International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Potsdam Institute for Climate Impact Research
PIK

SCENARIOS PROCESSING, VETTING AND FEASIBILITY ASSESSMENT FOR THE EUROPEAN SCIENTIFIC ADVISORY BOARD ON CLIMATE CHANGE

International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Potsdam Institute for Climate Impact Research
PIK

The analysis in this report was carried out in support of the European Scientific Advisory Board on Climate Change (Advisory Board), in the preparations of its advice on the EU 2030–2050 greenhouse gas budget and related emissions targets for 2040. The authors gratefully acknowledge inputs and suggestions received from the Advisory Board and Advisory Board Secretariat that helped frame the analysis and methodologies – in particular Miles Perry, Elsa Malki & François Dejean. All views expressed are those of the authors and not of IIASA, IIASA member organizations, PIK, nor the Advisory Board.

The IIASA authors acknowledge: funding from IIASA and the National Member Organizations that support the institute; and cooperation of the Climate Resource team who maintain the MAGICC climate model emulator that was used in the climate assessment. PIK authors acknowledge support from the German Federal Ministry of Education and Research via the Kopernikus-Project Ariadne (FKZ 03SFK5A). Both IIASA and PIK acknowledge funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101022622 (ECEMF).

Authors

Edward Byers[1], Elina Brutschin[1], Fabio Sferra[1], Gunnar Luderer[2], Daniel Huppmann[1], Jarmo S. Kikstra[1], Robert Pietzcker[2], Renato Rodrigues[2], Keywan Riahi[1]

[1] International Institute for Applied Systems Analysis, Laxenburg, Austria.

[2] Potsdam Institute for Climate Impact Research, Potsdam, Germany.

Queries about the work in this report should be directed to eu-climate-advisory-board-support@iiasa.ac.at .

Date of publication: 14.06.2023

Publisher: International Institute for Applied Systems Analysis, Schlossplatz1, 2361 Laxenburg, Austria

Cover image: Illustrates the recent annual mean surface air temperatures observed in Europe from 1850-2022, generated at www.showyourstripes.info, credit to Prof Ed Hawkins / University of Reading. Data: Berkeley Earth. CC-BY 4.0

Supporting material and citation

If citing, using or building upon the report contents, the database or the code, please cite:

Report: Byers, E., Brutschin, E., Sferra, F., Luderer, G., Huppmann, D., Kikstra, J., Pietzcker, R., Rodrigues, R., & Riahi, K., 2023. Scenarios processing, vetting and feasibility assessment for the European Scientific Advisory Board on Climate Change. International Institute for Applied Systems Analysis, Laxenburg. https://pure.iiasa.ac.at/18828

Database and Scenario Explorer: https://data.ece.iiasa.ac.at/eu-climate-advisory-board/

European Scientific Advisory Board on Climate Change, (2023). Emissions scenario database of the European Scientific Advisory Board on Climate Change, hosted by IIASA (v2.0 [Data set]. Zenodo. https://doi.org/10.5281/zenodo.8035686

The version of the database used in this report was v2.0 and was managed by Daniel Huppmann - metadata and access information for all versions of the database can be accessed at https://doi.org/10.5281/zenodo.7660149

Software code for analysis: The software, configuration, vetting and analysis scripts can be found at the GitHub repository: https://github.com/iiasa/eu-climate-advisory-board-workflow

Related further reading

ESABCC, 2023. Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. European Scientific Advisory Board on Climate Change. https://doi.org/10.2800/609405

Pelz, S., Rogelj, J., & Riahi, K., 2023. Evaluating equity in European climate change mitigation pathways for the EU Scientific Advisory Board on Climate Change. International Institute for Applied Systems Analysis, Laxenburg. https://pure.iiasa.ac.at/18830

Contents

List of Figures

List of tables

Executive summary

The European Climate Law (2021) legislated the targets set out in the European Green Deal of climate neutrality (net-zero GHGs) by 2050 and an intermediate target of 55% reduction by 2030 compared to 1990. Established as part of the European Climate Law in 2021, the European Scientific Advisory Board on Climate Change (Advisory Board), has been tasked with advising the EU on a subsequent intermediate target for 2040, and indicative budgets for EU greenhouse gas emissions for the 2030-2050 period. This advice should also be in line with other international commitments such as the Paris Agreement.

In 2022, via a Call for Scenarios, the Advisory Board invited the wider research community to submit emissions scenario data to support the evidence base for its advice. More than 1100 scenarios were collected and assessed in an emissions scenario database hosted online by IIASA, with thirty additional scenarios from the Potsdam Institute for Climate Impact Research (PIK) to further assist the analysis.

This report, and supporting data and code, aims to transparently document the additional scenario data processing and analysis that has been undertaken to assist the Advisory Board's deliberations. Much of the assessment presented here builds on best-practice methods recently used in the IPCC's latest report, the 6th Assessment Report (AR6).

Overall, the EU Advisory Board Scenarios Database[1] comprises 1062 scenarios from global, regional and national-level integrated assessment and energy system models. A series of data processing and quality control procedures have been undertaken on the database, preserving the original submissions, whilst adding additional post-processed indicators and metadata.

Of the 1062 scenarios with appropriate variable and regional data, 492 successfully passed through a vetting process to assess their quality with respect to recent trends near-term plausibility in emissions and energy supply. Where necessary, scenarios were rescaled for consistency at the EU level, and harmonised to observational estimates of emissions and energy supply in 2019. Scenarios were subsequently also assessed with respect to their climate outcomes, to determine compatibility with global emissions pathways that limit warming to 1.5 °C, as well as compliance with the EU 2030 and 2050 GHG targets.

Lastly, a multi-dimensional feasibility assessment evaluates the geophysical, technological, economic and socio-cultural dimensions of the scenarios to understand where feasibility concerns (and trade-offs) might arise. From 63 scenarios compatible with 1.5 °C and the European Climate

[1] https://data.ece.iiasa.ac.at/eu-climate-advisory-board/

Law, 27 were identified to have relatively high feasibility concerns, especially based on the assumed levels of carbon capture and utilisation in 2050, leaving a set of 36 scenarios that were recommended for further analysis by the Advisory Board.

This report, supporting data and software code, aims to transparently strengthen the evidence base available to the Advisory Board as well as the wider climate research community. Queries about the work in this report can be directed to eu-climate-advisory-board-support@iiasa.ac.at .

1 Introduction

The European Climate Law (2021) legislated the targets set out in the European Green Deal of climate neutrality (net-zero Greenhouse Gas emissions (GHGs)) by 2050 and an intermediate target of 55% reduction by 2030 compared to 1990. The legislation also established the European Scientific Advisory Board on Climate Change (Advisory Board) in 2021 as an independent body of 15 experts to provide the EU with scientific knowledge and advice on climate change. Amongst a number of remits, the Advisory Board has been tasked with advising the EU on a subsequent intermediate GHG reduction target for 2040, and a GHG budget for EU greenhouse gas emissions for the 2030-2050 period. Additionally, this advice should remain consistent other international climate commitments, namely the Paris Agreement and the EU's Nationally Determined Contributions and reporting requirements to the UNFCCC.

In 2022, the Advisory Board invited the wider research community to submit emissions scenario data that can support its work in advising the EU on policy measures, climate targets and greenhouse gas budgets. The call for scenarios[2] was addressed towards research institutions and modelling teams, with a view to collect data of European and national (EU Member State) greenhouse gas emission scenarios.

More than 1100 scenarios were collected and assessed in an emissions scenario database[3], making use of database infrastructure and a Scenario Explorer online interface provided by the International Institute for Applied Systems Analysis (IIASA). Thirty of these scenarios were specifically requested by the Advisory Board from the Potsdam Institute for Climate Impact Research (PIK) to further assist the analysis. A series of data processing and quality control procedures have been undertaken on the database, preserving the original submissions, whilst adding additional post-processed indicators and metadata, now hosted in a public Scenario Explorer and database[4].

This report, and supporting data and code, aims to transparently document the additional scenario data processing and analysis that has been undertaken to assist the Advisory Board's deliberations. Much of the assessment presented here builds on best-practice methods recently used in the Intergovernmental Panel on Climate Change's (IPCC) latest 6th Assessment Report (AR6), Working Group III (WGIII) (IPCC 2022a). The IIASA and PIK both have long-standing experience with creating and assessing emissions scenario data within large research projects such as the Network for Greening the Financial System and international assessments such as the IPCC. The intention of the systematic data processing and analysis has been to establish quality control, add value to

[2] https://www.eea.europa.eu/about-us/climate-advisory-board/call-for-scenario-data-contributions-closed
[3] https://data.ece.iiasa.ac.at/eu-climate-advisory-board-submission
[4] https://data.ece.iiasa.ac.at/eu-climate-advisory-board

the existing data, and provide quantitative assessment of the scenarios along key dimensions of interest to the Advisory Board, including emissions, climate, energy, land use, and *feasibility*. These steps are outlined in Table 1.1 and correspond to the remaining sections of the report.

Table 1.1. EU Advisory Board scenario ensemble processing workflow.

Section	Purpose	Implications for the scenario ensemble
2. The Scenario ensemble	Introduction to the scenario ensemble and database, including additional scenarios added at the request of the Advisory Board.	1094 scenarios successfully submitted during call phase 30 REMIND model scenarios additionally added at request (section 2.2)
3. Scenario assessment workflow	3.1 Introduction to scenario assessment workflows. 3.2 Quality control in terms of the dataset structure and format, and the Baseline and near-term plausibility vetting and filtering 3.3 Classification of scenarios into climate target categories that were developed in IPCC AR6 3.4 Rescaling and Harmonization to 2019 3.5 Selection of 1.5 °C compatible scenarios	1062 scenarios vetted, of which 492 passed Only global scenarios consistent with 1.5 °C (<low overshoot, C1) kept. Scenarios not reporting "EU-27" were downscaled All scenarios were harmonized to 2019 Keep only scenarios consistent with 2030 & 2050 EU targets 63 scenarios remaining
4. Feasibility evaluation	Scenarios were assessed along key variables from feasibility perspective	From a reduced set of 63, 36 scenarios pass the feasibility assessment

2 The scenario ensemble

2.1 Overview of scenarios considered and assessment

Overall, the EU Advisory Board Scenarios Database[5] comprises 1062 scenarios from global, regional and national-level integrated assessment and energy system models. This includes some scenarios from the IPCC AR6 Scenarios Database (Byers et al. 2022), modelling inter-comparison projects and scenarios submitted individually by model teams.

To encourage a wide range of submissions and diversity of evidence, researchers were encouraged to submit as much information and regional resolution as possible, as any material may be useful or could become relevant for the Advisory Board, both within this and future assessments.

All scenarios were assessed for variable and regional coverage. A total of 1124 scenarios were considered in this assessment, comprising 1094 submitted scenarios and 30 additionally solicited scenarios from the PIK REMIND model (section 2.2). After checking the region and variable coverage, 1062 scenarios were assessed through the vetting checks, of which 492 passed. Scenarios were then assessed for consistency with global and EU 1.5 °C climate targets, leaving 63 scenarios that were further evaluated from the feasibility perspective, of which a further 27 were identified to have relatively high feasibility challenges.

2.2 REMIND-EU scenarios

The analysis of the initial set of submitted scenarios showed that most of the pathways that reach climate neutrality in 2050 and deep emission reductions in 2040, feature emissions reductions for 2030 that by far exceed the current target of reducing EU emissions by 55% in 2030 relative to 1990 levels. Given recent developments - including the Covid pandemic and the 2022 energy crisis caused by the Russian invasion of Ukraine - and policy processes, it becomes increasingly unlikely that such deep emission reductions can be achieved in the remaining years until 2030. The scenarios submitted in response to the initial call for submissions do not include pathways with near-term developments until 2030 in line with the Fit-for-55 package, and high ambition towards an accelerated transition to climate neutrality in the 2030-2050 time span.

To fill this gap, 30 additional scenarios from recent research using the REMIND-EU model (Rodrigues et al. 2022) were included in the database and analysis. These scenarios explore high ambition decarbonization pathways for the EU, constrained in the near-term by recent

[5] https://data.ece.iiasa.ac.at/eu-climate-advisory-board/

developments as well as inertia in policy processes and technology development (Rodrigues et al., n.d.). They were calculated using the integrated energy-economy-climate modelling system REMIND (Baumstark et al. 2021) in its version 3.2 and a setup with 21 regions, thereof nine intra-EU subregions. The scenarios were especially refined to better represent a) the development of overall emission reductions over the last decade, b) the recent evolution of performance and market outlooks for key zero-emissions technologies like solar power, wind power, electric vehicles or CCS, and c) the expected effects of recent EU-level climate policy initiatives such as the expansion of carbon pricing beyond the energy and industry sectors, zero-emission vehicle standards through 2035, or key national policies such as coal phase-out plans by various countries.

2.2.1 Scenario description

To explore scenario dimensions most relevant for the definition of the EU decarbonization through mid-century, the assumptions in the scenario analysis are varied along the following three dimensions: (1) the policy stringency, (2) the short-term (pre-2030) flexibility, and (3) limitations on the use of bioenergy.

Climate policy stringency

Under its nationally determined contribution, the EU has committed to reducing emissions by at least 55% relative to 1990 levels by 2030. This target is underpinned by the Fit-for-55 package. The European Green Deal also establishes the objective of reaching greenhouse gas neutrality by 2050. Both the 55% reduction and greenhouse gas neutrality target are enshrined in the EU Climate Law adopted in 2021.

The NZero scenarios reflect the ambition level set by the EU Climate Law targets from 2030 and 2050. In the NZero scenarios, a carbon price level of about 80 €/tCO_2 in 2025, about 140 €/tCO_2 in 2030, rising to 210-260 in 2040 and 290-380 €/tCO_2 in 2050 is consistent with achieving an emission reduction of 55-58% in 2030 and GHG neutrality by 2050. For simplicity, carbon prices are assumed to apply uniformly across sectors.

Based on the reference scenario, three levels of higher climate policy stringency (300, 500, 800) are defined, expressed through exogenous CO_2 price trajectories (Figure 2.1). After EU Green Deal target year 2050, carbon prices are assumed to remain constant at the level achieved until then.

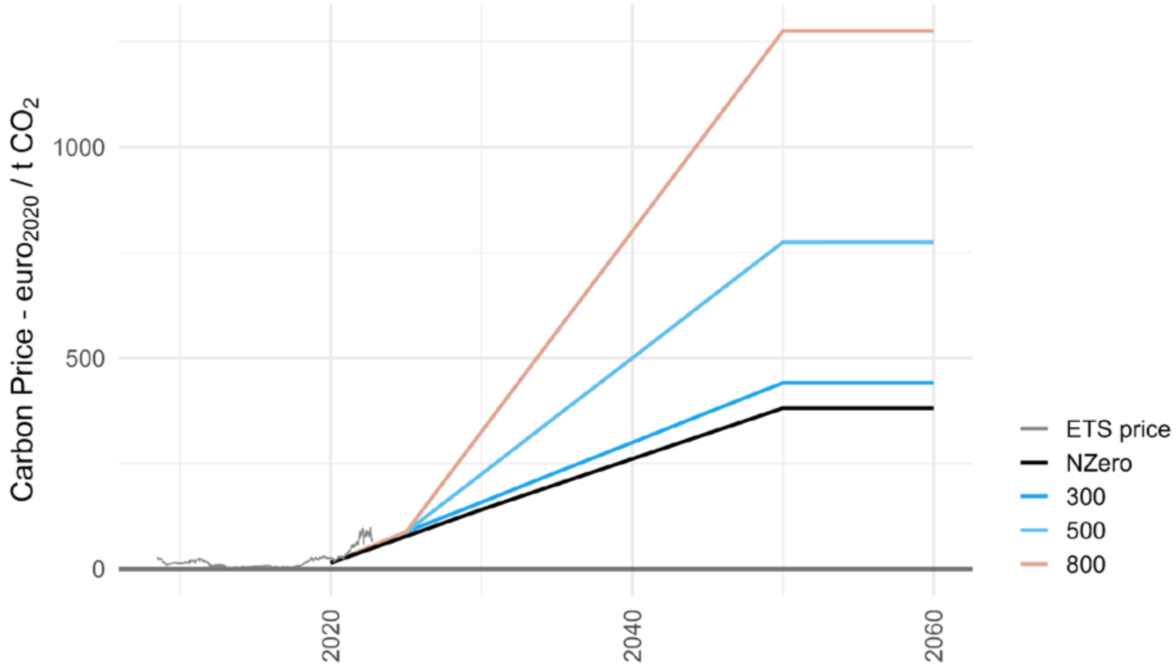

Figure 2.1. Climate policy stringency levels. NZero is the carbon price trajectory resulting from a reference scenario (corresponding to marginal abatement costs). 300, 500, 600, and 800 are exogenous carbon price trajectories used to model higher climate policy stringency.

CO_2 prices are assumed to start from 80 €/tCO_2 in 2025 - around current EU ETS prices and similar to the carbon price level of the NZero scenarios - and to reach 300, 500, or 800 €/tCO_2 in 2040, respectively, with further increases thereafter.

Short-term policy flexibility

The decarbonization progress achieved until 2030 is a crucial determinant of the transformation achievable until 2040 and 2050, as well as remaining cumulative CO_2 emissions from the EU-27. The short-term flexibility relates to the degree of deviation allowed from the reference scenario NZero (climate neutrality in 2050 and at least 55% GHG emissions reduction compared to 1990 levels) until 2030. In addition to NZero, we define 3 cases rigid, default and flex, summarised in Table 2.1.

Table 2.1. Short-term (pre-2030) flexibility levels.

