Examining pathways for a climate neutral Europe by 2050

A model comparison analysis including integrated assessment models and energy system models

Mikropoulos, Efstratios; Roelfsema, Mark; Chen, Hsing Hsuan; Staffell, Iain; Oreggioni, Gabriel; Hdidouan, Dan; Thellufsen, Jakob Zinck; Chang, Miguel Antonio; Pfenninger, Stefan; More Authors

DOI
10.1016/j.energy.2025.134809

Publication date
2025

Document Version
Final published version

Published in
Energy

Energy 319 (2025) 134809

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Examining pathways for a climate neutral Europe by 2050; A model comparison analysis including integrated assessment models and energy system models

Efstratios Mikropoulos [a,*], Mark Roelfsema [a], Hsing-Hsuan Chen [a], Iain Staffell [b], Gabriel Oreggioni [b], Dan Hdidouan [b], Jakob Zinck Thellufsen [c], Miguel Antonio Chang [c,d], Panagiotis Fragkos [e], Anastasis Giannousakis [e], Souran Chatterjee [f], Diana Ürge-Vorsatz [g], Stefan Pfenninger [h], Bryn Pickering [i], Marta Victoria [j], Tom Brown [k], Detlef P. van Vuuren [a,l]

[a] *Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, the Netherlands*
[b] *Centre for Environmental Policy, Imperial College London, United Kingdom*
[c] *Department of Sustainability and Planning, Aalborg University, Rendsburggade 14, 9000, Aalborg, Denmark*
[d] *Department of Energy Systems Analysis, Institute for Energy Technology (IFE), Post Box 40, 2027, Kjeller, Norway*
[e] *E3 Modelling, Athens, Greece*
[f] *University of Plymouth, Drake Circus, Plymouth, PL4 8AA, United Kingdom*
[g] *Central European University, Quellenstraße 51, 1100, Wien, Austria*
[h] *Faculty of Technology, Policy and Management, TU Delft, the Netherlands*
[i] *Department of Environmental Systems Science, ETH Zürich, Universitätstrasse 16, 8092, Zürich, Switzerland*
[j] *Department of Mechanical and Production Engineering, Aarhus University, Aarhus, Denmark*
[k] *Department of Digital Transformation in Energy Systems, Technische Universität Berlin, Berlin, Germany*
[l] *PBL Netherlands Environmental Assessment Agency, the Netherlands*

ARTICLE INFO

Handling Editor: Henrik Lund

Keywords:
Muti-model comparison
Energy system models
Integrated assessment models
European green deal
CO2 net neutrality
Decarbonization pathways
Current trends pathways

ABSTRACT

The European Union's goal of achieving climate neutrality by 2050, outlined in the European Green Deal, is supported by numerous studies providing insights into pathways and emission reduction strategies in the energy sectors. However, model comparisons of such pathways are less common due to the complex nature of climate and energy modelling. Our study brings together integrated assessment models and energy system models under a common framework to develop EU policy scenarios: a Current Trends scenario reflecting existing policies and trends and a Climate Neutrality scenario aligned with the EU's emission reduction target. Both scenarios project reduced final energy consumption by 2050, driven by increased electrification and decreased fossil fuel usage. Electricity consumption increases driven by electrification despite the improved efficiency of electrified technologies. Models align on a shift toward renewables but diverge in technology and fuel choices, reflecting various approaches to reach net-zero energy systems. Furthermore, trade-offs between energy demand and supply mitigation strategies, as well as between renewable energy, e-fuels, and CCS technologies are identified. Considering these model variations, our study highlights the importance of consistent model comparison to offer reliable recommendations to policymakers and stakeholders. We conclude that model diversity is a valuable asset when used sensibly.

1. Introduction

EU climate policy aims to achieve a climate-neutral Europe by 2050.

The ambition of EU climate policy is to achieve a climate-neutral Europe by 2050. This goal is outlined in the European Green Deal [1], which aims to combine economic growth, climate change mitigation,

This article is part of a special issue entitled: H2020 SENTINEL project published in Energy.
* Corresponding author.
E-mail address: e.mikropoulos@uu.nl (E. Mikropoulos).

https://doi.org/10.1016/j.energy.2025.134809
Received 1 October 2023; Received in revised form 7 January 2025; Accepted 30 January 2025
Available online 6 February 2025
0360-5442/

and various topics such as biodiversity, resource efficiency, and the circular economy. To realize climate neutrality by 2050, the European Commission (EC) has proposed a strengthened emissions target for 2030, calling for a reduction of at least 55 % in greenhouse gas emissions relative to 1990 levels [2]. This target is further supported by the "Fit-for-55″ legislative package [3], which plays a crucial role in guiding the pathway towards achieving climate neutrality in Europe. Supporting the strategy towards the climate-neutral goal, PRIMES model calculations have been conducted by the EC [4,5]. These model-based scenarios have contributed significantly to informing and guiding the pathway and policy decisions for a climate neutral Europe by 2050.

In the past, single model studies have provided insights into carbon-neutral pathways for the EU [6,7], for individual Member States [8–11], and for specific technologies and sectors [12–14]. However, comprehensive comparisons between pathways derived from different models at this scale are less common, primarily due to the complexity and multidimensional nature of climate modelling and scenario analysis. Nonetheless, studies comparing similar types of models, such as Integrated Assessment Models IAMs [15–18] and optimisation Energy System Models (ESMs) [19], have demonstrated how such comparative analyses can evaluate climate pledges, assess the feasibility of achieving long-term targets, identify key uncertainties, and evaluate topics such as specific technologies, policy/emission pathways, and methodologies across different models.

Recent research has expanded to include diverse model types for exploring policy-related pathways [20–22]. Nikas et al. employ eleven models, including seven global (IAMs) and four European energy models (macroeconometric and sectoral models), to assess the long-term impact of the EU's current policies. Rodrigues et al. examine carbon emissions net neutrality goals using stakeholder-designed narratives and a comparison of three ESMs: ETM-UCL, a bottom-up cost optimisation, PRIMES a bottom-up partial equilibrium hybrid (integrates optimisation and simulation) ESM, and REMIND, an energy-economy general equilibrium model. Boitier et al. use seven models, including three global IAMs (partial and general equilibrium models) and four region-specific European models (two economy wide and two sectoral models), to develop two scenarios reflecting the EU's updated climate ambition.

