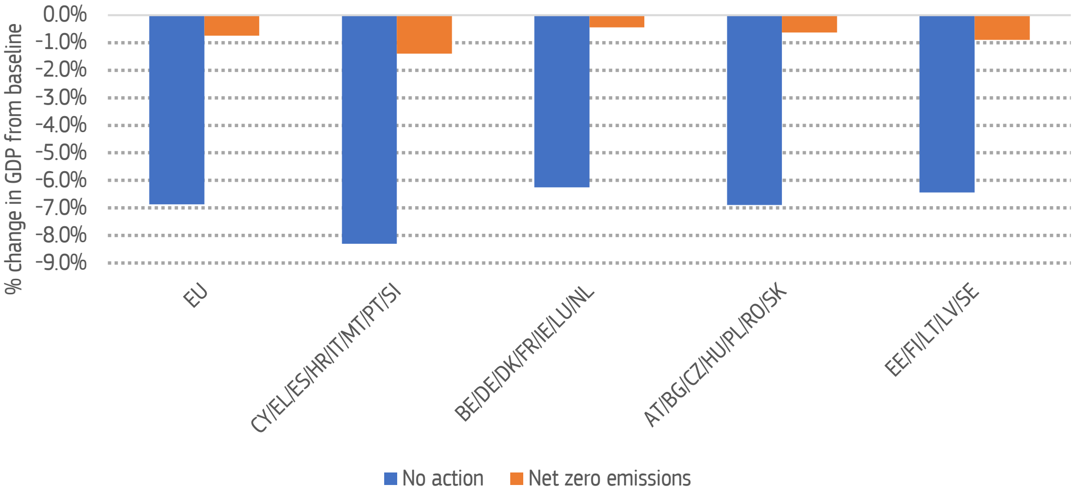
Note: Different shared socioeconomic pathways (SSP) implemented SSP1-1.9 and SSP3-7.0 Upper illustrates the timeline change per SSP, lower illustrates different warming levels per different areas.

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

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([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 Dimitrijevics 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]) Dimitrijevics 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 constrains 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 Ragin ([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 Organizarion. 2022. Small Businesess 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 with 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, manifactouring 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

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([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

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([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.

TABLE OF FIGURES

TABLE OF TABLES