Name	Assumption
NZero	Implementation of EU Green Deal and Fit-for–55 policies under anticipation of target to reach climate neutrality by 2050
rigid	Investments are fixed to reference pathway (NZero) until 2030

default	Limited pre-2030 deviation from reference pathway possible but subject to high adjustment costs
flex	Unlimited deviation from reference pathway before 2030 possible

The rationale behind these cases is (a) that currently agents are in the process of adjusting their investment decisions to the ambitious measures of the Fit-for-55 package that have been implemented in the last months or are in the process of being implemented in the next months, and (b) that there is only very limited scope for policy processes to implement more ambitious policies such as tighter ETS caps, lower ESR targets or tighter efficiency requirements up to 2030 beyond the level that emerged in the negotiations between EU parliament and EU Council about the various parts of the fit-for-55 package.

In the Default scenarios, it is assumed that investments are fixed to NZero pathways until 2025, while investments until 2030 can deviate from the NZero pathways, but such deviation is subject to adjustment costs. These adjustment costs represent that the current NetZero targets already stretch the currently available production capacities for most zero-emission technologies to their limit - thus any change in actual installed technical capacity first requires additional investments into factories and skilled workers that allow to produce and install additional electric vehicles, heat pumps, solar cells or wind turbines. These investments will only be taken after the targets and instruments – whose negotiation took the better part of the last two years – have been renegotiated, and the companies have redone their financial analysis of investment decisions and – after accounting for new subsidies, technological regulations or expected changes in CO_2 prices – have arrived at a different final investment decision than before the policy changes. The extended periods of planning and permitting required for some of these technologies (construction of factories, grid expansion for transmission grids or district heating grids) further slows down any upscaling of ambition.

In the Rigid scenarios, we assume that the transformation and investments do not deviate from the NZero pathways until after 2030. The Flex scenarios, by contrast, explore the most optimistic conceivable scenario in which investments can deviate from the NZero pathways in response to a change in policy ambition already from 2024 onwards.

Biomass availability

The potential for bioenergy in the EU is highly uncertain. To account for these uncertainties, we define three cases, summarised in Table 2.2. The HiBio scenario assumes no explicit bioenergy deployment constraints beyond the agri-economic and land-use limitations assumed in the bioenergy supply curves from the MAgPIE model (Dietrich et al. 2019). These bioLim12 scenario constrains bioenergy use in the EU-27 to 12 EJ, roughly twice the current demand level. The bioenergy deployment levels for 12 EJ roughly match the sustainable biomass potential derived in a bottom-up study (Ruiz 2019) as the medium reference scenario. Similarly, the bioLim7.5 case assumes a 7.5 EJ biomass limit, corresponding to the low scenario in Ruiz et al., reflecting the potential under more stringent sustainability exclusions.

Table 2.2. Three cases to explore uncertainties in the biomass potential for the EU were developed.

Scenario name	Assumption
bioLim7.5	Biomass availability limited to 7.5 EJ/yr
bioLim12	Biomass availability limited to 12 EJ/yr
Hibio	No explicit constraints on biomass beyond land use and sustainability constraints of the default model version

3 Scenario Assessment workflow

3.1 Introduction to scenarios assessment workflow

The need for a scenario assessment workflow arises from the difficulty in compiling and comparing multiple lines of evidence from different sources, in this case data from a variety of different energy systems and integrated assessment models. Over the past two decades, a number of methods, protocols, software and processes for scenarios assessment have been developed by researchers, with evolution through time as well as according to the needs of each assessment and project. Recent literature (Guivarch et al. 2022; Huppmann et al. 2018) has reflected and proposed improvements, as mitigation scenarios assessment plays an increasingly important role not just in scientific assessments like the IPCC, but also in policy and business. Much of this is driven by researchers working with the Integrated Assessment Modelling Consortium (IAMC), with coordination of the Scientific Working Group on Data Protocols and Management, and collaborating in modelling intercomparison projects and IPCC WGIII assessments.

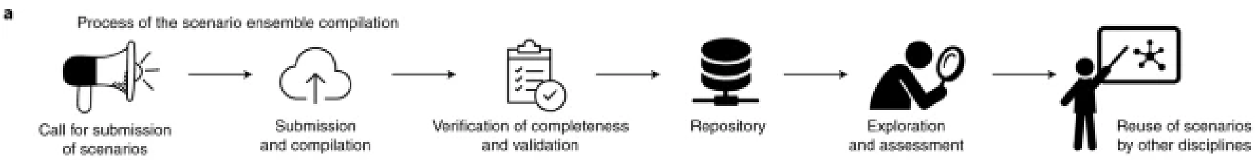

Figure 3.1 Illustration of a scenario workflow, adapted from (Huppmann et al., 2018).

IIASA has been involved in these activities for the past 15 years, developing the infrastructure and software to centrally handle scenario submissions and host online databases. This is supplemented by the open-source software *pyam* to facilitate scenario analysis (Huppmann et al. 2021) and *nomenclature* to handle ensemble structures and definitions, online connections to the databases (via APIs), and front-end web frameworks for data visualisation [6] (e.g. Scenario Explorer, Climate Solutions Explorer). This assessment contains a number of procedures for the scenario ensemble that check the quality through vetting, assess the climate implications and consistency with EU targets, and add value through the calculation of indicators that help assess and identify "iconic pathways". The purpose of this workflow is twofold, i) to curate a refined scenario ensemble of quality and relevance, and ii) to further help identify key scenarios of interest, e.g. *iconic pathways)*, and follows a very similar process as done in IPCC AR6 WGIII Chapter 3 (K. Riahi et al. 2022), for the global emissions and climate assessment, as well as for the selection of *Illustrative Mitigation*

[6] See e.g. https://iiasa.ac.at/scenario-ensembles-and-database-resources; www.climate-solutions-explorer.eu

Pathways (IMPs). The IMPs were high quality scenarios highlighted in the WGIII report with a focus on different strategies for mitigating to 1.5 °C, including low demand, high renewables and electrification, net-negative emissions, and sustainable development.

The workflow for this assessment comprises:

- data import quality control and scenario vetting
- climate assessment of global emissions scenarios
- compatibility with EU GHG targets and a climate assessment of global emissions scenarios
- rescaling of regional data and harmonisation to the baseline year of 2019.

3.2 Data import quality control and scenario vetting

Assessment of the scenarios database required a number of checks on the data quality and consistency of the scenarios. The procedure used in this assessment follows and extends the procedures developed in WGIII during the IPCC WGIII 6th Assessment Report, 2022[7], detailed in Chapter 3 and Annex III (IPCC 2022b; K. Riahi et al. 2022).
The database workflow set up for this work is documented in an open source and version-controlled online repository, and contains information on the model and region definitions, variable definitions, the data import code and the vetting procedure.
Checks that are made include:

- **Submission checks**: upon scenario upload, submitted data is screened for quality control in terms of the file format, structure of the dataset, variable names and units, model and scenario names, time horizon and regional designation. Data not passing these automated checks is not imported into the database.
- **Regional resolution checks:** once imported into the database, scenario data is scanned to assess the regional resolution of submitted data, equivalence to common regions (e.g. EU-27, EU-27&UK), and documentation from model teams on the regional definition of data (e.g. which countries are considered part of model region 'Western Europe")[8].
- **Baseline and near-term plausibility vetting**: the full scenario set is checked against recent baseline data on emissions and energy and near-term plausibility of the scenarios is assessed:

[7] IPCC WGIII Mitigation of Climate Change 2022, Annex III Scenarios and modelling methods.
[8] Variable, model and Regional definitions, and the are specified in the database workflow: https://github.com/iiasa/eu-climate-advisory-board-workflow

- This vetting is done at both the global and European region level and follow generally the same structure, with different values depending on the region.
- All checks are bounded. These are specified either in comparison (e.g. % change) to a reference value, or as absolute values.

Of the initial 1124 scenarios considered, 1062 scenarios from 47 models had either global or European region emissions data and were passed through for the full vetting. Six models[9] with a total of 62 scenarios were not processed further due to lacking relevant information for full vetting and not included in the published database. See Annex tables A1 and A2 for more information.

3.2.1 Reference datasets

Vetting of baseline and near-term plausibility checks requires the preparation of Reference datasets against which to check the scenario submissions. Checks were done against a selection of Emissions and Energy variables for 2019. Although more recent data is available, this includes the effects of COVID, which was not taken into account in the vast majority of scenarios.

Emissions

Emissions checks are based on two datasets:

- the EEA Greenhouse Gas Reporting dataset (EEA 2022)[10] which comprises reported data by EU member states and is used here for EU region vetting.
- the IPCC EDGAR v6 dataset (Minx et al. 2022; 2021), that was used by the IPCC 6th Assessment Report, used here for vetting of global emissions.

The datasets report historical emissions, by sector, gas, and country, using IPCC/UNFCCC conventions. The following variables are checked for 2019:

- CO_2 – Fossil-based carbon dioxide emissions, by country
- CH_4 – Methane emissions, by country

Energy datasets

Primary energy and electricity supply is based on the IEA Energy Statistics (IEA 2022) dataset produced by the International Energy Agency.

[9] RECC 2.4 and OSeMBE v1.0.0, lacked sufficient energy and emissions variables, respectively. ALADIN 1.0 and Roadmap v1.8 are transport sector models, thus also lacking sufficient variable coverage. EnergyVille TIMES BE 1.0.0 and TIMES-Ireland Model v1.0 contained data for only Belgium and Ireland, respectively. See Table A2 in Annex.

[10] National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism 2022.

Additionally, solar and wind electricity generation is checked using the following sources: International Renewable Energy Agency (2023), EMBER (2022) and the IEA.

3.2.2 Global and regional scales

Global vetting

For the baseline checks against the EDGAR and IEA datasets, the reported global scenario data was checked against the same historical reference values for the world region. This scenario vetting procedure is very similar to what was used in the IPCC AR6 WGIII report, albeit with updated values for the IEA (2019) (see Table 3.1 for details).

Europe region vetting

For the baseline checks against the EEA and IEA datasets, the reported regional scenario data was checked against different historical reference values, depending on the model and information about region definitions received from the model team.
Models report data at different regional resolutions, typically "native" and "common" region information.

- **Common reporting available, e.g., to EU-27, EU-27 & UK (EU28)**
    - National reporting, aggregated to a common EU region definition, i.e., 27 countries aggregated to a larger common region,
    - Regional reporting, aggregated to a common EU region definition, e.g., North-EU + South-EU, aggregated to an above common region,
    - In these cases, the reference data was aggregated using the e.g., 27 (or 28) country-level reference datasets for direct comparison to the model-reported data
- **Only native reporting available e.g., "Western Europe"**
    - Regional reporting, to a bespoke (native) European region definition, e.g., "Western Europe". This region would be specified by the model team as comprising countries $x_1 \ldots x_n$, and as being the region most comparable with the EU-27. For a different model, a region even with the same name, might be comprised of a slightly different set of countries.
    - Therefore, for each model and native European region, bespoke reference data for this region would be aggregated from the reference datasets.

Types of checks

Baseline checks – "Key historical" The baseline checks determine whether a scenarios' reporting for key emissions and energy variables corresponds to recently observed best estimates.

Near-term plausibility checks – "Key future" The future checks determine whether some key characteristics of the scenarios are plausible with respect to technological buildout. The intention is to identify highly implausible scenarios, noting that this is not the same as the feasibility assessment of scenarios, which characterises the feasibility of scenarios along multiple dimensions.

Table 3.1. Vetting criteria

	Criteria	Ref value EU-27 [a]	Ref value Global	Key historical or future [b]	If missing	Comments
Emissions, 2019: *EDGAR (Global), EEA (EU-27)*						
CO_2 – Energy & industrial processes (fossil CO_2)	+/- 20%	2896 Mt CO_2/yr	37771	Historical	FAIL	
CO_2 – Energy & industrial processes (fossil CO_2) - % change 2015-2020		+10 to -30%	0 to +20%	Historical	FAIL	Critical variable for reporting. Checks for model trend in emissions. Globally going up, in Europe going down.
CO_2 – Energy (fossil CO_2) - % change 2015-2020		+5 to -30%	-2.5 to +20%	Historical	FAIL	Critical variable for reporting. Checks for model trend in emissions. Globally going up, in Europe going down.
CH_4 (Mt CH_4/yr)	+/- 50%	15.5	363	Historical	Pass missing	Critical GHG in non-CO_2 mitigation strategies
Energy, 2019: *IEA Energy Statistics r2022, IRENA 2022, EMBERS 2022*						
Primary Energy (EJ/yr)	+/- 20%	58	582	Historical	FAIL	Critical variable for reporting

Primary Energy – Nuclear (EJ/yr)	+/- 30%	0.8	10	Historical	Pass missing	Used as check on primary-secondary energy accounting
Secondary Energy Electricity (EJ/yr)	+/- 30%	10.3	97	Historical	FAIL	Critical variable for reporting
Secondary Energy Electricity – Nuclear (EJ/yr)	+/- 30%	2.7	10	Historical	Pass missing	Used as check on primary-secondary accounting
Secondary Energy Electricity – Solar+Wind (EJ/yr)	+/- 50%	1.8	7.6	Historical	Pass missing	Checks that models have the recent growth in renewables well represented.
Emissions: Net negative CO_2		**Permitted range**				
		EU-27 [a]	**Global**			
CO_2 – Energy & industrial processes (fossil CO_2) in 2030	$MtCO_2$/yr	0 to 10000	0 to 80000	Future	Pass missing	
CO_2 – Energy (fossil CO_2) in 2030	$MtCO_2$/yr	0 to 10000	0 to 60000	Future	FAIL	Critical variable for reporting. Checks for implausibly soon net-negative
CO_2 – Carbon sequestration from Energy (incl. BECCS) in 2020	$MtCO_2$/yr	0 to 20	0 to 250	Historical	Pass missing	Checks that scenario has not over-estimated CCS
CO_2 – Carbon sequestration from Energy (incl. BECCS) in 2030	$MtCO_2$/yr	0 to 100	0 to 2000	Future	Pass missing	Checks that near-term scale-up of CCS is plausible.
Low carbon electricity production						

Secondary Energy Electricity – Nuclear in 2030	EJ/yr	0 to 5	0 to 20	Future	Pass missing	Checks that near-term scale-up of nuclear is plausible (max doubling)

Notes:

a - The criteria with absolute values (i.e., not % range) shown in this column are for "EU-27" common region. However, for the models that were checked against their native region values, these absolute values do not apply as bespoke ones would have been calculated, see section 3.2.2.

b - Notes whether a criterion is included in the baseline (Historical) or near-term plausibility (Future) checks.

If missing – this column denotes whether a scenario, which is missing a necessary variable for the check in a particular row, is either flagged as "Pass missing" or "FAIL". E.g. it is deemed acceptable to not report CH_4 emissions, in which case Pass missing is flagged, whereas not reporting CO_2 emissions from the Energy sector leads to a FAIL.

If a scenario is assessed on all checks with either Pass or Pass missing, then the scenario is classified as Pass missing.

3.2.3 Classification of vetting and outcomes

Depending on the outcomes of the Global and Regional vetting, the following table was used to classify the scenarios.

- Failing on either global or regional vetting leads to exclusion (FAIL).
- No global data and Pass missing on region leads to a WARNING
- Pass or Pass missing on both global and regional vetting leads to a PASS.

Scenarios must at least "Pass missing" in the regional assessment for an overall PASS

Table 3.2. Overall classification codes of Global and Regional vetting, including the number of scenarios per classification (bold).

		REGIONAL			
		PASS	Pass missing	FAIL	Europe region not available
GLOBAL	PASS	PASS **409** PASS_G+PASS_R	PASS (2) **12** PASS_G+Pass_missing_R	FAIL **89** PASS_G+FAIL_R	FAIL **23** PASS_G+NA_R
	Pass_missing	PASS **0** Pass_missing_G+PASS_R	PASS (3) **39** Pass_missing_G+Pass_missing_R	FAIL **0** Pass_missing_G+FAIL_R	FAIL **0** Pass_missing_G+NA_R
	FAIL	FAIL **173** FAIL_G+PASS_R	FAIL (4) **24** FAIL_G+Pass_missing_R	FAIL **87** FAIL_G+FAIL_R	FAIL **133** FAIL_G+NA_R
	Global region not available	PASS **12** NA_G+PASS_R	WARNING (4) **20** NA_G+ Pass_missing_R	FAIL **41** NA_G+FAIL_R	Total = 1062

OVERALL PASS/FAIL **#scenarios** Global+Regional code

3.2.4 Results of vetting outcomes

Overall, the number of scenarios passing through the vetting assessment are described in Table 3.3. Of a total 1062 scenarios, 492 passed the vetting and 570 failed. Of the passing scenarios, 460 had global coverage and 32 were for the Europe region only. 156 lacked sufficient regional information[11] to proceed, mostly due to reporting only at the R5 region level (global 5 regions) or only for a single country.

[11] Models needed to report either a commonly defined European region, e.g. EU27, EU27&UK,; the R10Europe region; or have a native model region(s) covering EU27 countries, e.g. "Western Europe"+"Eastern Europe" from which data could be re-scaled.

Table 3.3. Summary table quantifying the reduction of the full scenario set to the candidate pool for further analysis.

Model data available	PASS	Pass_missing	Fail	Total
- **Global+Regional**	409	51	373	833
- **Regional only**	12	20	41	73
- **No Europe region**	(23)	0	133	156
Total assessed	444	71	547	1062
Passing vetting	421	71		
- **Global+Regional**	460			
- **Regional only**	32			
	492		570	1062

3.3 Climate assessment of global scenarios

3.3.1 Overview of the climate assessment workflow

To compare the future global climate change outcomes of long-term mitigation scenarios, a systematic climate assessment is essential to streamline the process of going from emissions information of IAM scenarios into global surface temperatures. All scenarios reporting sufficient greenhouse gas emissions information at the global level were processed through this climate assessment described below. The climate assessment workflow applied for this report follows the same methodology as was used in the Working Group III report of the Sixth Assessment Report (AR6) (IPCC 2022a). The workflow is fully open source and allows for reproducing all climate data in the report (Kikstra, Nicholls, Smith, et al. 2022).