This study builds on these efforts by bridging IAMs, ESMs, and sectoral models uniquely under a unified scenario framework, providing a comprehensive evaluation of the EU's pathways to 2050 climate neutrality by highlighting the differences and synergies in assumptions, methodologies, and technology options across models. We conducted a multi-model comparison using a diverse set of frameworks, tools, and models, including two global IAMs (IMAGE and PROMETHEUS) and five ESMs (DESSTINEE, EnergyPLAN, Euro-Calliope, PyPSA-Eur, and HEB). For simplicity, we refer to all the above as "models". We explore two policy scenarios: a *Current Trends* scenario that incorporates existing climate and energy policies and trends, and a *Climate Neutrality* scenario aligned with the EU's short- and long-term emission reduction targets set by the European Green Deal. This approach allows us to compare current policies with climate neutrality goals, highlighting the additional efforts needed for a carbon-neutral energy system.

While previous model comparison studies have included IAMs and traditional time-series ESMs to develop energy and emissions pathways, our study goes further by additionally incorporating snapshot models, EnergyPLAN and Euro-Calliope. These models optimize energy systems for specific future years (2030 and 2050) and provide detailed solutions with hourly resolution. Since these snapshot models do not rely on socio-economic parameters as inputs, we linked them with demand-side models, DESTINNEE (its demand module) and HEB, to use harmonised high-level inputs across all models. This approach not only enables more harmonised and broader modelling results but also introduces a novel element to the comparative study. By integrating bottom-up ESMs focused on specific years with dynamic models exploring multi-year pathways, our approach offers a comprehensive perspective.

By comparing model-based projections and assumptions of key energy and emission indicators, our study aims to identify similarities and differences between the models and examine the underlying factors that contribute to these variations. We specifically focus on understanding how different techno-economic assumptions and modelling characteristics, such as the sectors covered, theoretical underpinnings, and methodological approaches, can influence model projections for climate neutrality pathways. For instance, national models tend to provide accurate assessments of past and present technology costs and performance, while incorporating country-specific factors. However, they may overlook global technology advancements and cost reductions driven by widespread deployment, as captured by global [23]. By systematically evaluating where differences between models arise we assess the strengths and shortcomings of each model. This approach provides deeper insights into the robustness and reliability of model-based projections, offering valuable information to guide policy decision-making and enhance the understanding of the necessary actions to achieve the EU's 2050 climate neutrality goals.

Hence, the research question of this study is the identification of additional actions required to achieve the EU's 2050 goals of climate neutrality, as assessed through a comprehensive multi-model comparison study. We aim to assess the robustness of the pathways provided by the examined models taking into account their respective strengths and limitations. This investigation will contribute to advancing our understanding of the necessary steps and challenges involved in realizing the EU's climate ambitions.

The article is structured as follows. First, it provides an overview of the methodology, the scenarios used, the models included in the study, and the steps used to provide a robust intercomparison exercise. Second, it presents the results of the multi-model comparison, highlighting the differences between models regarding assumptions, methodological approaches, and technology implementations. Models' estimations for energy demand and power supply and their respective emissions are presented alongside the findings from their analysis. Finally, conclusions are highlighted and discussed.

2. Methodology

2.1. Overview

The study included the following models: IMAGE [24,25], DESSTINEE [26,27], EnergyPLAN [28], Euro-Calliope [29], HEB (indirectly through linkages) [30], PROMETHEUS [31,32], and PyPSA-Eur [33]. Key model details and characteristics can be found in Table 2 (and Table A1 in Appendix A). The first five models were actively involved in the SENTINEL project, which aimed to develop a model platform to support EU energy and climate policy (https://sentinel.en

Table 1
Climate and energy targets of the EU energy transition by 2030 and 2050. The targets are used as calibration parameters for the two scenarios (Current Trends and Climate Neutrality).

	1990	2005	*"Current Trends"*		"Climate Neutrality"	
			2030*	2050	2030	2050
Total GHG emissions (incl. LULUCF) (Mt CO_2eq.)	5413	4940	2870	1950	2435	<25
Reduction 1990 (%)	-	9%	47%	64%	55%	Nearly 100%
Total GHG emissions (excl. LULUCF) (Mt CO_2eq.)	5659	5164	3150	2130	2640	350-500
Total CO_2 emissions (excl. LULUCF) (Mt CO_2eq.)	4475	4319	<2400	< 1600	<2000	< 200

Table 2
Spatial, temporal, and sectoral resolution for participating models. The parentheses indicate interlinkages between the models (the models in the parentheses provided data). The footnotes give additional information on the interlinkages.

Model	Type	Methodology	Sectors	Geographical granularity	Temporal granularity
DESSTINEE[a]	ESM	Simulation	Demand end users (final energy consumption, emissions, and efficiency). Power, heat, and H_2 production (fuel usage, emissions, efficiency, investment, and prices).	Country level for EU27+UK	Yearly and hourly results
HEB	Sectoral	Simulation	Service demand for heating in buildings.	Country level for EU27+UK	Yearly and hourly results
Euro-Calliope (+DESSTINEE and HEB)[b]	ESM	Optimisation	Supply of energy services demand in power, transport, heating, and industry sectors, including industrial feedstocks. Assumes energy self-sufficient Europe and fuel production based on biomass or H2 and air-captured carbon.	Country level for EU27+UK	Yearly and hourly results
EnergyPLAN (+DESSTINEE and HEB) [b]	ESM	Simulation	Highly aggregated data for demand users (final energy consumption, emissions, and efficiency). Power, heat and H_2 production (fuel usage, emissions, efficiency, investment, and prices).	EU27+UK	Yearly and hourly results
IMAGE	IAM	Simulation	Demand end users (final energy consumption, emissions, and efficiency). Power, heat, and H_2 production (fuel usage, emissions, efficiency, investment, and prices).	Europe[c]	Yearly
PROMETHEUS	IAM	Simulation	Demand end users (final energy consumption, emissions, and efficiency). Power, heat, and H_2 production (fuel usage, emissions, efficiency, investment, and prices).	Europe (EU27, the UK, Norway, and Switzerland)	Yearly
PyPSA-Eur	ESM	Optimisation/ Hybrid	Supply of energy services demand in building, transportation, and industry sector, including industrial feedstock. This includes power-to-gas and power-to-liquids, as well as energy consumed for carbon capture, use, and storage (CCUS).	Country level for EU27+UK	Yearly and hourly results

[a] Only the demand module of the DESSTINEE model was utilised for this research, and the hourly profiles were not included.
[b] Euro-Calliope and EnergyPLAN models have been run using the transport service demand and industrial value added projected by DESSTINEE and the heating service demand projected by HEB.
[c] 'Europe' region here stands for the sum of two IMAGE regions, namely CEU (Central Europe) and WEU (Western Europe), which together comprise 43 European countries.

ergy). The original model results were stored in the SENTINEL intercomparison database (SENTINEL database), enabling the communication of results in- and outside the SENTINEL project. A first experimental model round showcased that the model outputs varied significantly in terms of aggregation, technology and energy carrier coverage, units, and system boundaries. To deal with the wide set of models we developed a consistent data template, inspired by the IAMC format (IIASA, 2020), that fed into the intercomparison database [34]. Then a data transfer routine ensured a correct conversion of model outputs to the requested format.

The research was conducted within the geographical scope of the EU27+UK region and a temporal scope until 2050. Demonstrating a diverse spatial resolution, not all models could provide results for the EU27+UK region. Specifically, the IMAGE model reported a larger region, the sum of the Western Europe and Central Europe regions [35], and PROMETHEUS reported EU27+UK plus Norway and Switzerland [31,32]. For this reason, the term "Europe" was used when referring to the specific region each model reported. In addition, since not all models could provide time-series results until 2050, the research focused on three distinct years, 2015, 2030, and 2050.

2.2. Scenarios

This study is based on two scenarios: *Current Trends* and *Climate Neutrality*. In both scenarios, the socio-economic input parameters of GDP and population were harmonised across the models. These parameters were calibrated to the EU Reference Scenario 2020 [4], which aligns with the 'middle of the road' future developments described in the SSP2 scenario [36]. The EU Reference Scenario 2020 provided input parameters for GDP (in MER) and population, ensuring consistency in future projections. As some models do not treat socio-economic parameters as exogenous inputs, they obtained these through interlinkages (see section 2.3).

Additional to the socio-economic parameters, the models' scenarios were harmonised regarding climate policy assumptions for 2030 and 2050. The GHG emission target for the *Current Trends* scenario was a 47 % reduction relative to 1990 by 2030, and for the *Climate Neutrality* scenario a 55 % reduction relative to 1990 by 2030 and carbon neutrality by 2050 (see Table 1). For models unable to implement a holistic emission target (e.g., sectoral models), additional guidance could be found in the 1.5TECH scenario from the 'A Clean Planet for All' [5] report and the MIX scenario from the impact assessment accompanying the '2030 Climate Target Plan' [37]. For instance, models covering only CO_2 emissions used the CO_2 emission reduction reported by these two scenarios. To align with the geographical scope, the emission targets for EU were translated to EU27+UK, by assuming that the UK will follow a similar emissions reduction pathway as the EU. Notable, the UK has approved even more ambitious targets for 2030 [38]. The scenarios are briefly described below, with further details available in the model protocol [39].

The **Current Trends scenario** was the reference scenario and represented the currently implemented climate- and energy policies. In this scenario, the EU will only implement the current policies defined in the 2030 energy and climate framework as legislated until 2021. Beyond 2030, no specified further strengthening of these policies was assumed; instead, the participating models were free to interpret the continuation of policies with the constraint of meeting the emissions targets outlined in Table 1. The Current Trends scenario emission cap aligned with the EU Reference Scenario 2020 [4].

The **Climate Neutrality scenario** was linked to the European Green Deal and the 2030 Climate Target Plan from the EC [37,5]. These included the recently approved emission caps aimed at achieving climate neutrality by 2050, which were also submitted to the UNFCCC in the EU's Mid-century strategy [40]. The 1.5TECH scenario, used as guidance for this scenario, allows for some residual CO_2 emissions (below 200 $MtCO_2eq$) in the energy and industry sectors in 2050. Furthermore, the carbon sink in the Land Use, Land-use Change, and Forestry (LULUCF) sector compensates for the remaining non-CO_2 emissions in agriculture by 2050. Notably, the carbon sink of 315 $MtCO_2$ is based on UNFCCC reporting and differs from the definitions used in most IAM models and inventories [41].

Each modelling team was allowed to choose their methodology for developing the scenarios, provided they adhered to the established guidelines (Table A1 provides a synopsis of the models and the scenarios' implementation and protocol-based adjustments). For instance, the IMAGE and PROMETHEUS models developed the Current Trends scenario based on a previously defined "Current Policies" scenario [42,43], incorporating sectoral modelling adjustments based on countries' Nationally Determined Contributions (NDCs) and the National Energy and Climate Plans of EU Member States. The scenarios were calibrated to the socio-economic parameters mentioned earlier, with a small carbon price introduced to slightly adjust the projected emissions to meet the targets. For the Climate Neutrality scenario, similar assumptions were applied, but with a significantly higher carbon price, particularly after 2030, to meet the more ambitious emission reduction targets.

Likewise, the Climate Neutrality scenario in PyPSA-Eur is also based on a previously developed scenario [44]. This scenario represents the transformation of the European energy system under a carbon budget aligned with a 1.7 °C temperature increase, with 67 % confidence. Europe's share of the global carbon budget is estimated using an equal per capita distribution. The carbon budget is applied throughout the pathway assuming an exponential decay, ensuring net-zero CO2 emissions by 2050. For the Current Trends scenario, no CO2 limit is imposed. The model runs from 2020 to 2050 with a planning horizon every five years, using a myopic approach. At each planning step, the total system cost is minimised subject to the CO2 constraint determined by exponential decay, without foresight into future constraints. In both scenarios, Europe is assumed to be energy self-sufficient.

The Euro-Calliope set an upper boundary on total EU27+UK emissions, using the emission target percentage applied to their combined 1990 emission levels (excluding 1990 steel and chemical industry feedstock emissions for 2030, but including them for 2050). Mitigation targets were not set for individual countries, nor were they differentiated by sector. Additionally, NDC emission limits were applied to non-EU countries, which influenced the Euro-Calliope results for EU27+UK due to electricity imports from these regions. The data used to constrain emissions in the model are available online.

The energy system design in EnergyPLAN is based on the "A Clean Planet for All" PRIMES models, which have been replicated in EnergyPLAN [45]. Consequently, the Current Trends scenario in EnergyPLAN represents a replication of the "A Clean Planet for All" Baseline 2050 scenario. The Climate Neutrality scenario, on the other hand, is designed to achieve annual CO2 emissions of −0.139 Gt, consistent with the 1.5TECH scenario.

In DESSTINEE, the EU-wide climate neutrality targets outlined in the 'Green Deal' were applied, incorporating sectoral emissions caps based on the 1.5TECH and 1.5LIFE scenarios from the European Commission's '1.5 Degree Objective [5].