In total, 460 global scenarios passed the vetting, and their temperature outcomes are described in Table 3.4 below. Of these, 86 are in the C1 Category[12], maintaining global mean temperatures in 2100 below 1.5 °C with greater than 50% likelihood and with no or low overshoot. This is the most

[12] See Box SPM1 of the IPCC AR6 WGIII Summary for Policymakers for the full definitions.

ambitious categorisation of scenarios as used in the latest IPCC AR6 WGIII report and used as the basis for further filtering.

3.3.2 Processing emissions pathways

The first step in the workflow, "harmonisation", is to ensure that differences in projected climate change result from differences in future emissions reduction strategies, rather than differences stemming from either past emissions estimates or the extent to which emissions species with minor climatic effects are covered. This increases comparability of scenarios by ensuring they start from the same historical emission levels. Resulting differences in climate outcome are therefore a consequence of future emissions due to structural change in mitigation scenarios rather than different historical emissions estimates or assumptions. The global emissions are harmonised for the year 2015[13], with convergence targets to original emissions data depending on the specific emissions species. Details and methodological background can be found in Gidden et al. (2019; 2018), here following specific harmonisation settings as in Kikstra, Nicholls, Smith, et al. (2022).

The comparability of scenario temperature outcomes is further increased by applying a process known as "infilling". Models differ slightly in the emissions species reported, so this process ensures the same complete set of climatically relevant emissions species are considered by the climate model. Information on the projections of minor emissions species is inferred based on the information provided for other emissions in the scenario. This infilling infers information from the scenario database of the Sixth Assessment Report (Byers et al. 2022; Kikstra, Nicholls, Lewis, et al. 2022). Details and methodological background can be found in Lamboll et al. (2020), here following specific infilling settings as in Kikstra, Nicholls, Smith, et al. (2022).

3.3.3 Climate emulator

Following the emissions harmonisation and infilling, a reduced complexity climate model (also known as a climate emulator) is used to project the physical climate response to emissions. The climate emulator used here is MAGICC (Model for Assessment of Greenhouse gas Induced Climate Change) v7.5.3[14] (Meinshausen, Raper, and Wigley 2011; Nicholls et al. 2022). The Working Group I report of the Sixth Assessment Report (Forster et al. 2021; IPCC 2021) assessed that this climate emulator is fit-for-purpose and endorsed its use in WG III.

MAGICC v7.5.3 represents the atmosphere as four interconnected boxes (northern and southern hemisphere ocean, northern and southern hemisphere land). The ocean boxes are coupled to a 50-

[13] Harmonisation of global emissions was done to 2015, consistent with the assessment in the IPCC AR6, noting that this is different to the harmonisation of the EU27 emissions (and other energy variables), that is performed after the rescaling.
[14] www.magicc.org

layer upwelling-diffusion-entrainment ocean model. The model simulates the change in global mean temperature given a specified evolution of climate-relevant emissions. These emissions include all greenhouse gases (carbon dioxide, methane, nitrous-oxide, and fluorinated gases) as well as aerosols and aerosol precursors like black carbon, organic carbon or sulfur dioxide, and are provided by the IAMs.

Scenarios are assessed in a probabilistic setup as used in IPCC AR6 WGIII (K. Riahi et al. 2022; Kikstra, Nicholls, Smith, et al. 2022), ensuring comparability of the climate outcomes with the latest IPCC report and assessment. For each IAM scenario, the emulator is run 600 times, each with an alternative set of model parameters in a way such that a range of responses consistent with the latest climate sensitivity assessment of the IPCC (Forster et al. 2021) is captured. Information beyond an average, deterministic response only is reported, enabling the exploration of uncertainties in the warming response to emissions, including risks at the higher end of current scientific understanding. For instance, projected temperatures at various percentiles of climate response are reported (at percentiles 5, 10, 16.7, 17, 25, 33, 50, 66, 67, 75, 83, 83.3, 90, and 95) (e.g., AR6 climate diagnostics|Surface Temperature (GSAT)|MAGICCv7.5.3|95.0th Percentile). The setup clearly highlights the possibility and range of future changes in global mean temperature projections as scientific understanding progresses.

3.3.4 Climate outcomes and climate uncertainty

The 460 scenarios with global climate change information have been grouped in seven distinct global warming outcome categories (Table 3.4), which follow IPCC AR6 WGIII (Kikstra, Nicholls, Smith, et al. 2022; K. Riahi et al. 2022). The categorization is based on the median, or best estimate, of the temperature response to any emissions pathway. This means that it estimated that it is equally likely that temperature could be higher or lower than this temperature. The table shows that including such climate uncertainty means that even if a scenario is classified as “C1: Below 1.5°C with no or low OS”, there is a non-negligible chance that peak temperatures cross 2°C of warming above pre-industrial.

Table 3.4. Global mean temperature outcomes and ranges resulting from the scenario set, categorised by global warming levels as used in the IPCC AR6 WGIII report.

Category [# scens.]	Category name	Global mean temperature outcomes median [p5-p95]			
		Scenario range [a]		Climate range [b]	Combined range [c]
		At peak	In 2100	At peak	At peak
C1 [86]	C1: limit warming to 1.5°C (>50%) with no or limited overshoot	1.59 [1.46-1.61]	1.35 [1.16-1.47]	1.59 [1.21-2.14]	1.59 [1.12-2.25]
C2 [59]	C2: return warming to 1.5°C (>50%) after a high overshoot	1.69 [1.62-1.8]	1.42 [1.22-1.48]	1.69 [1.27-2.32]	1.69 [1.23-2.5]
C3 [116]	C3: limit warming to 2°C (>67%)	1.75 [1.63-1.83]	1.62 [1.51-1.74]	1.75 [1.31-2.5]	1.75 [1.17-2.66]
C4 [57]	C4: limit warming to 2°C (>50%)	1.9 [1.84-1.99]	1.8 [1.64-1.99]	1.9 [1.39-2.78]	1.9 [1.25-2.98]
C5 [84]	C5: limit warming to 2.5°C (>50%)	2.14 [2.01-2.4]	2.12 [1.93-2.39]	2.14 [1.52-3.24]	2.14 [1.44-3.58]
C6 [34]	C6: limit warming to 3°C (>50%)	2.66 [2.51-2.93]	2.66 [2.51-2.93]	2.66 [1.85-3.89]	2.66 [1.74-4.35]
C7 [24]	C7: limit warming to 4°C (>50%)	3.37 [3.07-3.89]	3.37 [3.07-3.89]	3.37 [2.45-4.86]	3.37 [2.2-5.49]

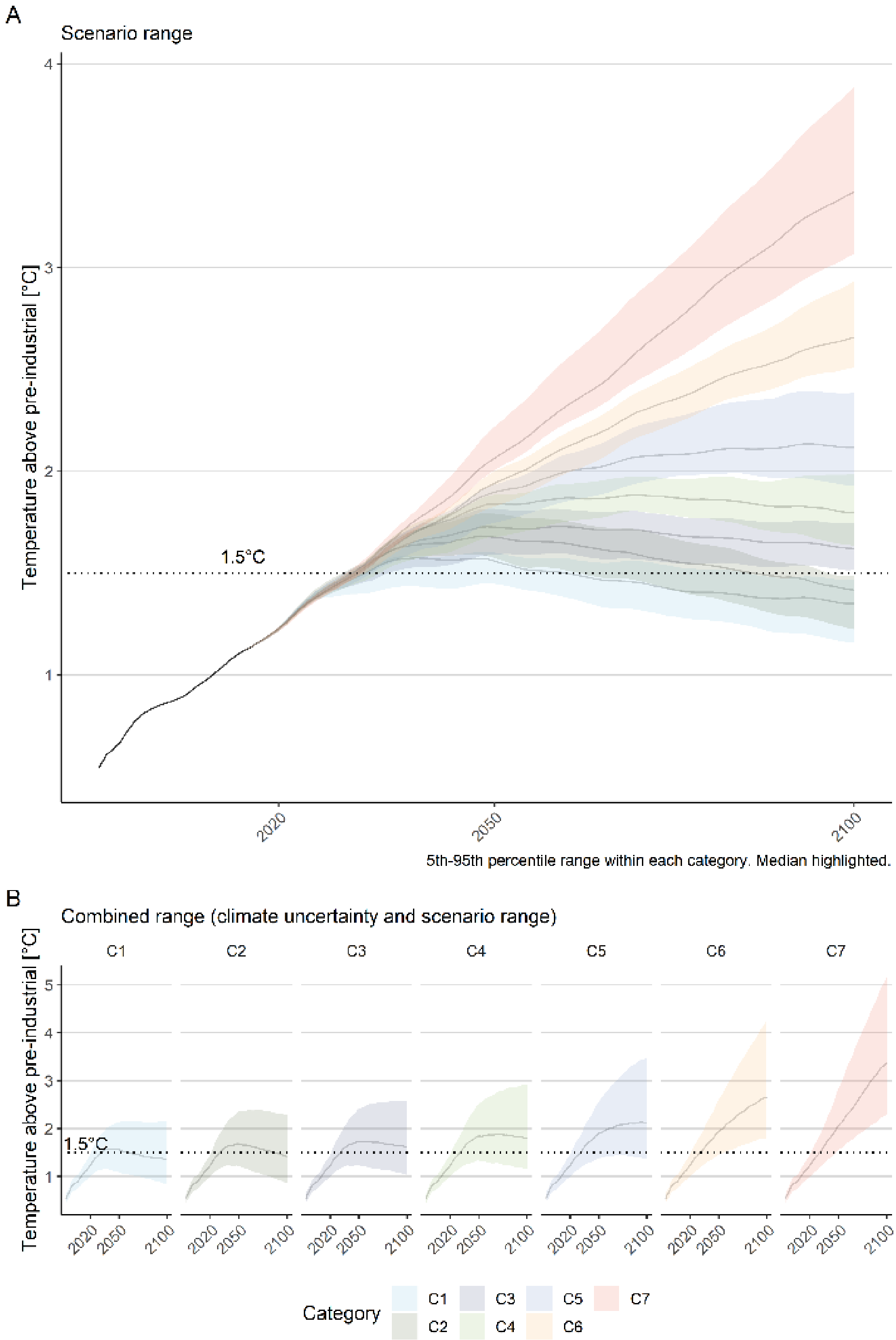

Figure 3.2. Global mean surface air temperatures for the climate categories

3.4 Rescaling and harmonisation of global scenarios

To ensure a high level of consistency and comparability of the scenario data, a process of rescaling and harmonisation was performed. For model scenarios not reported for the EU-27 region, European region results were rescaled to the EU level (EU-27 post-Brexit) by using a rescaling algorithm (Sferra, van Ruijven, and Riahi 2021). The algorithm produces pathways consistent with the regional results, based on a range of criteria including historical data, planned capacities, country-available resources in the form of supply cost-curves, quality of governance as well as regional benchmarks.

Subsequently, results for the EU are harmonised to match historical data, using a base year of 2019. This is done by using either offset or ratio methods, which utilise the difference (ratio) of unharmonized and harmonised results, combined with convergence methods, and converge to the long-term original results at a given point in time (Gidden et al. 2018).

Table 3.5. Scenario variables which were harmonised, summarising the method, convergence time and historical data sources.

Variable	Harmonisation method	Time of convergence
Emissions	Historical data source: EEA (2022)	
Emissions|CO2|Energy	offset	2050
Emissions|LULUCF (Land Use Land Use Change and Forestry)	offset	None (constant offset over time)
Emissions|Total Non-CO2	offset	2050
Energy	Historical data source: IEA (2022)	
Primary energy (by fuel)	ratio	2050
Secondary energy (by fuel)	ratio	2050

Total Kyoto GHG emissions are calculated (including indirect LULUCF emissions) using an AR4 GWP-100 metric (in line with the EEA historical data and official document submitted to the UNFCCC) as the sum of:

- Emissions|CO2|Energy
- Emissions|CO2|Industrial Processes
- Emissions|CO2|LULUCF Direct+Indirect
- Emissions|Total Non-CO2

Table 3.6. Description of the emissions variables considered in consistently calculating GHGs across the scenario set.

IAM Variable	IAM Description
Emissions|CO2|Energy	CO_2 emissions from energy use on supply and demand side (IPCC category 1A, 1B)
Emissions|CO2|Industrial Processes	CO_2 emissions from industrial processes (IPCC categories 2A, B, C, E)
Emissions|CO2|LULUCF Direct+Indirect [1]	CO_2 emissions from agriculture, forestry and other land use (IPCC category 3) + Net LULUCF CO_2 flux|Indirect
Emissions|Total Non-CO2	This variable is calculated as the difference between Kyoto Gases and CO_2 emissions from energy use on supply and demand side (IPCC category 1A, 1B), from industrial processes (IPCC categories 2A, B, C, E) and from agriculture, forestry and other land use (IPCC category 3)
Emissions|Kyoto gases (incl. Indirect AFOLU) [2]	Kyoto gases (including Indirect AFOLU CO_2)

Notes:
[1] This variable is harmonised to match historical emission inventories from EEA (including net LULUCF Indirect CO_2 flux).
[2] This variable is assumed to be equivalent to `Total Net Emissions (UNFCCC)` reported by the EEA, as in Table x below.

We align Kyoto GHG emissions with historical national inventories, which include indirect LULUCF emissions (Grassi et al. 2021). Therefore, LULUCF emissions are harmonised with the historical EEA data by using a constant offset over time. Carbon budget and emissions targets are calculated for each country and for the EU-27 using an AR4 GWP-100 metric.

Table 3.7. from the EEA (European Energy Agency greenhouse gas - data viewer) illustrates the different components included in the different aggregations of total gross and net greenhouse gas emissions. Reproduced from EEA (EEA 2021)).

	Energy, IPPU, agriculture, waste, indirect CO_2	LULUCF	International aviation	International navigation
Total Emissions (UNFCCC)	✓			
Total emissions with international aviation (EU 2020)	✓		✓	
Total emissions with international transport (EEA)	✓		✓	✓
Total net emissions (UNFCCC)	✓	✓		
Total net emissions with international aviation (EU NDC)	✓	✓	✓	
Total net emissions with international transport (EEA)	✓	✓	✓	✓

3.5 Assessment and selection of 1.5 °C climate compatible scenarios

To assist the Advisory Board in its assessment, more than 200 quantitative indicators were systematically calculated across the 63 scenarios to enable consistent comparison of the scenarios across a number of dimensions. Initially, these indicators help assess compatibility with EU climate targets. Additionally, they can reveal key dynamics and outcomes of the scenarios and their relation to assumptions regarding policy, economics, technology, environmental, climate and societal change.

3.5.1 Compatibility with EU climate targets

To assess compatibility with EU climate targets, consistent comparison was facilitated by the climate assessment of global scenarios (section 3.3) and harmonisation of scenario GHG emissions data (section 3.4).

All vetted scenarios (492) were assessed for compatibility with EU climate targets and commitments under the Paris Agreement, summarised in Table 3.8.

- All scenarios with global data were assessed for consistency with the IPCC AR6 WGIII C1 Category, of keeping global warming below 1.5 °C in 2100 (>50% likelihood) with no or low overshoot. Of 460 global emissions scenarios, 86 were found to be in the C1 Category (section 3.3.4), of which 83 were rescaled and harmonised.
- Eighty-three global C1 scenarios and 3 regional scenarios reported sufficient variables and information for complete rescaling and harmonisation, whilst thirty scenarios were unable to be rescaled correctly due to lack of reported variables (Table 3.8).
- This 86 were assessed for compatibility with a 55% reduction from 1990 levels in 2030[15] and net-zero[16] GHGs in 2050, in line with the EU 2050 long-term strategy_(European Commission 2020). Of the 86, 77 and 71 were found to be compliant with the 2030 and 2050 targets, respectively, with 63 complying with both targets and thus remaining for the Feasibility Assessment (Figure 3.3).

[15] Value for 1990 (Mt CO_2-equiv/yr): 4790.123 -99.40 (4790 is Total net emissions with international transport, source EEA; from which we subtract 99.4 of extra-EU international transport). To calculate the % change in 2030 we used the variable 'GHG incl. International transport (intra-EU only)' divided by the 1990 value.

[16] Scenarios with less than or equal to 300 Mt CO_2-equiv/yr, to take into account uncertainties and modelling artefacts.