System boundaries were allowed to vary between the models, reflecting their differing scopes and design choices. Specifically, process emissions from industry are not harmonised between the models within the intercomparison, as this reveals a further dimension across which model assumptions and methods can differ. Instead, models were required to adhere to a harmonised overall emissions target (across all sectors), so that any differences in process emissions must be balanced out by stronger or weaker mitigation effort in other sectors. In common with other energy model intercomparisons [46], this deliberate design choice allows this study to provide a broader perspective on the feasibility and trade-offs of achieving climate neutrality. Supplementary results are provided for direct emissions from demand sectors, to allow for consistent comparison across models with process emissions excluded.

2.3. Models and interlinkages

The multi-model comparison includes models of different type, temporal, spatial, and sectoral coverage (Table 2). In an earlier phase, key interlinkages were identified and developed based on the models' needs, such as gaps in sectoral focus or resolution, and their respective strengths and weaknesses. These interlinkages enhanced the details, scope, and range of results of the (originally) sectoral models. In addition, linking certain energy supply models with DESSTINEE, an energy demand model, and HEB, a buildings demand model (Table 2), allowed for (i) the harmonisation of the socio-economic parameters of GDP and population by introducing them as drivers in the demand side, and (ii) the implementation of the emission targets for 2030 and 2050. For further details on the models, refer to the SENTINEL - Model Catalogue, while specific information on interlinkages can be found in Ref. [47].

The modelling results were compared with relevant scenarios published by the EC for validation: the EU Reference Scenario 2020 ('REF2020 scenario') [4], and the 'OFFICIAL scenario', a group of EU official scenarios consisted of the 'Baseline' and 1.5TECH scenarios from 'A Clean Planet for all' report [5] and the MIX scenario from '2030 Climate Target Plan' [37]. Specifically, historical values for 2015 and projections under the Current Trends scenario were compared with the REF2020 scenario and the OFFICIAL-Baseline scenario. Projections under the Climate Neutrality scenario were compared with the MIX and 1.5TECH scenarios for 2030 and 2050, respectively (Table 3). In addition, Section 3.3 compares high-level indicators with updated European policies to assess their alignment and relevance.

3. Results

This section discusses energy demand and energy supply results separately. We first examine the energy demand of the buildings, transportation, and industry sectors and the corresponding direct CO_2 emissions, and in the following sections the power supply. Smaller energy sectors (e.g., the agriculture sector) and other GHGs are not included as not all models could provide the necessary data.

3.1. Energy demand sectors

3.1.1. Final energy consumption for Europe

Projections of total final energy demand from the industry, transportation, and buildings sectors show an overall decrease towards 2050 for both the Current Trends and Climate Neutrality scenarios (Fig. 1). Still, there are clear differences between the two scenarios and across the models. The latter is caused by differences in model structure, technologies included and their economic and geographical potential, and in assumptions for electrification and energy efficiency improvements.

There are already some differences in 2015 across the models, but deviations from historical data are rather limited. For instance, the IMAGE model indicates lower demand despite its larger geographic scope, driven by sector-specific variations. While the IMAGE's industry and buildings sectors report values slightly higher than the OFFICIAL scenario (2 % higher for buildings and 8 % higher for industry), consistent with its broader coverage, the transportation sector reports 12 % lower final energy demand.

In the Current Trends scenario, the models agree on two main trends: (i) accelerated electrification of the demand sectors towards 2050, and (ii) the mitigation of fossil fuels use, especially coal and liquids, with both trends accelerated in the Climate Neutrality scenario. A unique case

Table 3
Validation scenarios published by the EC.

EU official scenarios		Year(s)	Compared with	Source
REF2020		2015	Historical values	EU Reference Scenario 2020
OFFICIAL	Baseline	2030, 2050	Current Trends	A Clean Planet for all
	MIX	2030	Climate Neutrality	2030 Climate Target Plan
	1.5TECH	2050	Climate Neutrality	A Clean Planet for all

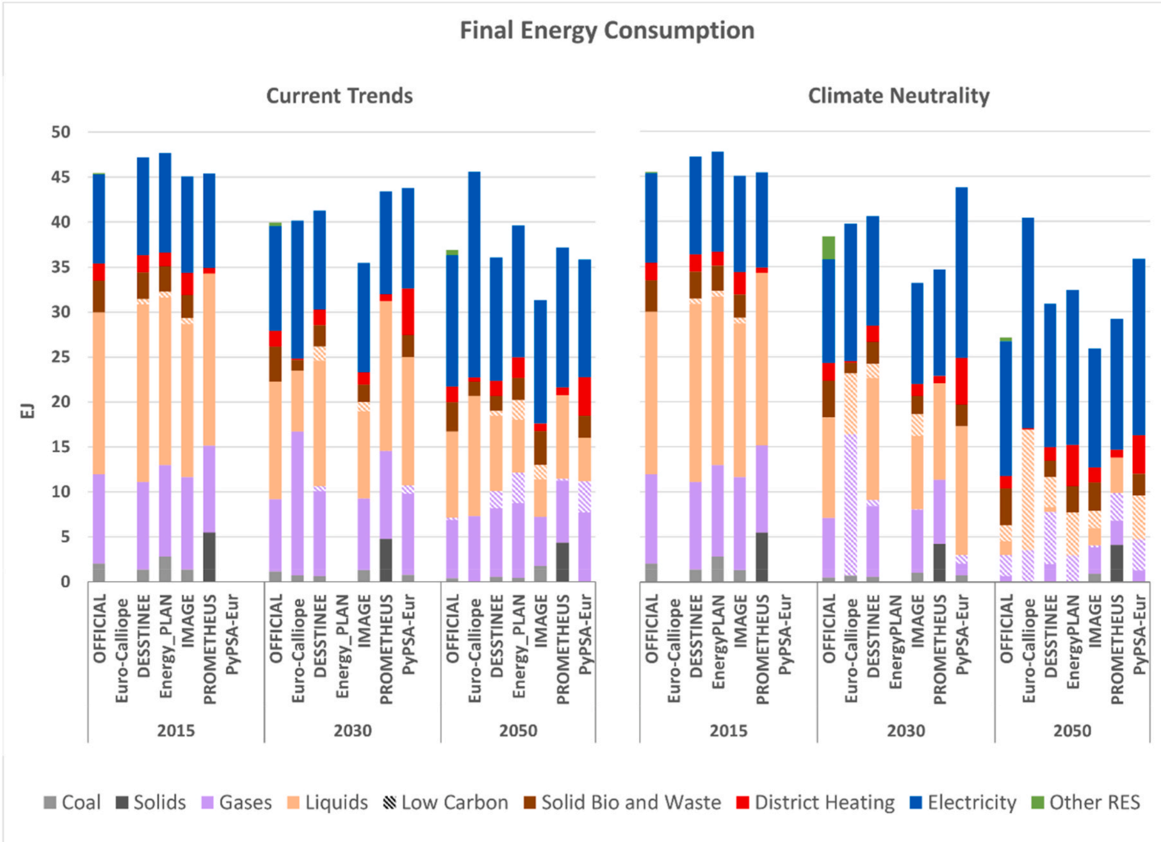

Fig. 1. Final energy consumption in the Europe region by energy carrier for the industry, transportation, and buildings sectors. 'Solids' reported by PROMETHEUS represents both coal and solid biomass. 'Other RES' for the OFFICIAL scenario represents 'other renewable energy sources'. Some models include low-carbon alternatives for fossil fuels (e.g., e-fuels and hydrogen) denoted by 'Low Carbon' (diagonal stripes) layered on top of a specific energy carrier.