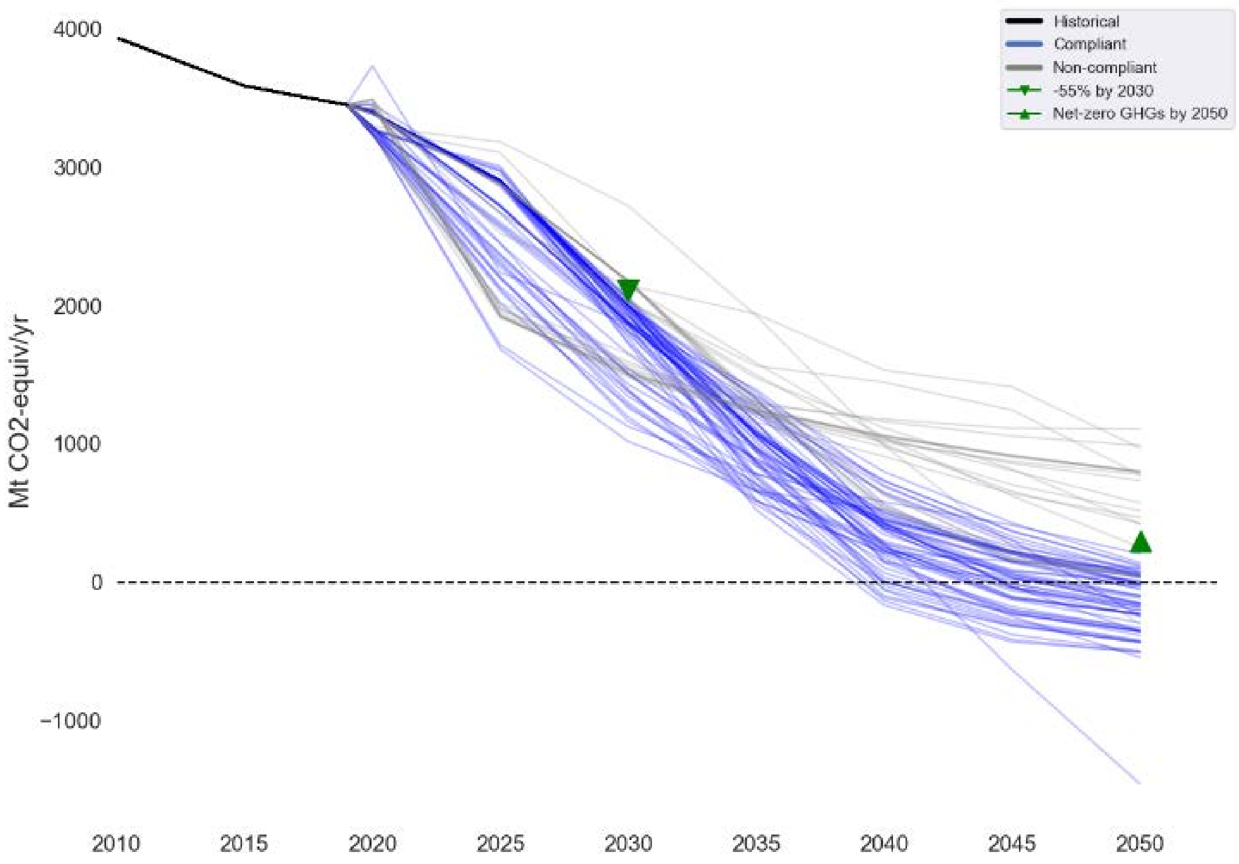

Figure 3.3. Net greenhouse gas emissions including intra-EU bunkers for the 86 pathways, of which 63 were compliant with the 2030 and 2050 targets.

Table 3.8. Summary table indicating how scenarios were assessed for compatibility with EU climate and emissions targets.

	492 vetted scenarios from Table 3.3			
Climate & emissions	**Pass**	Fail	**NA**	Total
- **C1 <1.5 °C scenarios** [a]	86	374	32 [b]	492
- **Rescaling and harmonisation** [c]	83+3	27+3 [d]	2 [e]	118
- **2030 GHGs ≥ 55% reduction**	77	9		86
- **2050 GHGs ≤ 300 Mt CO_2-equiv/yr**	71	15		
Scenarios remaining	**63**	23 [f]		

Notes

a - Scenarios categorised in the climate assessment to be in “C1” Category, i.e., end of century warming below 1.5 °C with a >50% likelihood and no or low overshoot.

b - 32 regional scenarios without climate assessment from 5 models E4SMA-EU-TIMES, GEMINI-E3, GCAM-PR, NEMESIS, PRIMES).

c – Number of global + regional scenarios passing/failing the rescaling and harmonisation.

d – 27 (of 32 above) scenarios unable to rescale to EU-27 due to missing variables (E4SMA-EU-TIMES, GEMINI-E3, NEMESIS, PRIMES), thus here not considered further.

e – Two GCAM-PR scenarios not rescaled because are by definition Current Policies scenarios.

f - One scenario fails both criteria, hence 23 not 24.

3.5.2 Quantitative assessment of emissions, climate, and energy

To assess the 63 scenarios, more than 120 quantitative indicators were calculated across dimensions including emissions, climate, energy and trade, summarised in Table 3.9 and some of which shown in Figure 3.4-Figure 3.8. Further analysis of the indicators is available from the code in the GitHub workflow.

Table 3.9. Summary of indicators calculated for the final 63 scenarios.

Variables	Time ranges
Year of net-zero emissions	
GHGs, net CO_2	-
Cumulative emissions	
CO_2, CO_2-FFI, CO_2 AFOLU, non-CO_2, CCS, BECCS, GHGs,	2020 to year of net-zero CO_2, 2020-2030, 2020-2050, 2030-2050
Emissions reductions	
GHGs, non-CO_2	1990-2020, 1990-2025, 1990-2030, 1990-2035, 1990-2040, 1990-2050, 2019-2030, 2019-2035, 2019-2040, 2019-2050,
Emissions in year	
CO_2, GHGs, non-CO_2, CCUS (including DACCS), CCS, BECCS, CCS-FFI, CCS-Industry, EU share of World Emissions|CO_2, EU share of World Emissions|GHGs,	Year of net-zero CO_2, 2020, 2030, 2050
Energy & trade	
Primary energy Primary energy total Biomass Renewables (incl.Biomass) Non-biomass renewables Fossil Fossil|w/o CCS Secondary energy electricity production Secondary energy electricity total Renewables (incl.Biomass) Non-Biomass Renewables Hydrogen production|Final Energy Final Energy Final Energy total Electrification Industry|Fossil Residential and Commercial Transportation Trade and imports Primary Energy import dependency Primary Energy import dependency|Fossil Trade Trade|Fossil Trade|Primary Energy|Fossil	Year of net-zero CO_2, 2050
Climate	
Category, Global mean temperatures, peak temperatures, year of peak temperature, exceedance probability	

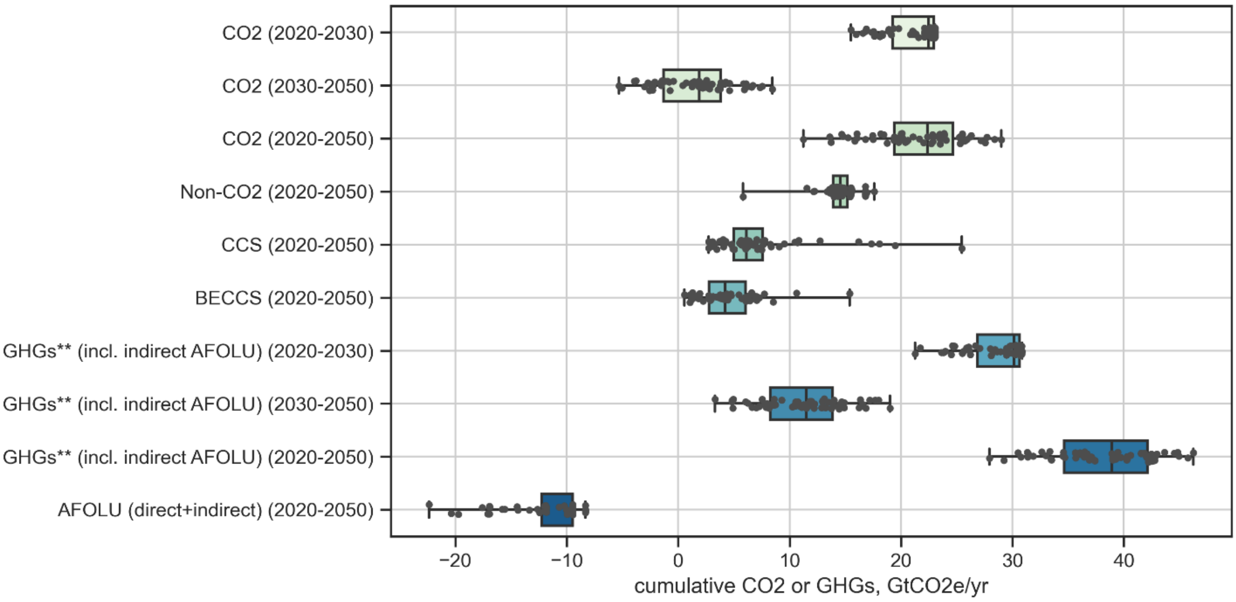

Figure 3.4. Distributions of cumulative CO2 and GHG emissions across the 63 scenarios.

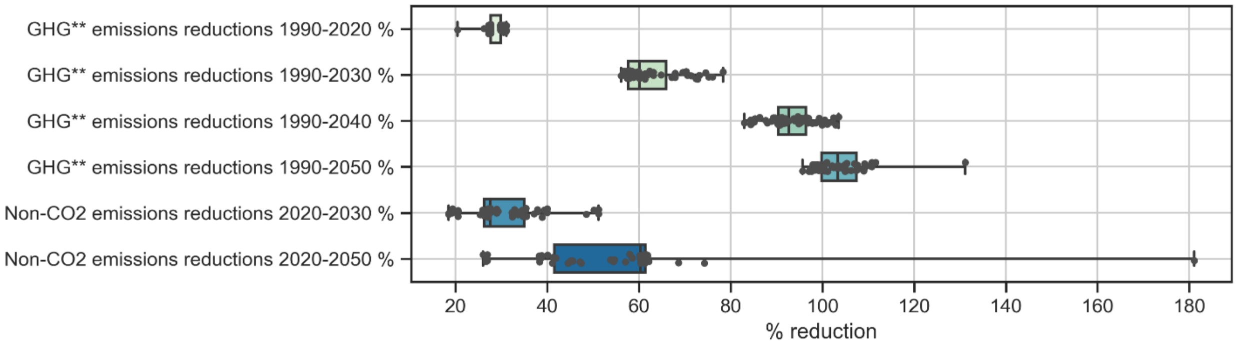

Figure 3.5. Distributions of GHG and non-CO2 emissions reductions across the 63 scenarios.

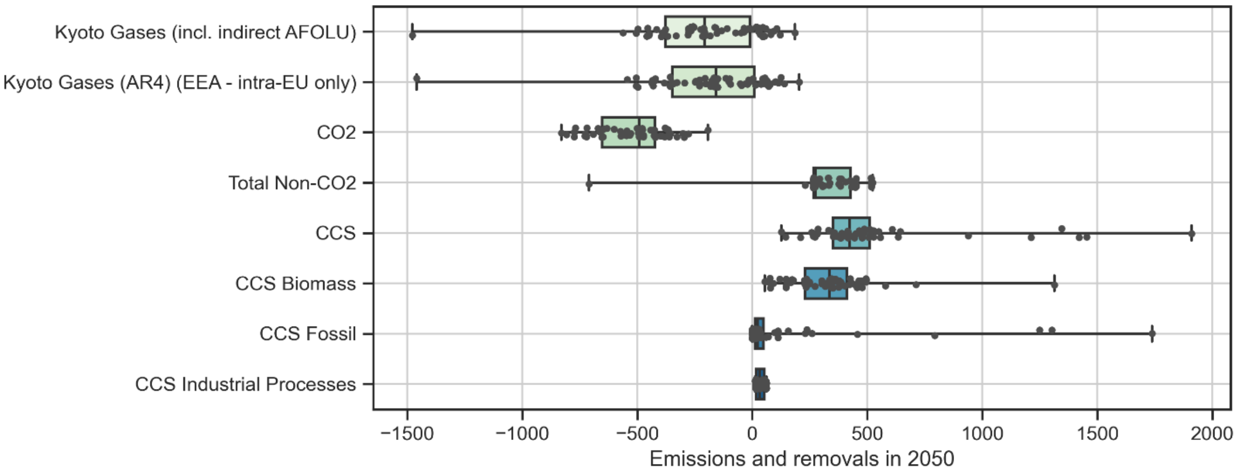

Figure 3.6. Distributions of emissions and removals in 2050 across the 63 scenarios.

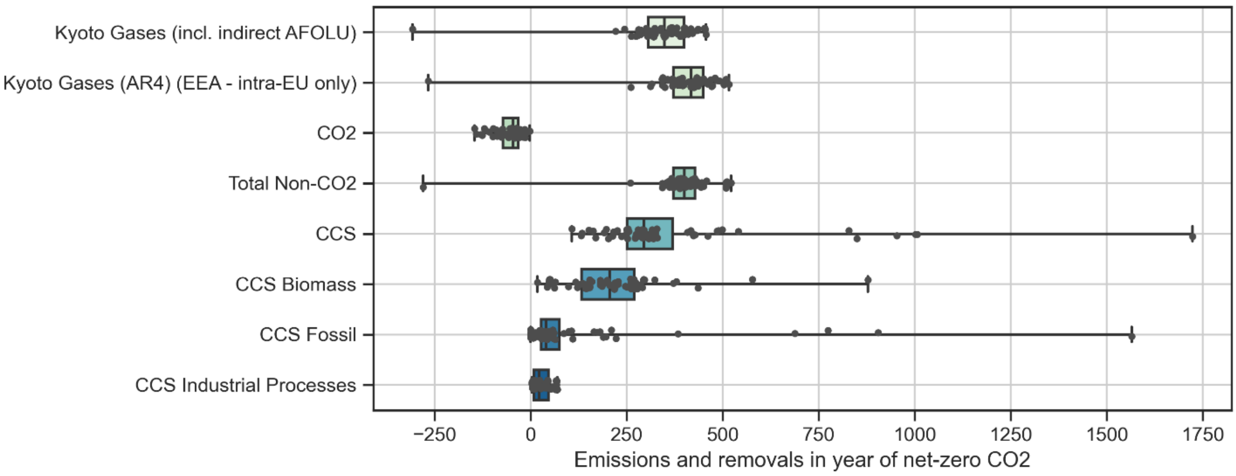

Figure 3.7. Distributions of emissions and removals in the year of net-zero CO_2 across the 63 scenarios.

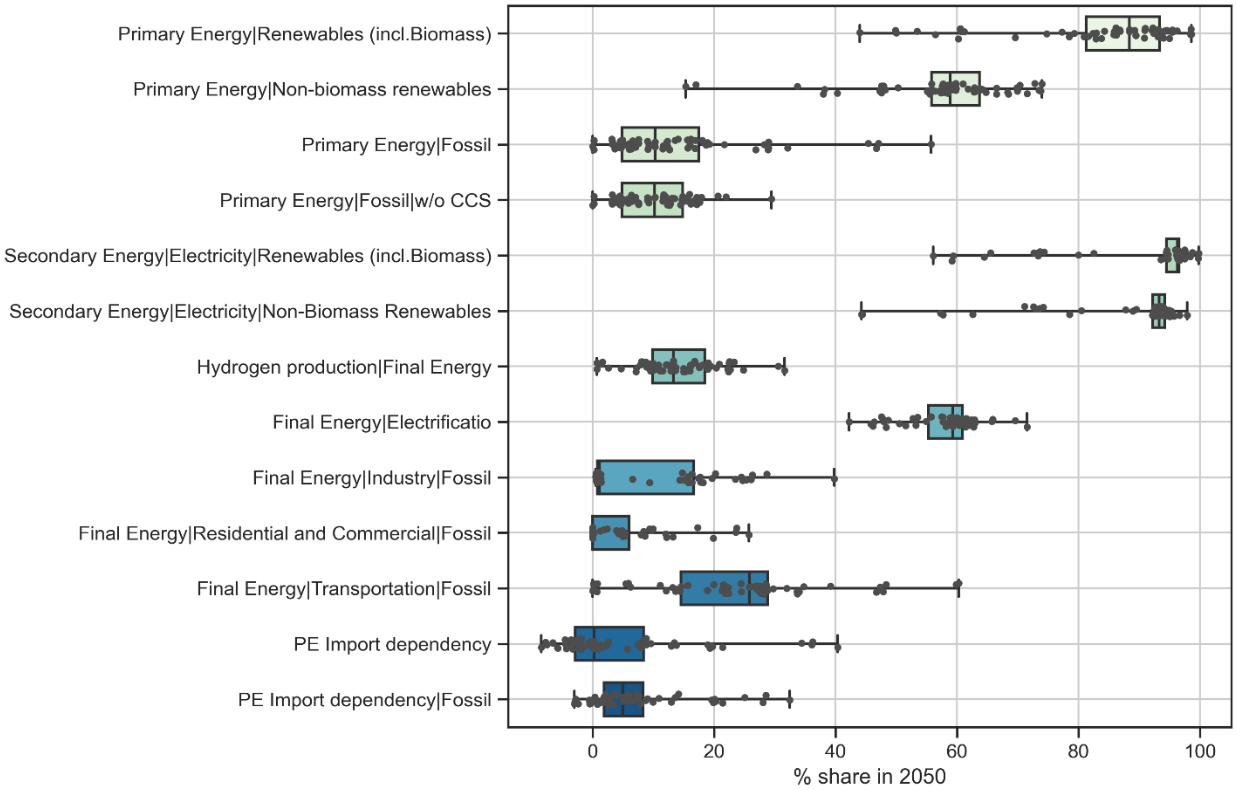

Figure 3.8. Distributions of energy indicators shares in 2050 across the 63 scenarios.

4 Multidimensional feasibility assessment of 1.5 °C consistent pathways for the EU

4.1 Overview

Integrated Assessment Models (IAM) are one of the key tools to aid policymakers with long-term planning when designing climate policies. Yet in recent years, the outputs from IAMs have been criticised from many different angles, and there are many calls to think more systematically about which IAM pathways might not be feasible in the real world (Brutschin et al. 2021; Jewell and Cherp 2020; Gambhir et al. 2017; Napp et al. 2017). Given the long-term nature of climate mitigation scenarios, the level of uncertainty about what is feasible and what is not, is high. Nonetheless, evaluation of scenarios from a feasibility perspective can be useful for additional scenario vetting by benchmarking the projections against different lines of evidence. In this report, we focus on contextualising key insights about pathways for the EU region as reported by IAM mitigation scenarios with insights from other types of models, empirical evidence, and EU goals.