is PyPSA-Eur, which reports similar total final energy demand for both scenarios due to unchanged exogenous assumptions for energy service demands and electrification of transport. However, in the Climate Neutrality scenario energy demand is mostly met by electrified alternatives and e-fuels.

3.1.1.1. Current Trends. In the Current Trends scenario, the total energy consumption decreases towards 2050 as a result of energy efficiency improvements, the shift to more efficient technologies, and the electrification of end-use technologies, such as heat pumps and electric vehicles. In 2030, the energy consumption decreases compared to 2015 by around 12 % for the OFFICIAL scenario and between 4 and 21 % for the models. By 2050, the consumption further decreases by 8 % for the OFFICIAL scenario, and 12–18 % for the DESSTINEE, IMAGE, PROMETHEUS, and PyPSA-Eur models (17–30 % compared to 2015). Contrary, Euro-Calliope projects a 13 % increase in energy consumption between 2030 and 2050. This is also the highest demand model in 2050, due to its wider sectoral scope (inclusion of international bunkers (around 7 EJ) and industrial feedstocks (8.2 EJ)).

Under the Current Trends scenario, the electricity share in final energy consumption increases significantly from an average of 23 % in 2015 to 30 % in 2030 and 41 % in 2050. Euro-Calliope projects the highest electricity shares: 38 % in 2030 and 50 % in 2050. This increase in electrification combined with a large uptake of renewable energy led to a significant fossil fuel reduction. This reduction is further supported by the use of alternative low-emission fuels (e.g., hydrogen, e-fuels, biofuels). By incorporating low-carbon fuels, the models increase the detail and flexibility in mitigation options for their future pathways. PROMETHEUS and IMAGE include hydrogen and solid and liquid biomass. Euro-Calliope, DESSTINEE, PyPSA-Eur, and EnergyPLAN incorporate additional biofuels, P2L (power to liquid), and P2G (power to gas). On average, the models start with a 6 % low-carbon fuel share in 2015, which under the Current Trends scenario increases to 7 % in 2030, and 13 % in 2050. The model results show that under this scenario the direct use of fossil fuels in the demand sectors reduces by 9–34 % in 2030, and 40–60 % in 2050, compared to 2015. The respective reductions for the OFFICIAL scenario are 26 % in 2030, and 45 % in 2050. Despite the transition to greener energy carriers, fossil fuels still play a significant role.

3.1.1.2. Climate neutrality. Under the Climate Neutrality scenario, the models project a greater reduction in energy consumption compared to Current Trends, especially in 2050. In 2030, the OFFICIAL scenario projects a decrease of around 16 %, while the range of models here project a range from 14 to 25 %. In 2050, energy consumption further decreases compared to 2015, with reductions of slightly above 40 % in the OFFICIAL scenario and 32–42 % in most of the models included here. In contrast, Euro-Calliope projects a small increase of 2 % between 2030 and 2050, despite increased electrification, due to a significant rise in electricity demand (see Section 3.2.1).

In 2030 Climate Neutrality scenario, the electrification rates are similar to those of the Current Trends scenario for the OFFICIAL scenario, IMAGE, and Euro-Calliope, DESSTINEE (30–38 %), while it increases for DESSTINEE, PROMETHEUS, and PyPSA-Eur by 3 %, 8 %, and 17 %, respectively. This noticeable increase in electrification for PyPSA-Eur is due to the assumption that under the Climate Neutrality scenario the direct heating for the building and industry sectors will be almost completely electrified. By 2050, all electrification projections are notably higher (50–57 % electricity shares). This indicates that electrifying energy end uses will be a significant driver in reaching the EU's

2050 climate neutrality goal. For instance, in Transportation electricity is assumed to become the primary energy source for passenger and light-duty freight road transport in 2050, and it will play a crucial role in providing heat for buildings and industries.

Additional to the increase of electrification in the demand sectors, significant changes in the rest of the carriers are required to meet the deep decarbonization targets for a net-zero EU by 2050. In the Climate Neutrality scenario, the shift to alternative low-carbon fuels is notably greater than in the reference scenario. In 2050, the models that incorporate both e-fuels and biofuels, i.e., Euro-Calliope, EnergyPLAN, DESSTINEE, PyPSA-Eur, and the OFFICIAL scenario assume the highest shares of low-carbon fuels (30–42 % in 2050). For IMAGE and PROMETHEUS, which only include biomass and hydrogen, the low-carbon fuels shares are 20 % and 10 % (solid biomass for PROMETHEUS could not be taken into account as it is reported together with coal).

In 2030 Climate Neutrality scenario, the projected share of fossil energy for most models shows only a slight decline (4–8%), compared to the Current Trends scenario. The outlier is Euro-Calliope which assumes an almost complete fossil phase-out already in 2030 (most directly used fossil fuels have been replaced by low-carbon alternatives). This modelling result also reflects Euro-Calliope's methodology nature, which cost-effectively optimised the system constrained by an emission target with limited constrains by existing infrastructure. In 2050, more models follow, with fossil fuel shares in energy demand ranging between 0 % and 11 %. However, for IMAGE and PROMETHEUS fossil fuels still play a significant role with shares of 22 % and 37 % (for PROMETHEUS, fossil fuels include solid biomass in their accounting), respectively. This is compensated by the use of BECCS (Bioenergy with Carbon Capture and Storage) during the energy generation (see Section 3.2). The above observations indicate a correlation between the inclusion of a variety of low-carbon fuels and the fossil fuels shares in energy consumption.

A final observation is the role of district heating in final energy use in the Current Trends and Climate Neutrality scenarios. District heating networks are projected to account for 1 %–14 % by 2050. This relatively big range in model projections illustrates the diversity of model structure and assumptions. For example, the PROMETHEUS model results include district heating in industry, but not in the building sector. The opposite is true for Euro-Calliope. For PyPSA-Eur and EnergyPLAN district heating is important for thermal energy provision both in industry and buildings sectors (11–14 % share on total energy demand).

3.1.2. Demand sector direct CO_2 emissions for Europe

Direct CO_2 emissions from the industry (including industrial process emissions), transportation, and buildings sectors (Fig. 2) vary between models due to differences in system boundaries, assumptions regarding carbon content for different fuels, and sector-specific fuel mix. Overall, the differences in reported emissions for the buildings and transportation sectors are relatively small in 2015, with deviations from the average value (including the OFFICIAL scenario) ranging from 10 to 15 %. However, these discrepancies become more pronounced in the industrial sector, where the OFFICIAL scenario reports emissions approximately 50 % higher than in the other models. In contrast, IMAGE industrial emissions are relatively low (11 % lower than the average of the models). These variations stem from differences in industrial feedstock and process emissions which account for 21 % of total industry emissions in the OFFICIAL scenario, while their share is significantly lower in the other models. Figure B1 (Appendix B) further supports this by providing re-estimated direct CO2 emissions from demand sectors, excluding process emissions, limiting the deviations to a maximum of 10 %. Additionally, differences in system boundary definitions in the

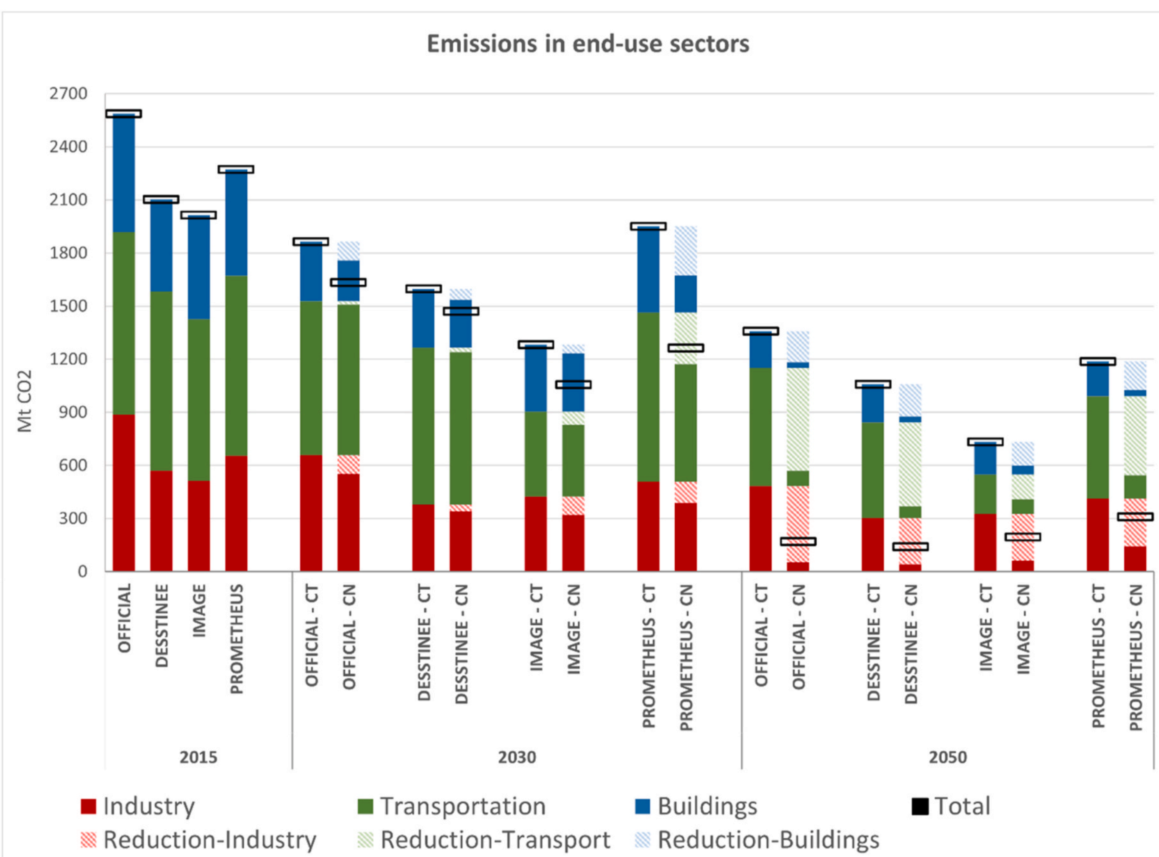

Fig. 2. Direct CO_2 emissions for Europe region including industry, transportation, and buildings sectors under the Current Trends (CT) and Climate Neutrality (CN) scenarios. The shaded lighter colours in the CN scenarios show the CO_2 emission reduction in each sector (compared to the respective CT scenarios). The black bars indicate the total CO_2 emissions for the sum of the sectors.

transportation sector also contribute. The EEA inventory reports 2.4 GtCO2eq emissions for 2015 from manufacturing, construction, industrial processes, transport, buildings, and agriculture energy use [48]. The OFFICIAL scenario and PROMETHEUS show historic final energy consumption for transportation comparable with IEA [49], while DESSTINEE and IMAGE value's (similarly to other IAMs as well [18]) are closer to Eurostat database [50].

Due to fuel switching and efficiency improvements across the end-use sectors, significant reductions in direct demand related CO_2 emissions are projected under both scenarios (Fig. 2). For the Current Trends scenario, the projected CO_2 emission reduction compared to 2015 values ranges between 28 % and 36 % in 2030, and 47 % and 64 % in 2050 among the participating models (Table 1). This is in line with Fig. 1 that shows that fossil fuels are still used in 2050, despite the decline of energy consumption and the transition to greener fuels. Under the Climate Neutrality scenario, due to the large-scale replacement of fossil fuels with low-carbon fuels and electrification, the direct CO_2 emissions are significantly decreasing. In 2030, direct fossil CO_2 emissions are between 30 % and 48 % lower than in 2015. By 2050, most of the CO_2 emissions are mitigated, with DESSTINEE, IMAGE, and PROMETHEUS estimating reductions up to 93 % from 2015 levels. The residual emissions from the demand sectors are mitigated in the energy supply sector to meet the overall neutrality target. This is endogenous in the participating IAMs, where emission reductions for demand and supply are interlinked, and therefore carbon budgets or emissions reduction targets can be implemented cost-effectively and calibrated in a straightforward way. Other models develop energy demand separately or take energy demand as input. The range of mitigation efforts across the demand and supply sectors are based on different assumptions on techno-economic trends and carbon intensity of energy use and production methods.