Feasibility is a latent concept, and its operationalization is not straightforward. Given that feasibility evaluation of IAMs is constrained by the type of variables reported by the models, and each scenario represents a set of stylized internally consistent assumptions, Brutschin et al. (2021) developed a multidimensional approach for scenario evaluation that focuses on geophysical, technological, economic, socio-cultural and institutional dimensions to understand where feasibility concerns (and trade-offs) might arise. The main strength of this framework is that it is flexible because it provides a general guidance regarding which dimensions should be looked at and which indicators could be included, but leaves it open, which thresholds and benchmarks are used for evaluation of scenarios from the feasibility perspective, and therefore many different methods could be applied and combined. It is also open in terms of which additional indicators could be included or which indicators could be dropped depending on the specific research interest. The first application of this framework was used to evaluate global 1.5°C scenarios as a proof of concept (Brutschin et al. 2021) and more recently also applied to evaluate a set of post Glasgow scenarios (van de Ven et al. 2022) or scenarios that include Direct Air Capture and Storage technology (Gidden et al. 2023). In this report, we modify this framework in order to be useful for scholars and policymakers that are interested in the climate mitigation pathways of the European Union and want to gain a better understanding about certain characteristics of scenarios using the feasibility lens.

4.2 Feasibility concept

Academic discussions pertaining to the concept of feasibility in the context of climate mitigation scenarios are growing (Nielsen et al. 2020; Stern, Dietz, and Vandenbergh 2022), with the most recent IPCC report prominently discussing feasibility of different mitigation options and different mitigation pathways (K. Riahi et al. 2022). While evaluations of feasibility options focus on the possible constraints and enablers of a given mitigation option, such as for example scale-up of solar photovoltaics (PV) in electricity generation; evaluations of feasibility of a scenario have to cover a wide range of options because a scenario represents a combination of assumptions regarding the trends in energy, economy and land systems, and thus covers many different options (i.e. a scenario is a set of internally consistent assumptions about how different mitigation options interact). Therefore, the most recent IPCC WGIII report treated discussions of both the feasibility at the option level and the feasibility at the systems level, separately. This report focuses on the feasibility evaluation of mitigation scenarios, i.e., at the systems level.

4.3 Feasibility Definition

While many slightly different definitions of feasibility exist (see Table 4.1 for an overview), feasibility scholars are generally interested in assessing whether the scale of transformation implied in mitigation scenarios is out of range of what could be considered feasible in the real world. However, scholars disagree about feasibility ranges given the high level of uncertainty surrounding the scale-up and diffusion of existing technologies, and particularly regarding technologies that have not yet been deployed at a large scale.

Table 4.1. Overview of key definitions of feasibility in the context of climate mitigation scenarios

Study	Definition of feasibility
Jewell & Cherp (2020)	Focus on "political feasibility": "an outcome as politically feasible if there is an agent or group of agents who have the capacity to carry out a set of actions which will lead to that outcome in a given context" (Gilabert and Lawford-Smith 2012). Taken from Jewell & Cherp (2020).
Brutschin et al. (2021)	"feasibility as the degree to which scenarios lie within the boundaries of societal capacities for change in a given period"
Nielsen et al., (2020)	"The concept of feasibility combines two elements: the potential for change agents to adopt and implement initiatives (IF) and the extent to which the targets of initiatives respond to them as intended (BP)."
Turnheim & Nykvist, (2019)	"the conditions under which transitions pathways may have greater chances of becoming realized"
Gambhir et al. (2017)	"the degree of difficulty in meeting mitigation pathways"

There is an agreement that as the first step of any feasibility evaluation, it should be identified "feasibility of what?" is being evaluated (Gilabert and Lawford-Smith 2012). First of all, scenarios should be comparable in terms of the temperature goal and the key set of assumptions. Scenarios should thus be compared within the same temperature goal and within the same Shared Socioeconomic Pathways (SSP) group (Keywan Riahi et al. 2017). Scenarios with the most ambitious climate targets require much faster speed of transformation across all sectors, and thus are more challenging from the feasibility perspective compared to less ambitious targets. Scenarios are aligned along SSPs in terms of key socio-economic assumptions such as population and GDP trajectories. It is thus not surprising that scenarios along the SSP1 trajectory (assuming more optimistic GDP and technology developments) pose less feasibility challenges as for example SSP2 scenarios (Rogelj et al. 2018).

Additionally, given that IAMs combine a set of assumptions pertaining to many different sectors, it is essential to evaluate a set of multiple indicators, otherwise certain trade-offs might be missed (for example more feasible levels of solar scale-up might be observed because later less feasible levels of CCS are assumed). A multidimensional framework of feasibility evaluation (Brutschin et al. 2021) is thus particularly suitable for the evaluation of mitigation scenarios. Building on the past IPCC work, Brutschin et al., (2021) propose four dimensions to be evaluated: (1) geophysical, (2) technological, (3) economic, (4) socio-cultural. The institutional dimension is dropped from the EU focused analysis given that all of the EU member countries have a relatively high level of institutional capacity. The environmental dimension, which is a sixth dimension considered in the IPCC categorization, is not included in the framework as it pertains more to the aspect of desirability rather than feasibility concerns. This approach applies similar logic as the one used in the assessments of viability of certain technologies, where the potential of a technology is assessed through a set of multiple criteria, such as geophysical, economic or institutional constraints. Figure 1 highlights the key feasibility dimensions and the key areas of focus.

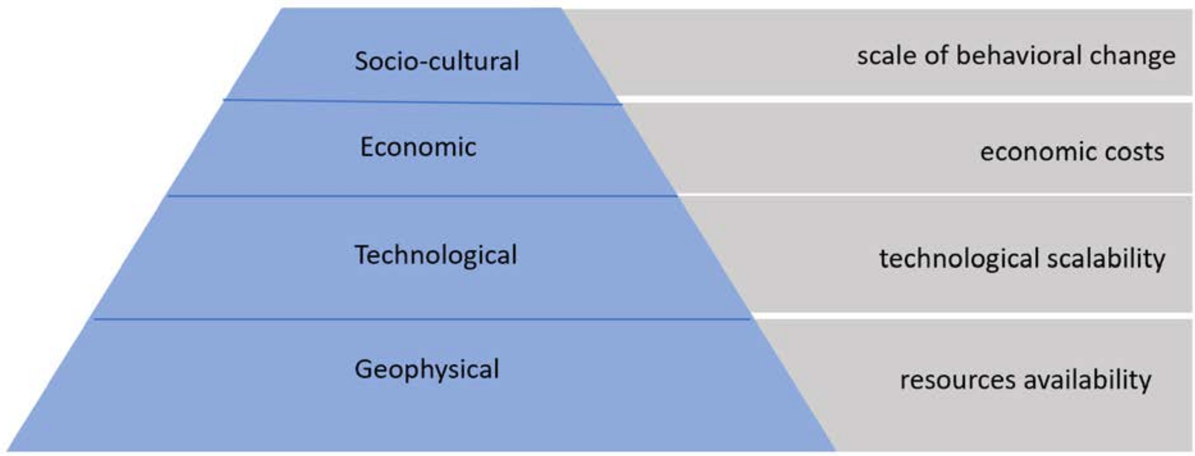

Figure 4.1. Key dimensions of scenario feasibility evaluation.

Note: Based on the framework from Brutschin et al. (2021).

4.4 Scenario Evaluation Approach

Our overall approach can be described as follows (see Figure 4.2). Initially, the key dimensions that are suitable for scenario evaluation at the EU level (Step 1) were identified. Subsequently, a set of indicators was selected for each dimension (Step 2). The indicator selection was driven by indicator availability and by making sure that many key goals and targets specified in the EU Climate Law or other policy documents could be benchmarked to the values reported in scenarios.

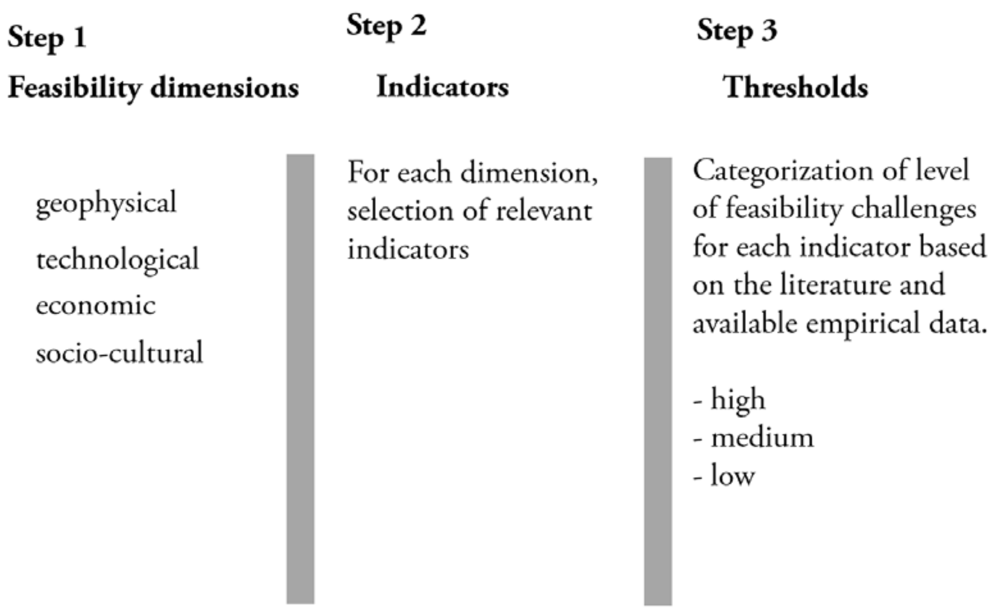

Figure 4.2. Main steps of scenario evaluation.

For each indicator, thresholds were defined for low (1), medium (2) and high (3) feasibility challenges based on a review of the literature and empirical data (see Figure 4.3). A traffic light methodology, similarly, to Warszawski et al. (2021), is adopted to visualise levels of a particular indicator that may present feasibility challenges.

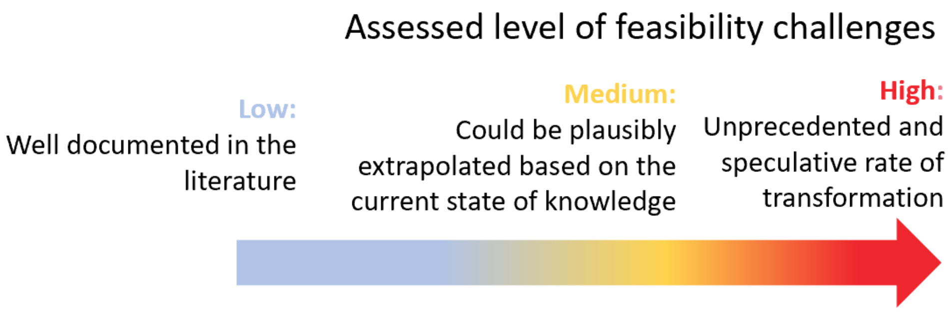

Figure 4.3. Proposed categorization for scenario evaluation.

To indicate the key feasibility concerns in climate mitigation scenarios a few different approaches have been implemented so far. For example, some studies (Warszwaski et al. 2021) have applied a filtering approach (i.e., excluding scenarios that are above the proposed bounds along feasibility indicators) to show that “none can achieve 1.5 °C with no or low overshoot whilst keeping all the mitigation levers at reasonable levels”. Given the high uncertainty about many indicators, Brutschin et al., (2021) proposed a more comparative approach where none of the scenarios are filtered out but rather the trade-offs along key indicators (high near-term feasibility concerns versus long term concerns because of negative emissions) are explored and compared.

In this report, both approaches (Figure 4.4) are used. First, a set of indicators is proposed where there is more general agreement about the upper bounds in the literature (Creutzig et al. 2021; Warszawski et al. 2021; Grant et al. 2022; Odenweller et al. 2022) to filter out highly implausible or undesirable scenarios. By applying this filtering approach, we then arrived at a sample of 36 scenarios. This sample was then used to identify iconic scenarios that cover a range of key mitigation strategies and can be compared using quantitative and qualitative indicators. In this step of the analysis, scenarios are filtered based on the following global indicators: (1) primary energy biomass, and (2) the speed of scale-up of carbon storage capacity. Then, scenarios are checked along four key indicators at the EU level: (1) primary energy biomass, (2) the speed of scale-up of carbon storage and utilization capacity, (3) the scale-up of hydrogen and (4) reductions in final energy demand by 2030 compared to 2020.

In the second part of our analysis, a set of indicators is then applied at the EU-level to allow for a systematic exploration and comparison of scenarios from a feasibility perspective, similarly to the approach in Brutschin et al., (2021). Using this approach enables identification of broader patterns where there are more general feasibility challenges across all scenarios.

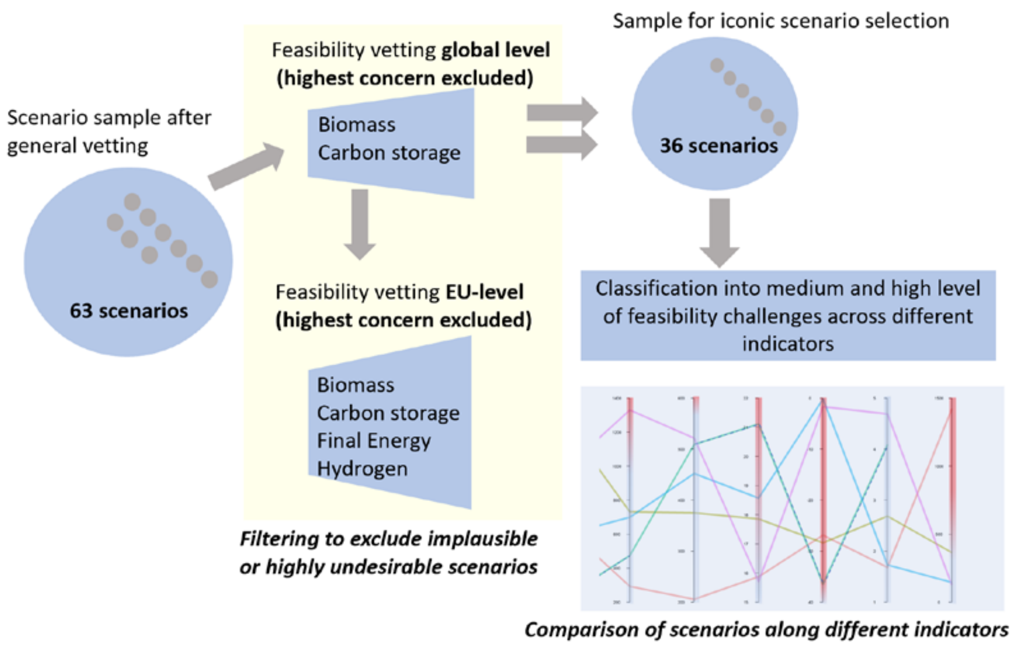

Figure 4.4 Scenario processing by adding a feasibility perspective.

4.5 Indicators Overview

Table 4.2 provides an overview of indicators that were used for the initial filtering of scenarios from a feasibility perspective, using only upper bounds. Table 4.3 provides an overview of indicators and thresholds that were used for the comparative analysis of scenarios and includes lower and upper bound thresholds.

Table 4.2. Key indicators and thresholds for initial scenario filtering using only upper bound thresholds.

Level	Dimension	Indicator (IAMC format)	Thresholds	Justification
Global-filtering	Geophysical (Sustainability)	Primary Energy|Biomass	Any year >240 EJ/year – high	Based on the estimates in Creutzig et al., (2015) and Frank et al., (2021).
Global-filtering	Technological (Storage scale-up capacity)	Carbon Sequestration CCS	Any year >8.6 Gt/year – high	Based on calculations from Luderer et al., (2022) assuming 0.1% of regional technical potential and Grant et al. (2022). McKinsey scenarios estimate around 4 Gt CO_2/year globally, which they also consider to be challenging (McKinsey 2022).
EU-27-filtering	Geophysical (Sustainability)	Primary Energy|Biomass	2050 >20 EJ/year - high	Based on the literature overview from other reports and assessments. (European Commission, Joint Research Centre (JRC) 2019; Material Economics 2021).
EU-27-filtering	Technological (Storage scale-up capacity)	CCUS	2050 >500 Mt/year - high	Holz et al., (2021) for the indicative values for the lower and upper bounds. Similar values are also indicated in the Sustainable carbon cycles for a 2050 climate-neutral EU Technical Assessment[17]. International Association of Oil and Gas Producers builds its policy proposal around 300 Mt CO_2/year. (International Association of Oil and Gas Producers, 2023).
EU-27-filtering	Technological	Secondary Energy|Hydrogen in EJ/year converted to GW	2030 >150 GW - high	The lower bound is approximately the 95 percentile from the study by Odenweller et al. (2022) assuming the emergence growth rate. The upper bound is the 50% increase compared to the current EU ambition which roughly aligns with the projections from Monitor Deloitte (2022) for an ambitious hydrogen scale-up (170 GW by 2030).
EU-27-filtering	Socio-cultural	Final Energy Demand decline in %	2030 >20pp - high	Based on the global threshold derived in Brutschin et al., (2021) motivated by Grübler et al. (2018).

[17] https://climate.ec.europa.eu/system/files/2021-12/swd_2021_451_parts_1_to_3_en_0.pdf.

	100 - Final Energy in 2030/Final Energy in 2020*100		

Table 4.3. Key indicators and thresholds for scenario comparison applied at the EU-27 level using upper and lower feasibility thresholds.