The differences in the projections between models become even more evident when examining the CO_2 emission reductions in each demand sector separately (Table 4). For context, the range spanned by the our projections (Fig. 3) is 45 % wider than found in an intercomparison of the US Inflation Reduction Act's impacts [46], although this could be expected as our projections run further, to 2050 rather than to 2035. In 2030, and under both scenarios, the results from OFFICIAL, DESSTINEE, and PROMETHEUS indicate that transportation is the sector with the lowest emission reduction, whereas IMAGE shows transportation as the sector with the highest reductions. By 2050, under the Current Trends scenario, transportation remains a challenging sector for emission reductions in the OFFICIAL scenario. In contrast, IMAGE projects relatively high emission reductions in this sector. Another multi-model study [22] showcases similar results, indicating lower CO2 emission reductions in the transportation sector in 2050 compared to other sectors. This study also indicates that for ALADIN, a model with a detailed representation of the transportation sector, almost complete

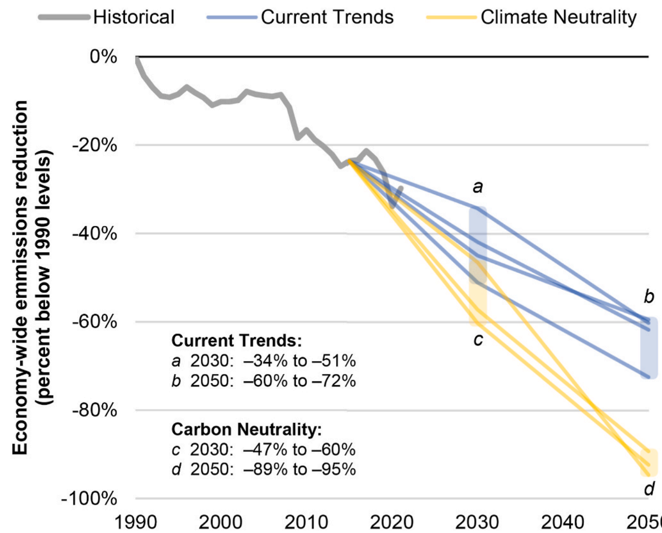

Fig. 3. Economy-wide CO_2 emissions reductions since 1990, showing historical progress across the European region, and the model projections under the Current Trends and Climate Neutrality scenarios.

decarbonization of the sector is achievable. This finding further supports our argument that models become more flexible with increased sectoral details.

Under the 2050 Climate Neutrality scenario, both DESSTINEE and IMAGE estimate nearly equal reductions across all sectors compared to 2015. PROMETHEUS, however, shows that heavy industry has fewer reductions compared to other sectors, indicating that it might be more cost-effective to achieve emission reductions in other sectors. In general, in optimisation energy system models, sectors with fewer emission reductions likely represent the most expensive sectors to decarbonize. However, simulation-based energy system models (ESMs) introduce complexity through feedback loops, altering the straightforward relationship between emission reductions and decarbonization costs. This complexity necessitates a broader analysis that considers additional indicators beyond emissions alone.

3.2. Power sector

3.2.1. Power generation for Europe

The power generation for "Europe" region under the Current Trends and Climate Neutrality scenarios is presented in Fig. 4 (Figure B2 in Appendix B provides additional details on the carriers). The total generation of electricity increases towards 2050 in both scenarios, despite

Table 4

CO_2 emission reductions compared to 2015 values, under Current Trends and Climate Neutrality scenarios for Europe region. Results include the end-use sectors of Industry, Transportation, and Buildings, and their total sum.

CO_2 reductions compared to 2015						
Scenario	Year	Model	Industry	Transportation	Buildings	Total
Current Trends	2030	OFFICIAL	26 %	16 %	50 %	28 %
		DESSTINEE	33 %	13 %	36 %	24 %
		IMAGE	17 %	48 %	35 %	36 %
		PROMETHEUS	22 %	6 %	19 %	14 %
	2050	OFFICIAL	45 %	35 %	69 %	47 %
		DESSTINEE	47 %	47 %	59 %	50 %
		IMAGE	36 %	76 %	69 %	64 %
		PROMETHEUS	37 %	43 %	67 %	48 %
Climate Neutrality	2030	DESSTINEE	40 %	15 %	48 %	30 %
		IMAGE	38 %	56 %	44 %	48 %
		PROMETHEUS	41 %	35 %	65 %	44 %
	2050	DESSTINEE	93 %	93 %	94 %	93 %
		IMAGE	88 %	91 %	91 %	90 %
		PROMETHEUS	78 %	87 %	94 %	86 %