Indicator (IAMC format)	Thresholds	Justification	EU target/goal
Geophysical			
Biomass scale-up Primary Energy|Biomass	2050 <9 EJ/year - low >20 EJ/year - high	The lower bound as identified in the report by Material Economics, while upper bound is similar to that calculated by JRC and across many other studies (European Commission, Joint Research Centre (JRC) 2019; Material Economics 2021)	
Technological			
Solar scale-up Capacity Electricity|Solar	2030 <900 GW - low >1245 GW - high	900 GW assumes 20% yearly growth rate, 1245 GW assumes 25% yearly growth rate (based on the average historical growth rates). We use 2022 and the reported capacity of 208.9 GW as the base value (Solar Power Europe 2022).	600 GW (European Commission 2022).
Wind scale-up Capacity Electricity|Wind	2030 <623 GW - low >875 GW - high	623 GW assumes 15% yearly growth rate, 875 GW assumes 20% yearly growth rate (based on historical growth rates). We use 2022 and the reported capacity of 204 GW as the base value (IRENA, 2023; Wind Europe, 2023).	510 GW (European Commission 2022).
Hydrogen scale-up Secondary Energy|Hydrogen in EJ/year converted to	2030 <50 GW - low >150 GW - high	The lower bound is approximately the 95 percentile from the study by Odenweller et al., (2022) assuming the emergence growth rate. The upper bound is the 50% increase compared to the current EU ambition which roughly aligns with the projections from Monitor Deloitte	2030: 100 GW capacity (European Commission, 2022, calculations based on Odenweller et al., (2022), when taking 10 Mt domestic production[19]).

[19] Capacity = (Prod [Mt] * Lower Heating Value [kWh/kg]) / (Full Load Hours [h] * Efficiency), Prod = 10Mt, LHV = 33.3 kWh/kg, FLH = 5000h, Efficiency = 0.7).

GW[18] assuming 70% efficiency and 5000 full load hours		(2022) for an ambitious hydrogen scale-up (170 GW by 2030).	
CCS scale-up Carbon capture, use and sequestration	2050 <300 Mt/year - low >500 Mt/year - high	Holz et al., (2021) for the indicative values for the lower and upper bounds. Similar values are also indicated in the Sustainable carbon cycles for a 2050 climate-neutral EU Technical Assessment[20]. The upper bound is comparable to the regional calculations for Western and Eastern Europe in the study by Grant International Association of Oil and Gas Producers built its policy proposal around 300Mt/year (International Association of Oil and Gas Producers 2023).	2030: 50 Mt (Net Zero Indusrty Act 2023).
Economic			
Coal phase out Secondary Energy|Electricity|Coal in 2030 / Secondary Energy|Electricity|Coal in 2020	2030 <30 % - medium	Poland[21] represents currently around one third of EUs coal consumption and has later coal phase-out goals compared to other countries. For other countries the proposed phase out as in PPCA around 2030 would be ambitious but with some historical precedents[22] (Muttitt et al. 2023).	Many EU member states are members of the PPCA[23] and have a clear coal phase out date[24].
Socio-cultural			

[18] To convert from EJ/year to GW the following conversion was applied (assuming 5000 hours load): Generation in GW=Generation in EJ/year *10^6/3.6/5000. To account for efficiency losses the value was then divided by 0.7 as in Odenweller et al., (2022).

[20] https://climate.ec.europa.eu/system/files/2021-12/swd_2021_451_parts_1_to_3_en_0.pdf.

[21] https://ember-climate.org/countries-and-regions/countries/poland/.

[22] "This suggests that, for most of the largest coal consumers, the PPCA timelines are close to the limits of feasibility based on historical precedent such that it is hard to imagine a faster phase-out: in other words, they could be characterized as 'difficult but possible'."(Muttitt et al. 2023).

[23] Our members - PPCA (poweringpastcoal.org).

[24] Europe's coal exit - Europe Beyond Coal : Europe Beyond Coal (beyond-coal.eu).

Final Energy Demand decline in % 100 - Final Energy in 2030/Final Energy in 2020*100	2030 >20pp - high <10pp - low	Based on the global threshold derived in Brutschin et al. (2021) motivated by Gruebler et al. (2018).	reduce final energy consumption at EU level by 11.7% in 2030[25]

4.5.1 Indicators for global evaluation

Estimations of the potential for biomass are often derived from complex land models that differ greatly due to variations in key assumptions and uncertainty regarding land data. As a result, the literature contains a wide range of estimates, ranging from approximately 10 EJ/year to over 650 EJ/year by 2050 (Beringer, Lucht, and Schaphoff 2011; Cornelissen, Koper, and Deng 2012; Creutzig et al. 2015; Daioglou et al. 2020; Frank et al. 2021; Hanssen et al. 2020; Kalt et al. 2020). According to Creutzig et al., (2015) the literature shows high agreement that the sustainable technical potential of biomass, taking land availability concerns into account, is up to 100 EJ/year. There is medium agreement that biomass potential could increase up to 300 EJ/year (Creutzig et al. 2015). Recently, Frank et al. (2021) estimated that biomass potential, without considering SDGs, could be approximately 240 EJ/year. Therefore, we use 100 EJ as the upper limit for medium concern and 240 EJ/year as the upper limit for high concern.

The extent of available geologic storage for carbon remains uncertain, as noted in Budinis et al. (2018). While the potential range of storage is estimated to be between 10,000–42,000 Gt CO_2 (Budinis et al. 2018; Kearns et al. 2017), the fossil industry suggests a commercial capacity of only 550 Gt CO_2[26]. The cumulative estimates of storage potential do not capture the speed of scale-up, which might be one of the major concerns from the feasibility perspective. We thus propose to focus on the yearly reported scale of carbon storage across the technologies such as bioenergy-CCS and fossil-CCS, as well as Direct Air Capture if reported by a model. While the level of uncertainty remains high, recent literature has proposed a few possible benchmarks to evaluate the scale-up of carbon storage. For example, the REMIND-MAgPIE Model estimates an upper bound for geologic CCS storage of 4 Gt/year (Luderer et al. 2022) by assuming 0.1% of technical geological storage potential in each region (A similar level is also calculated in a McKinsey analysis of required

[25] https://www.consilium.europa.eu/en/press/press-releases/2023/03/10/council-and-parliament-strike-deal-on-energy-efficiency-directive/&sa=D&source=docs&ust=1681374535453019&usg=AOvVaw2dOb3I0p2QQoyCQowOv4kz

[26] https://www.globalccsinstitute.com/wp-content/uploads/2021/11/Global-Status-of-CCS-2021-Global-CCS-Institute-1121.pdf

levels to achieve Net Zero targets (McKinsey 2022)). Grant et al. (2022) estimate the global potential based on historical oil and gas extraction rates to be around 8.6 Gt CO_2/year. Based on the ranges currently discussed in the literature, we propose as a medium level of concern the benchmark of 4 Gt CO_2/year, while for a high level of concern 8.6 Gt/year.

4.5.2 Indicators for EU level evaluation

Solar

The level of uncertainty regarding feasible levels of solar deployment is quite high. For instance, even the IRENA's REmap scenario, developed in 2018, projected only 270 GW of installed solar capacity by 2030 for the EU 28[27]. However, more recent studies and projections are far more optimistic. A comprehensive EU study, for example, assumes 1250 GW of solar capacity in the EU-28 by 2030 in 1.5 °C scenarios (Victoria, Zeyen, and Brown 2022). Another study investigating the impacts of limited gas imports reported an estimated 2000 GW of installed solar capacity by 2030 (Pedersen et al. 2022).

To evaluate the scenarios outlined in this report, we suggest a simple method for determining upper bounds on potential feasibility challenges. We gather the most recent capacity data up to 2022 and create two upper bounds. If the annual capacity growth rate exceeds 25 percent, we highlight the challenges as high, while a 20 percent capacity growth rate or less results in the challenges being classified as low (see Figure 4.5). While it is technically feasible to reach higher levels, this would necessitate a substantial policy shift, as demonstrated in other scenarios (Pedersen et al. 2022; Victoria, Zeyen, and Brown 2022).

Annual data can fluctuate significantly, with some years seeing growth rates of over 50 percent (e.g., from 2007 to 2008), while others only reach around 5 percent (e.g., in 2014 and 2015). The mean growth rate for the EU-27 from 2000 to 2022 is 26 percent, while China's average yearly capacity growth rate is 30 percent and the United States' is approximately 24 percent for the same period. As a result, we suggest using the 25 percent yearly growth benchmark as a guide for identifying particularly high challenges, since sustaining levels similar to those seen in China and already achieved in the EU until 2030 may be difficult. The 20 percent benchmark, on the other hand, is more consistent with observed trends.

[27] https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Feb/IRENA_REmap_EU_2018.pdf

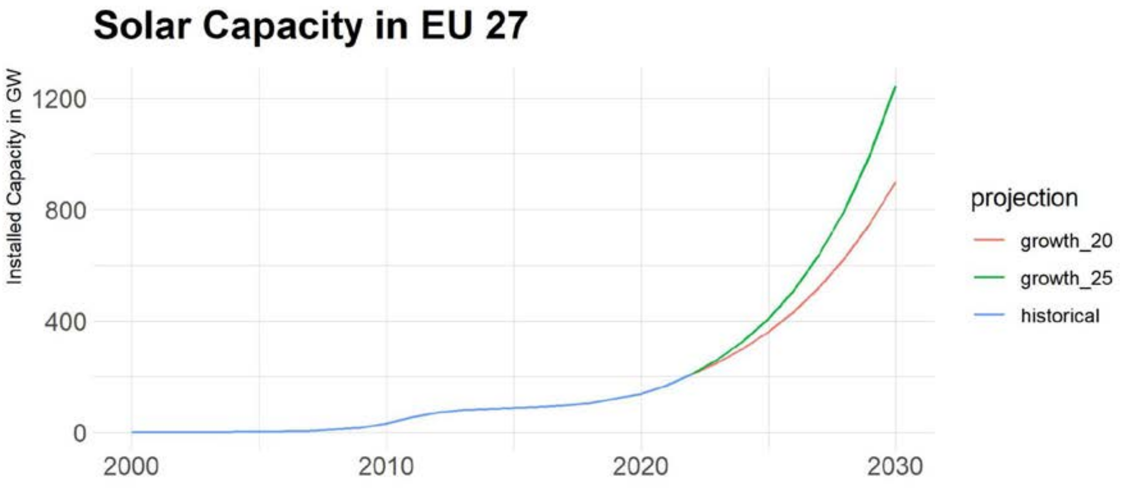

Figure 4.5. Historical and projected solar capacity in EU-27 (2000-2030).

Note: This Figure reports historical capacity data as reported by (IRENA, 2023) until 2021. The value for 2022 is taken from a report by (Solar Power Europe, 2023). Green line indicates the upper capacity bound assuming yearly capacity growth of 25 percent, while red line indicates upper capacity bound assuming yearly capacity growth of 20 percent.

Wind

To determine the feasible bounds for wind energy, a methodology similar to that for solar energy was utilised. However, due to the slower diffusion rates of wind energy, we assumed slightly lower yearly growth rates compared to solar energy (Wilson et al. 2020). This assumption is supported by observed yearly capacity growth rates, with the average yearly growth rate for wind energy in the EU-27, China, and the USA during the period under consideration being around 12%, 26%, and 18%, respectively (based on capacities reported by (IRENA 2023)).

Despite generally lower yearly capacity growth rates being around 6 percent in the past five years, recent trends suggest that EU member states are ramping up their wind scale-up ambition (Janipour 2023). Therefore, it can be reasonably assumed that yearly growth rates below 15% would pose a low feasibility challenge (for example those were consistently observed in the period from 2005 to 2009), while values above 20% would be more challenging in the EU context (see Figure 4.6).

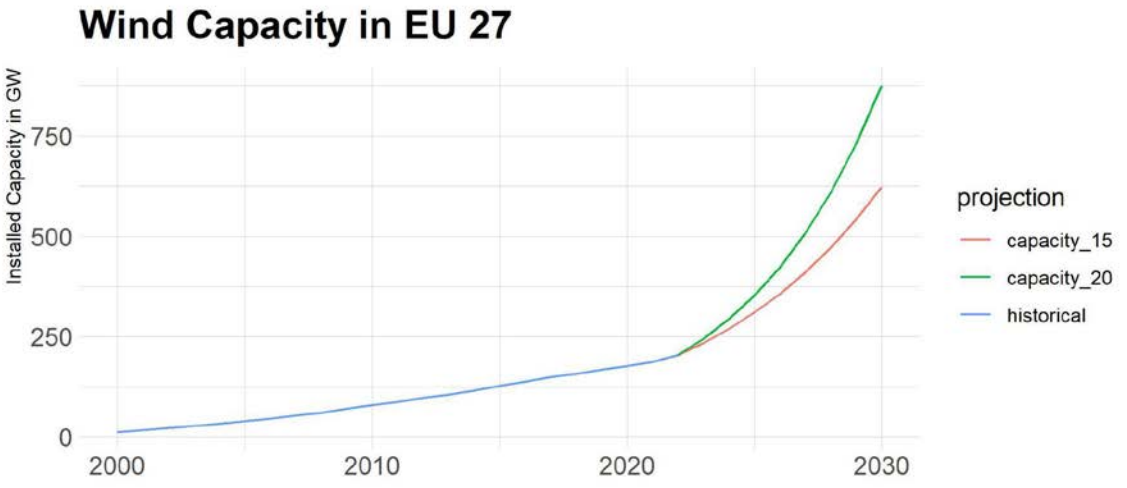

Figure 4.6. Historical and projected wind capacity in EU-27 (2000-2030).

This Figure reports historical capacity data as reported by IRENA (2023) until 2021. The value for 2022 is taken from a report by Wind Europe (2023). Green line indicates the upper capacity bound assuming yearly capacity growth of 20 percent, while red line indicates upper capacity bound assuming yearly capacity growth of 15 percent.

4.6 Scenario comparison along key quantitative indicators

Applying indicators and thresholds from Table 4.3 provides a general overview of how the scenario ensemble under consideration (63 scenarios that are consistent with the EU 2030 and 2050 targets) compares along key indicators. Overall, most of the scenarios are below what have been considered as highly concerning levels from the feasibility perspective. Especially in terms of assumed wind capacity in 2030, most scenarios are below the proposed 623 GW that assumes a 15% yearly growth rate and are less ambitious than the EU target of 510 GW. Similarly, most scenarios (approximately 75%) are below the lower threshold for solar capacity. However, most scenarios fall within the medium level of concerns regarding biomass and hydrogen, and over 40% of scenarios are highly concerning in terms of the scale-up of carbon storage and utilization by 2050. This main finding aligns with the general insights from global analyses that highlight the assumed medium-term levels of carbon storage capacity, unless there is a major political shift, might be concerning from a feasibility perspective (Grant et al. 2022). Nearly all scenarios raise medium level concerns in terms of the assumed speed of coal phase-out and declines in final energy consumption by 2030.

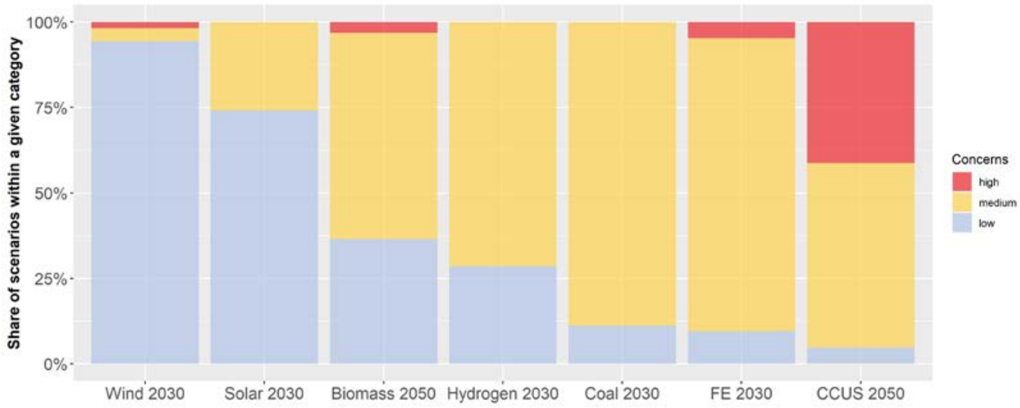

Figure 4.7. Results from scenario categorization.

Note: Based on 63 scenarios that pass GHG** vetting in 2030.

As described in section 4.4, the next step involves excluding scenarios that were categorized as highly concerning in at least one of the four key indicators (biomass, CCUS, final energy, hydrogen). This exclusion results in a scenario ensemble consisting of 36 scenarios. From these 36 scenarios, we then focus on three iconic scenarios that represent different mitigation strategies: (1) Demand-side focus pathway (REMIND-MAgPIE 2.1-4.2 SusDev_SDP-PkBudg1000), (2) High renewable energy pathway (REMIND 3.2 NZero_bioLim7p5_withICEPhOP), and (3) Mixed options pathway (MESSAGEix-GLOBIOM 1.1 EN_NPi2020_600_DR1p).

To gain a better understanding of the feasibility concerns and key trade-offs, a more qualitative assessment of the iconic pathways was conducted and is presented in Figure 4.8. This assessment focused on a wider range of indicators, which are presented in Table 4.3.

The first panel (from the left) in Figure 4.8 displays the level of ambition across the three iconic scenarios. The Mixed options pathway assumes a 69% reduction in greenhouse gas (GHG) emissions (excluding international trade) by 2030 compared to 1990. The Demand-side focus pathway assumes a 65% reduction in GHG emissions, while the High renewable energy pathway assumes a 57% reduction. These varying levels of ambition are reflected in the differences across key mitigation levers.

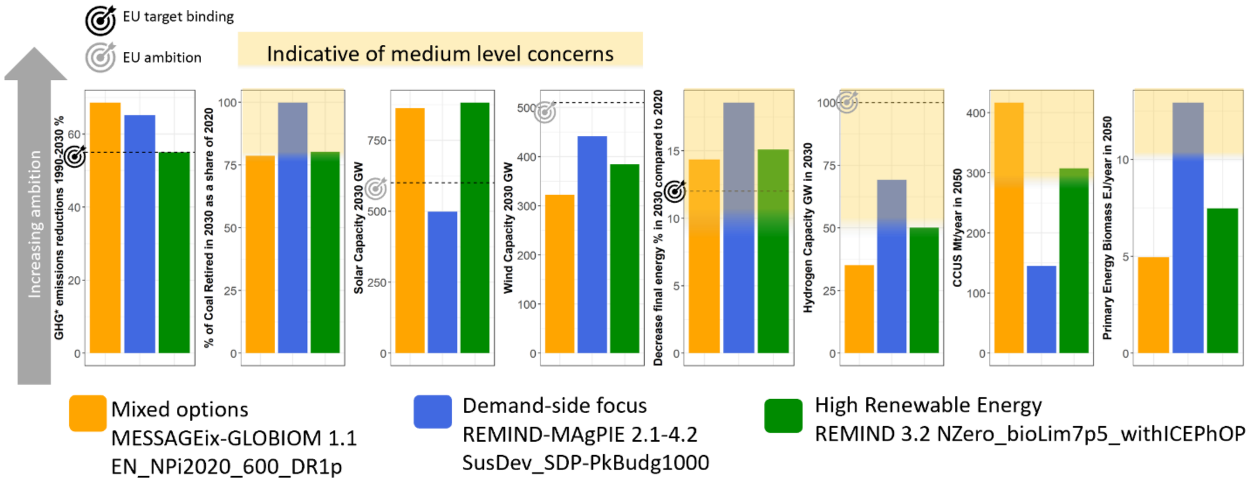

Figure 4.8. Iconic scenarios across key feasibility indicators.

Note: An overview of the iconic scenarios is provided along key dimensions, with yellow shading indicating areas where medium levels of concern arise. Since scenarios with any of the indicators categorized as having a high level of feasibility concern not considered further, none of the iconic scenarios raise high-level feasibility concerns based on the proposed thresholds. The dashed lines indicate EU targets or goals where applicable (see also Table 4.3).

Both the Mixed options and High renewable energy pathways assume relatively high levels of solar deployment, surpassing the current EU target outlined in the REPowerEU Plan. However, the reported wind capacity levels in these scenarios fall below the EU's ambition.

The Demand-side focus pathway, on the other hand, assumes a complete coal phase-out by 2030, which could be feasible but would require a major policy shift in some EU countries. This pathway also anticipates a significant decline in final energy consumption levels compared to other pathways, necessitating a major shift in lifestyles, particularly in terms of meat consumption, as described in the scenario narrative (Soergel et al. 2021). Additionally, the Demand-side focus pathway projects higher levels of biomass by 2050 (13 EJ/year).

In contrast, the Mixed options pathway assumes a relatively high level of overall carbon capture and storage by 2050 (417 Mt CO_2 per year). However, all scenarios fall below the EU hydrogen target, which has been deemed extremely ambitious by other studies (Odenweller et al. 2022).

This explorative comparison of the iconic scenarios indicates that similar goals could be achieved through different combinations of levers. Some of these levers align with the current EU plans, while others would require additional policies to ensure the attainment of overall climate goals.

5 References

Baumstark, Lavinia, Nico Bauer, Falk Benke, Christoph Bertram, Stephen Bi, Chen Chris Gong, Jan Philipp Dietrich, et al. 2021. 'REMIND2.1: Transformation and Innovation Dynamics of the Energy-Economic System within Climate and Sustainability Limits'. *Geoscientific Model Development* 14 (10): 6571–6603. https://doi.org/10.5194/gmd-14-6571-2021.

Beringer, Tim, Wolfgang Lucht, and Sibyll Schaphoff. 2011. 'Bioenergy Production Potential of Global Biomass Plantations under Environmental and Agricultural Constraints'. *GCB Bioenergy* 3 (4): 299–312. https://doi.org/10.1111/j.1757-1707.2010.01088.x.

Brutschin, Elina, Silvia Pianta, Massimo Tavoni, Keywan Riahi, Valentina Bosetti, Giacomo Marangoni, and Bas J van Ruijven. 2021. 'A Multidimensional Feasibility Evaluation of Low-Carbon Scenarios'. *Environmental Research Letters* 16 (6): 064069. https://doi.org/10.1088/1748-9326/abf0ce.

Budinis, Sara, Samuel Krevor, Niall Mac Dowell, Nigel Brandon, and Adam Hawkes. 2018. 'An Assessment of CCS Costs, Barriers and Potential'. *Energy Strategy Reviews* 22 (November): 61–81. https://doi.org/10.1016/j.esr.2018.08.003.

Byers, Edward, Volker Krey, Elmar Kriegler, Keywan Riahi, Roberto Schaeffer, Jarmo Kikstra, Robin Lamboll, et al. 2022. 'AR6 Scenarios Database'. International Institute for Applied Systems Analysis. Zenodo. https://doi.org/10.5281/zenodo.7197970.

Cornelissen, Stijn, Michèle Koper, and Yvonne Y. Deng. 2012. 'The Role of Bioenergy in a Fully Sustainable Global Energy System'. *Biomass and Bioenergy* 41 (June): 21–33. https://doi.org/10.1016/j.biombioe.2011.12.049.

Creutzig, Felix, Karl-Heinz Erb, Helmut Haberl, Christian Hof, Carol Hunsberger, and Stephanie Roe. 2021. 'Considering Sustainability Thresholds for BECCS in IPCC and Biodiversity Assessments'. *GCB Bioenergy* 13 (4): 510–15. https://doi.org/10.1111/gcbb.12798.

Creutzig, Felix, N. H. Ravindranath, Göran Berndes, Simon Bolwig, Ryan Bright, Francesco Cherubini, Helena Chum, et al. 2015. 'Bioenergy and Climate Change Mitigation: An Assessment'. *GCB Bioenergy* 7 (5): 916–44. https://doi.org/10.1111/gcbb.12205.

Daioglou, Vassilis, Steven K. Rose, Nico Bauer, Alban Kitous, Matteo Muratori, Fuminori Sano, Shinichiro Fujimori, et al. 2020. 'Bioenergy Technologies in Long-Run Climate Change Mitigation: Results from the EMF-33 Study'. *Climatic Change* 163 (3): 1603–20. https://doi.org/10.1007/s10584-020-02799-y.

Dietrich, Jan Philipp, Benjamin Leon Bodirsky, Florian Humpenöder, Isabelle Weindl, Miodrag Stevanović, Kristine Karstens, Ulrich Kreidenweis, et al. 2019. 'MAgPIE 4 – a Modular Open-Source Framework for Modeling Global Land Systems'. *Geoscientific Model Development* 12 (4): 1299–1317. https://doi.org/10.5194/gmd-12-1299-2019.

EEA. 2021. 'EEA GHG Data Viewer (Readme)'. European Environment Agency. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer.

———. 2022. 'National Emissions Reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism — European Environment Agency'. Data. 2022. https://www.eea.europa.eu/data-and-maps/data/national-emissions-reported-to-the-unfccc-and-to-the-eu-greenhouse-gas-monitoring-mechanism-18.

EMBER. 2022. 'Global Electricity Review 2022'. EMBER. https://ember-climate.org/insights/research/global-electricity-review-2022/.

European Commission. 2020. '2050 Long-Term Strategy'. 3 June 2020. https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.

———. 2022. 'REPowerEU Plan: COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS'. 2022. https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF.

European Commission, Joint Research Centre (JRC). 2019. 'ENSPRESO - BIOMASS'. http://data.europa.eu/89h/74ed5a04-7d74-4807-9eab-b94774309d9f.

Forster, P., T. Storelvmo, K. Armour, W. Collins, J.-L. Dufresne, D. Frame, D.J. Lunt, et al. 2021. 'The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity'. Edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, et al. *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, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.009.

Frank, Stefan, Mykola Gusti, Petr Havlík, Pekka Lauri, Fulvio DiFulvio, Nicklas Forsell, Tomoko Hasegawa, Tamás Krisztin, Amanda Palazzo, and Hugo Valin. 2021. 'Land-Based Climate Change Mitigation Potentials within the Agenda for Sustainable Development'. *Environmental Research Letters* 16 (2): 024006. https://doi.org/10.1088/1748-9326/abc58a.

Gambhir, Ajay, Laurent Drouet, David McCollum, Tamaryn Napp, Dan Bernie, Adam Hawkes, Oliver Fricko, et al. 2017. 'Assessing the Feasibility of Global Long-Term Mitigation Scenarios'. *Energies* 10 (1). https://doi.org/10.3390/en10010089.

Gidden, Matthew J, Elina Brutschin, Gaurav Ganti, Gamze Unlu, Behnam Zakeri, Oliver Fricko, Benjamin Mitterrutzner, Francesco Lovat, and Keywan Riahi. 2023. 'Fairness and Feasibility in Deep Mitigation Pathways with Novel Carbon Dioxide Removal Considering Institutional Capacity to Mitigate'. Preprint. Preprints. https://doi.org/10.22541/essoar.167768147.71711451/v1.

Gidden, Matthew J., Shinichiro Fujimori, Maarten van den Berg, David Klein, Steven J. Smith, Detlef P. van Vuuren, and Keywan Riahi. 2018. 'A Methodology and Implementation of Automated Emissions Harmonization for Use in Integrated Assessment Models'. *Environmental Modelling & Software* 105 (July): 187–200. https://doi.org/10.1016/j.envsoft.2018.04.002.

Gidden, Matthew J., Keywan Riahi, Steven J. Smith, Shinichiro Fujimori, Gunnar Luderer, Elmar Kriegler, Detlef P. van Vuuren, et al. 2019. 'Global Emissions Pathways under Different Socioeconomic Scenarios for Use in CMIP6: A Dataset of Harmonized Emissions Trajectories through the End of the Century'. *Geoscientific Model Development* 12 (4): 1443–75. https://doi.org/10.5194/gmd-12-1443-2019.

Gilabert, Pablo, and Holly Lawford-Smith. 2012. 'Political Feasibility: A Conceptual Exploration'. *Political Studies* 60 (4): 809–25. https://doi.org/10.1111/j.1467-9248.2011.00936.x.

Grant, Neil, Ajay Gambhir, Shivika Mittal, Chris Greig, and Alexandre C. Köberle. 2022. 'Enhancing the Realism of Decarbonisation Scenarios with Practicable Regional Constraints on CO2 Storage Capacity'. *International Journal of Greenhouse Gas Control* 120 (October): 103766. https://doi.org/10.1016/j.ijggc.2022.103766.

Grassi, Giacomo, Elke Stehfest, Joeri Rogelj, Detlef van Vuuren, Alessandro Cescatti, Jo House, Gert-Jan Nabuurs, et al. 2021. 'Critical Adjustment of Land Mitigation Pathways for Assessing Countries' Climate Progress'. *Nature Climate Change* 11 (5): 425–34. https://doi.org/10.1038/s41558-021-01033-6.

Grubler, Arnulf, Charlie Wilson, Nuno Bento, Benigna Boza-Kiss, Volker Krey, David L. McCollum, Narasimha D. Rao, et al. 2018. 'A Low Energy Demand Scenario for Meeting the 1.5 °c

Target and Sustainable Development Goals without Negative Emission Technologies'. *Nature Energy* 3 (6): 515–27. https://doi.org/10.1038/s41560-018-0172-6.

Guivarch, Céline, Thomas Le Gallic, Nico Bauer, Panagiotis Fragkos, Daniel Huppmann, Marc Jaxa-Rozen, Ilkka Keppo, et al. 2022. 'Using Large Ensembles of Climate Change Mitigation Scenarios for Robust Insights'. *Nature Climate Change* 12 (5): 428–35. https://doi.org/10.1038/s41558-022-01349-x.

Hanssen, S. V., V. Daioglou, Z. J. N. Steinmann, J. C. Doelman, D. P. Van Vuuren, and M. a. J. Huijbregts. 2020. 'The Climate Change Mitigation Potential of Bioenergy with Carbon Capture and Storage'. *Nature Climate Change* 10 (11): 1023–29. https://doi.org/10.1038/s41558-020-0885-y.

Holz, Franziska, Tim Scherwath, Pedro Crespo del Granado, Christian Skar, Luis Olmos, Quentin Ploussard, Andrés Ramos, and Andrea Herbst. 2021. 'A 2050 Perspective on the Role for Carbon Capture and Storage in the European Power System and Industry Sector'. *Energy Economics* 104 (December): 105631. https://doi.org/10.1016/j.eneco.2021.105631.

Huppmann, Daniel, Matthew J. Gidden, Zebedee Nicholls, Jonas Hörsch, Robin Lamboll, Paul N. Kishimoto, Thorsten Burandt, Oliver Fricko, Edward Byers, and Jarmo Kikstra. 2021. 'Pyam: Analysis and Visualisation of Integrated Assessment and Macro-Energy Scenarios'. *Open Research Europe* 1. https://doi.org/10.12688/openreseurope.13633.2.

Huppmann, Daniel, Joeri Rogelj, Elmar Kriegler, Volker Krey, and Keywan Riahi. 2018. 'A New Scenario Resource for Integrated 1.5 °C Research'. *Nature Climate Change* 8 (12): 1027–30. https://doi.org/10.1038/s41558-018-0317-4.

IEA. 2022. 'Energy Statistics 2022'. Paris: International Energy Agency. www.iea.org.

International Association of Oil and Gas Producers. 2023. 'Scaling up CCS in Europe'. https://iogpeurope.org/wp-content/uploads/2021/09/IOGP_Scaling-up-CCS-in-Europe-factsheet.pdf.

IPCC. 2021. 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'. Edited by V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, et al. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.

———. 2022a. 'Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change'. Edited by P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, et al. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157926.

———. 2022b. 'Scenarios and Modelling Methods'. Edited by C. Guivarch, E. Kriegler, J. Portugal-Pereira, V. Bosetti, J. Edmonds, M. Fischedick, P. Havlík, et al. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157926.022.

IRENA. 2023. 'Installed Renewable Electricity Capacity (MW) by Region/Country/Area, Technology and Year'. PxWeb 2020 V1. 2023. https://pxweb.irena.org:443/pxweb/en/IRENASTAT/IRENASTAT__Power Capacity and Generation/RECAP_2022_cycle2.px/.

Janipour, Zahra. 2023. 'Great Efforts Required To Achieve EU Countries' National Offshore Wind Energy Targets'. Rabobank. 2023. https://www.rabobank.com/knowledge/d011347929-great-efforts-required-to-achieve-eu-countries-national-offshore-wind-energy-targets.

Jewell, Jessica, and Aleh Cherp. 2020. 'On the Political Feasibility of Climate Change Mitigation Pathways: Is It Too Late to Keep Warming below 1.5°C?' *Wiley Interdisciplinary Reviews: Climate Change* 11 (1): 1–12. https://doi.org/10.1002/wcc.621.

Kalt, Gerald, Christian Lauk, Andreas Mayer, Michaela C. Theurl, Katrin Kaltenegger, Wilfried Winiwarter, Karl-Heinz Erb, Sarah Matej, and Helmut Haberl. 2020. 'Greenhouse Gas Implications of Mobilizing Agricultural Biomass for Energy: A Reassessment of Global Potentials in 2050 under Different Food-System Pathways'. *Environmental Research Letters* 15 (3): 034066. https://doi.org/10.1088/1748-9326/ab6c2e.

Kearns, Jordan, Gary Teletzke, Jeffrey Palmer, Hans Thomann, Haroon Kheshgi, Yen-Heng Henry Chen, Sergey Paltsev, and Howard Herzog. 2017. 'Developing a Consistent Database for Regional Geologic CO2 Storage Capacity Worldwide'. *Energy Procedia*, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland, 114 (July): 4697–4709. https://doi.org/10.1016/j.egypro.2017.03.1603.

Kikstra, Jarmo S., Zebedee R. J. Nicholls, Christopher J. Smith, Jared Lewis, Robin D. Lamboll, Edward Byers, Marit Sandstad, et al. 2022. 'The IPCC Sixth Assessment Report WGIII Climate Assessment of Mitigation Pathways: From Emissions to Global Temperatures'. *Geoscientific Model Development* 15 (24): 9075–9109. https://doi.org/10.5194/gmd-15-9075-2022.

Kikstra, Jarmo S., Zebedee R.J. Nicholls, Jared Lewis, Christopher J. Smith, Robin D. Lamboll, Edward Byers, Marit Sandstad, and Laura Wienpahl. 2022. 'Infiller Database for Silicone: IPCC AR6 WGIII Version'. International Institute for Applied Systems Analysis. https://doi.org/10.5281/zenodo.6390768.

Lamboll, Robin D., Zebedee R. J. Nicholls, Jarmo S. Kikstra, Malte Meinshausen, and Joeri Rogelj. 2020. 'Silicone v1.0.0: An Open-Source Python Package for Inferring Missing Emissions Data for Climate Change Research'. *Geoscientific Model Development* 13 (11): 5259–75. https://doi.org/10.5194/gmd-13-5259-2020.

Luderer, Gunnar, Silvia Madeddu, Leon Merfort, Falko Ueckerdt, Michaja Pehl, Robert Pietzcker, Marianna Rottoli, et al. 2022. 'Impact of Declining Renewable Energy Costs on Electrification in Low-Emission Scenarios'. *Nature Energy* 7 (1): 32–42. https://doi.org/10.1038/s41560-021-00937-z.

Material Economics. 2021. 'EU Biomass Use In A Net-Zero Economy - A Course Correction for EU Biomass'. https://www.climate-kic.org/wp-content/uploads/2021/06/MATERIAL-ECONOMICS-EU-BIOMASS-USE-IN-A-NET-ZERO-ECONOMY-ONLINE-VERSION.pdf.

McKinsey. 2022. 'Scaling the CCUS Industry to Achieve Net-Zero'. 2022. https://www.mckinsey.com/industries/oil-and-gas/our-insights/scaling-the-ccus-industry-to-achieve-net-zero-emissions.

Meinshausen, M, S C B Raper, and T M L Wigley. 2011. 'Emulating Coupled Atmosphere-Ocean and Carbon Cycle Models with a Simpler Model, MAGICC6 – Part 1: Model Description and Calibration'. *Atmospheric Chemistry and Physics* 11 (4): 1417–56. https://doi.org/10.5194/acp-11-1417-2011.

Minx, Jan C., William F. Lamb, Robbie M. Andrew, Josep G. Canadell, Monica Crippa, Niklas Döbbeling, Piers Forster, et al. 2022. 'A Comprehensive and Synthetic Dataset for Global, Regional and National Greenhouse Gas Emissions by Sector 1970-2018 with an Extension to 2019'. Zenodo. https://doi.org/10.5281/zenodo.6483002.

Minx, Jan C., William F. Lamb, Robbie M. Andrew, Josep G. Canadell, Monica Crippa, Niklas Döbbeling, Piers M. Forster, et al. 2021. 'A Comprehensive and Synthetic Dataset for Global, Regional, and National Greenhouse Gas Emissions by Sector 1970–2018 with an Extension to 2019'. *Earth System Science Data* 13 (11): 5213–52. https://doi.org/10.5194/essd-13-5213-2021.

Monitor Deloitte. 2022. 'The European Hydrogen Economy – Taking Stock and Looking Ahead An Outlook until 2030'. https://www2.deloitte.com/content/dam/Deloitte/fr/Documents/financial-advisory/European_hydrogen_economy_FINAL.pdf.

Muttitt, Greg, James Price, Steve Pye, and Dan Welsby. 2023. 'Socio-Political Feasibility of Coal Power Phase-out and Its Role in Mitigation Pathways'. *Nature Climate Change* 13 (2): 140–47. https://doi.org/10.1038/s41558-022-01576-2.

Napp, Tamaryn, Dan Bernie, Rebecca Thomas, Jason Lowe, Adam Hawkes, and Ajay Gambhir. 2017. 'Exploring the Feasibility of Low-Carbon Scenarios Using Historical Energy Transitions Analysis'. *Energies* 10 (1). https://doi.org/10.3390/en10010116.

Net Zero Indusrty Act. 2023. 'Net Zero Industry Act Proposal'. 2023. https://single-market-economy.ec.europa.eu/publications/net-zero-industry-act_en.

Nicholls, Z., M. Meinshausen, J. Lewis, C. J. Smith, P. M. Forster, J. S. Fuglestvedt, J. Rogelj, J. S. Kikstra, K. Riahi, and E. Byers. 2022. 'Changes in IPCC Scenario Assessment Emulators Between SR1.5 and AR6 Unraveled'. *Geophysical Research Letters* 49 (20): e2022GL099788. https://doi.org/10.1029/2022GL099788.

Nielsen, Kristian S, Paul C Stern, Thomas Dietz, Jonathan M Gilligan, van Detlef P Vuuren, Maria J Figueroa, Carl Folke, et al. 2020. 'Improving Climate Change Mitigation Analysis: A Framework for Examining Feasibility'. *One Earth* 3 (3): 325–36. https://doi.org/10.1016/j.oneear.2020.08.007.

Odenweller, Adrian, Falko Ueckerdt, Gregory F. Nemet, Miha Jensterle, and Gunnar Luderer. 2022. 'Probabilistic Feasibility Space of Scaling up Green Hydrogen Supply'. *Nature Energy* 7 (9): 854–65. https://doi.org/10.1038/s41560-022-01097-4.

Pedersen, Tim Tørnes, Ebbe Kyhl Gøtske, Adam Dvorak, Gorm Bruun Andresen, and Marta Victoria. 2022. 'Long-Term Implications of Reduced Gas Imports on the Decarbonization of the European Energy System'. *Joule* 6 (7): 1566–80. https://doi.org/10.1016/j.joule.2022.06.023.

Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). 2021. *OJ L*. Vol. 243. http://data.europa.eu/eli/reg/2021/1119/oj/eng.

Riahi, K., R. Schaeffer, J. Arango, K. Calvin, C. Guivarch, T. Hasegawa, K. Jiang, et al. 2022. 'Mitigation Pathways Compatible with Long-Term Goals'. Edited by P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, et al. *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, UK and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157926.005.

Riahi, Keywan, Detlef P. van Vuuren, Elmar Kriegler, Jae Edmonds, Brian C. O'Neill, Shinichiro Fujimori, Nico Bauer, et al. 2017. 'The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview'. *Global Environmental Change* 42 (January): 153–68. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Rodrigues, Renato, Robert Pietzcker, Panagiotis Fragkos, James Price, Will McDowall, Pelopidas Siskos, Theofano Fotiou, Gunnar Luderer, and Pantelis Capros. 2022. 'Narrative-Driven Alternative Roads to Achieve Mid-Century CO2 Net Neutrality in Europe'. *Energy* 239 (January): 121908. https://doi.org/10.1016/j.energy.2021.121908.

Rodrigues, Renato, Robert Pietzcker, Joanna Sitarz, Anne Merfort, Robin Hasse, Johanna Hoppe, Michaja Pehl, Murtaza Ershad, Lavinia Baumstark, and Gunnar Luderer. n.d. '2040 Greenhouse Gas Reduction Targets and Energy Transitions in Line with the EU Green Deal'. Potsdam Institute for Climate Impacts Research.

Rogelj, J, A Popp, K V Calvin, G Luderer, J Emmerling, D Gernaat, S Fujimori, et al. 2018. 'Scenarios towards Limiting Global Mean Temperature Increase below 1.5 °c'. *Nature Climate Change* 8 (4): 325–32. https://doi.org/10.1038/s41558-018-0091-3.

Ruiz, P. 2019. 'ENSPRESO - an Open, EU-28 Wide, Transparent and Coherent Database of Wind, Solar and Biomass Energy Potentials'. *Energy Strategy Reviews*, 12. https://doi.org/10.1016/j.esr.2019.100379.

Sferra, F., B. van Ruijven, and K. Riahi. 2021. 'Downscaling IAMs Results to the Country Level – a New Algorithm'. Monograph. IIASA, Laxenburg, Austria. 15 October 2021. https://iiasa.dev.local/.

Soergel, Bjoern, Elmar Kriegler, Benjamin Leon Bodirsky, Nico Bauer, Marian Leimbach, and Alexander Popp. 2021. 'Combining Ambitious Climate Policies with Efforts to Eradicate Poverty'. *Nature Communications* 12 (1): 2342. https://doi.org/10.1038/s41467-021-22315-9.

Solar Power Europe. 2022. 'New Report Reveals EU Solar Power Soars by Almost 50% in 2022 - SolarPower Europe'. 19 December 2022. https://www.solarpowereurope.org/press-releases/new-report-reveals-eu-solar-power-soars-by-almost-50-in-2022.

Stern, Paul C., Thomas Dietz, and Michael P. Vandenbergh. 2022. 'The Science of Mitigation: Closing the Gap between Potential and Actual Reduction of Environmental Threats'. *Energy Research & Social Science* 91 (September): 102735. https://doi.org/10.1016/j.erss.2022.102735.

Turnheim, Bruno, and Björn Nykvist. 2019. 'Opening up the Feasibility of Sustainability Transitions Pathways (STPs): Representations, Potentials, and Conditions'. *Research Policy* 48 (3): 775–88. https://doi.org/10.1016/j.respol.2018.12.002.

Ven, Dirk-Jan van de, Shivika Mittal, Ajay Gambhir, H. Doukas, Sara Giarola, Adam Hawkes, Konstantinos Koasidis, et al. 2022. *A Multi-Model Analysis of Post-Glasgow Climate Action and Feasibility Gap*. https://doi.org/10.21203/rs.3.rs-2319580/v1.

Victoria, Marta, Elisabeth Zeyen, and Tom Brown. 2022. 'Speed of Technological Transformations Required in Europe to Achieve Different Climate Goals'. *Joule* 6 (5): 1066–86. https://doi.org/10.1016/j.joule.2022.04.016.

Warszawski, Lila, Elmar Kriegler, Timothy M. Lenton, Owen Gaffney, Daniela Jacob, Daniel Klingenfeld, Ryu Koide, et al. 2021. 'All Options, Not Silver Bullets, Needed to Limit Global Warming to 1.5 °C: A Scenario Appraisal'. *Environmental Research Letters* 16 (6): 064037. https://doi.org/10.1088/1748-9326/abfeec.

Wilson, C., A. Grubler, N. Bento, S. Healey, S. De Stercke, and C. Zimm. 2020. 'Granular Technologies to Accelerate Decarbonization'. *Science* 368 (6486): 36–39. https://doi.org/10.1126/science.aaz8060.

Wind Europe. 2023. 'The EU Built Only 16 GW New Wind in 2022: Must Restore Investor Confidence and Ramp up Supply Chain'. WindEurope. 2023. https://windeurope.org/newsroom/press-releases/the-eu-built-only-16-gw-new-wind-in-2022-must-restore-investor-confidence-and-ramp-up-supply-chain/.

Annex

Table A1. Details of the regional information available for each model, the vetted regions, and the vetting procedure applied.

Model version	Relevant regions	Full EU ISO3 country data	Vetted regions	Vetted type	# scens.
Models with World region, considered for global vetting and climate assessment					
AIM/CGE 2.0	R5	FALSE	None	NA	24
AIM/CGE 2.1	R5	FALSE	None	NA	8
AIM/CGE 2.2	Europe (R10), AIM/CGE 2.2|EU	FALSE	AIM/CGE 2.2|EU	native	40
COFFEE 1.1	Europe (R10), COFFEE 1.1|Western Europe, COFFEE 1.1|Eastern Europe	FALSE	COFFEE 1.1|Western Europe	native	72
GCAM 4.2	R5	FALSE	None	NA	21
GCAM 5.3+ NGFS	EU-27 & UK, EU-27, GCAM 5.3|Europe_Eastern, GCAM 5.3|Eastern EU, GCAM 5.3|Europe_Non_EU, GCAM 5.3|European Free Trade Association, GCAM 5.3|Western EU & UK	TRUE	EU-27	common	6
GEM-E3 v2021	Europe (R10), GEM-E3 v2021|EU28	FALSE	GEM-E3 v2021|EU28	native	41
GENeSYS-MOD 3.1	EU-27 (excl. Malta & Cyprus)			common	4
IMAGE 3.0	Europe (R10), IMAGE 3.0|Western Europe, IMAGE 3.0|Central Europe	FALSE	IMAGE 3.0|Western Europe,IMAGE 3.0|Central Europe	native	23
IMAGE 3.0.1	Europe (R10)	FALSE	Europe (R10)	common	30
IMAGE 3.2	Europe (R10), IMAGE 3.2|Western Europe, IMAGE 3.2|Central	FALSE	IMAGE 3.2|Western Europe,IMAGE	native	45

	Europe		3.2|Central Europe		
MESSAGE-GLOBIOM 1.0	R5	FALSE	None	NA	15
MESSAGEix-GLOBIOM 1.0	Europe (R10), MESSAGEix-GLOBIOM 1.0|Western Europe, MESSAGEix-GLOBIOM 1.0|Eastern Europe	FALSE	MESSAGEix-GLOBIOM 1.0|Western Europe	native	29
MESSAGEix-GLOBIOM 1.1	Europe (R10), MESSAGEix-GLOBIOM 1.1|Western Europe, MESSAGEix-GLOBIOM 1.1|Eastern Europe	FALSE	MESSAGEix-GLOBIOM 1.1|Western Europe	native	164
MESSAGEix-GLOBIOM 1.1-M-R12	EU-27 & UK, EU-27, MESSAGEix-GLOBIOM 1.1-M-R12|Western Europe, MESSAGEix-GLOBIOM 1.0|Eastern Europe	TRUE	EU-27	common	6
MESSAGEix-GLOBIOM 1.2	Europe (R10), MESSAGEix-GLOBIOM 1.2|Western Europe, MESSAGEix-GLOBIOM 1.2|Eastern Europe	FALSE	MESSAGEix-GLOBIOM 1.2|Western Europe	native	29
POLES-JRC	EU-27 & UK, EU-27, Europe (R10)	FALSE	EU-27	common	3
POLES-JRC ENGAGE	Europe (R10)	FALSE	Europe (R10)	common	70
PROMETHEUS 1.2	Europe , PROMETHEUS 1.2|Central Europe, PROMETHEUS 1.2|Western Europe	FALSE	PROMETHEUS 1.2|Western Europe,PROMETHEUS 1.2|Central Europe	native	8
REMIND 2.1	EU-27 & UK, EU-27, Europe, Europe (R10), REMIND 2.1|EU Center-East Europe, REMIND 2.1|EU Center-South Europe,REMIND 2.1|EU North-Center Europe, REMIND 2.1|EU North-West Europe, REMIND 2.1|EU South-Center	FALSE	EU-27	common	14

	Europe, REMIND 2.1|EU South-West Europe, REMIND 2.1|Non-EU Northern Europe, REMIND 2.1|Non-EU Southern Europe				
REMIND 3.0	EU-27 & UK, EU-27, Europe, Europe (R10)	FALSE	EU-27	common	7
REMIND 3.2	EU-27 & UK, EU-27, Europe, Europe (R10)	FALSE	EU-27	common	30
REMIND-EU 2.0	EU-27 & UK, Europe (R10), lots of europe regions	FALSE	EU-27 & UK	common	9
REMIND-MAgPIE 1.5	R5	FALSE	None	NA	16
REMIND-MAgPIE 1.7-3.0	Europe (R10)	FALSE	Europe (R10)	common	10
REMIND-MAgPIE 2.1-4.2	EU-27 & UK, Europe (R10), REMIND 2.1|EU 28	FALSE	REMIND 2.1|EU 28	native	83
REMIND-MAgPIE 2.1-4.3	EU-27 & UK , Europe (R10), REMIND 2.1|EU 28	FALSE	EU-27 & UK	common	8
REMIND-MAgPIE 3.0-4.4	EU-27 & UK , REMIND 3.0|EU 28	TRUE	EU-27 & UK	common	6
TIAM-ECN 1.1	Europe (R10), TIAM-ECN 1.1|Western Europe, TIAM-ECN 1.1|Eastern Europe	FALSE	TIAM-ECN 1.1|Western Europe,TIAM-ECN 1.1|Eastern Europe	native	46
TIAM-ECN 1.2	Europe (excl. Turkey), TIAM-ECN 1.2|Western Europe, TIAM-ECN 1.2|Eastern Europe	FALSE	TIAM-ECN 1.2|Western Europe,TIAM-ECN 1.2|Eastern Europe	native	9
WITCH-GLOBIOM 3.1	R5	FALSE	None	NA	22
WITCH-GLOBIOM 4.4	R5	FALSE	None	NA	8
WITCH 5.0	Europe (R10), WITCH 5.0|Europe	FALSE	WITCH 5.0|Europe	native	78
WITCH 5.1	EU-27 & UK, EU-27	FALSE	EU-27	common	9
Models considered only in the regional assessment (no World data)					

E4SMA-EU-TIMES 1.0	EU-27 & UK, EU-27, EU ISO-3	TRUE	EU-27	common	6
Euro-Calliope 2.0	EU-27 & UK, EU-27, EU ISO-3	TRUE	EU-27	common	10
FORECAST v1.0	EU-27 & UK, EU-27	TRUE	EU-27	common	3
GCAM-PR 5.3	EU-27 & UK , GCAM-PR 5.3|Eastern EU, GCAM-PR 5.3|Western EU & UK	FALSE	EU-27 & UK	common	5
GEMINI-E3 7.0	EU-27 & UK	FALSE	EU-27 & UK	common	7
ICES-XPS 1.0	EU-27 & UK, EU-27, some EU ISO-3	FALSE	EU-27	common	3
MUSE 1.0	EU-27 & UK, Europe (R10), EU ISO-3	FALSE	EU-27 & UK	common	2
NEMESIS 5.1	EU-27 & UK, EU-27,	TRUE	EU-27	common	6
PRIMES 2022	EU-27 & UK, EU-27	FALSE	EU-27	common	8
PyPSA-Eur-Sec 0.0.2	EU-27 & UK, EU-27, EU ISO-3	TRUE	EU-27	common	6
PyPSA-Eur-Sec 0.5.0	EU-27 & UK, EU-27, EU ISO-3	TRUE	EU-27	common	7
PyPSA-Eur-Sec 0.6.0	EU-27 & UK, EU-27, EU ISO-3	TRUE	EU-27	common	4
TIAM-Grantham v3.4	Europe (R10), TIAM-Grantham v3.4|Eastern Europe, TIAM-Grantham v3.4|Western Europe	FALSE	TIAM-Grantham v3.4|Eastern Europe,TIAM-Grantham v3.4|Western Europe	native	2

Table A2. Models whose scenarios lacked either sufficient variable or region information for further assessment.

Model version	Relevant regions	Full EU ISO3 country data	Reason for no further assessment	# scens.
ALADIN 1.0	EU-27, EU ISO-3	FALSE	Insufficient variables reported – only transport sector	2
EnergyVille TIMES BE 1.0.0	Belgium	FALSE	Insufficient regional coverage – only Belgium	2
OSeMBE v1.0.0	EU-27 & UK, EU-27	FALSE	Insufficient variables reported – only CO2 for electricity supply	2
RECC 2.4	EU-27, various Europe regions	FALSE	Insufficient variables reported – only 3	24
Roadmap v1.8	EU-27, R5	FALSE	Insufficient variables reported – only transport sector	7
TIMES-Ireland Model v1.0	Ireland	FALSE	Insufficient regional coverage – only Ireland	25