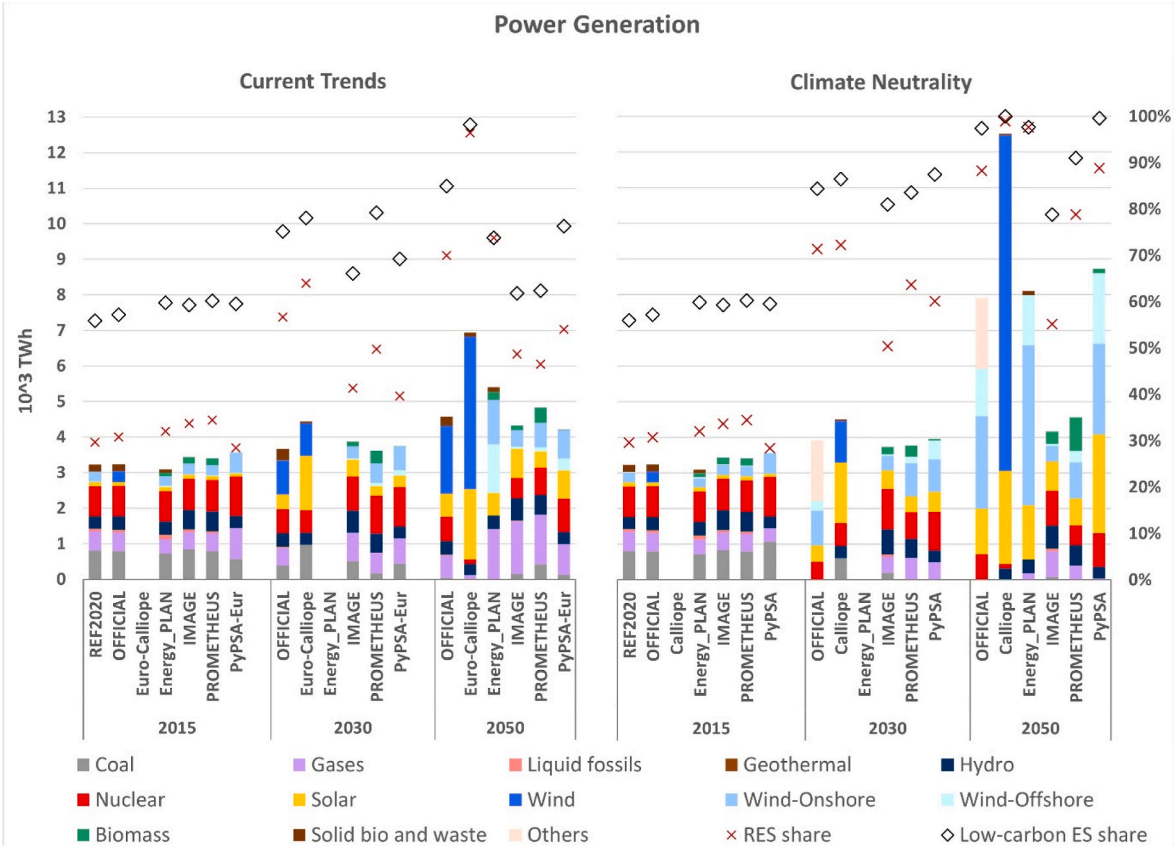

Fig. 4. Electricity production for the EUROPE region under Current Trends and Climate Neutrality scenarios. "Others" category stands for other renewables for REF2020, and other renewables and fossils for the official EU scenario. The renewable energy share calculations include the "Solid bio and waste" carrier under the assumption that it mainly consists of biomass. Low-carbon Energy Sources share includes RES and nuclear.

the overall reduction in energy demand (Fig. 1), caused by the increased electrification of the energy system and the increase in hydrogen production. In 2015, models' reported values are in line with the REF2020 and the official EU (OFFICIAL) scenarios; IMAGE and PROMETHEUS report slightly higher values due to the larger geographical areas they cover (e.g., including Norway and Switzerland), while EnergyPLAN is on the low side. However, all models overall agree on the energy carriers and power generation technologies used. Another similarity between the Current Trends and Climate Neutrality scenarios is the projected shift in fuel mix towards renewables and the fossil fuels phase-out; however, these phenomena are accelerated and more evident in the neutrality scenario.

Under the Current Trends scenario, most models project comparable power generation ranging between 3618 and 3869 TWh in 2030, and 4198 and 5395 TWh in 2050. The IMAGE and PROMETHEUS models report similar results with some differences in preferred electricity technologies. Euro-Calliope forms an outlier with a considerably higher overall electricity production linked to the higher electricity demand (Fig. 1). In addition, Euro-Calliope has the highest renewables share in electricity generation, and projects an almost complete fossil phase-out by 2050 (98 % RES share). EnergyPLAN and PyPSA-Eur also project a relatively high renewable energy share in 2050 (around 75 %).

Under the Climate Neutrality scenario, the model projections for 2030 are similar to the Current Trends scenario, but significantly different for 2050. In 2030, power generation slightly decreases for IMAGE (4 % decrease), while it increases for the rest of the models. This is the net result of two contradictory trends: the electrification of the energy system, which increases the demand for power generation, and simultaneously drives the adoption of more efficient and better-integrated technologies (e.g., smart grids), resulting in lower overall power generation requirements. All models project an increase in renewable energy, and a decrease in coal which is replaced by gases and renewables. In 2050, the OFFICIAL scenario, Euro-Calliope, and PyPSA-Eur, show near-doubling of power production compared to the Current Trends scenario, while EnergyPLAN projects an 50 % increase. For the OFFICIAL scenario, this increase is due to extensive electrification of various sectors, increased production of e-fuels and hydrogen, and overall growth in electricity demand to replace fossil fuels and support new low-carbon technologies (for details, see the 1.5TECH scenario in the "A Clean Planet for All" report [5]). Similarly, the relatively high-power production in the Euro-Calliope, EnergyPLAN, and PyPSA-Eur models is mainly due to the higher amounts of green hydrogen production. In contrast, IMAGE and PROMETHEUS project a decrease in power generation of 4 %–6 % relative to the Current Trends scenario, suggesting that the reduction in total energy demand combined with efficiency improvements outweigh the effect of electrification in the energy system. Most models project a fossil phase-out, without Carbon Capture and Storage (CCS), by 2050; unabated Fossil fuels get replaced by renewables and hydrogen, and, in the case of Euro-Calliope, EnergyPLAN, and PyPSA-Eur also by e-fuels. The introduction of alternative low-carbon fuels allows for an easier transition to neutrality and at the same time increases the flexibility of the models to represent the energy system transformation pathways. IMAGE projects a significant increase of renewable energy but retains around 20 % of fossil fuels. However, almost 100 % of the fossil energy is used in combination with CCS, resulting in low emissions.

A significant difference between the models emerges in the 2030 results for the Climate Neutrality scenario. While most models show coal being replaced by low-carbon energy sources and gas, Euro-Calliope phases out gas plants first. Although this outcome may seem unusual for a climate neutrality scenario, it is not entirely unexpected, as Calliope is an optimisation model. In the context of rising gas prices, the model minimizes costs by maximizing renewable energy production and relying on the cheapest remaining option, which, in this case, is coal. Notably, Calliope operates as a snapshot model, meaning it does not account for long-term dynamics typically captured in time-series models, such as sunk costs and potential lock-ins associated with gas infrastructure. This behavior highlights a limitation of "greenfield" optimisation models, which are more suitable for analysing longer-term horizons, such as 2050.

Another key difference between the models arises from the assumptions regarding the use of nuclear energy towards 2050. For example, EnergyPLAN assumes no nuclear energy in 2050 for both Current Trends and Climate Neutrality scenarios, while Euro-Calliope assumes nuclear deployment and phaseout in line with countries' stated plans, resulting in shares of 1 % and 2 %, respectively. In the OFFICIAL scenario, IMAGE, PROMETHEUS, and PyPSA-Eur nuclear energy declines towards 2050. However, it still plays a role in 2050 with shares ranging between 13 % and 22 % in the Current Trends, and 9 % and 24 % in the Climate Neutrality scenarios. Fig. 4 highlights a trade-off between nuclear power and RES, as reflected in the difference between low-carbon energy sources and RES shares.

It is important to note that the presented and analysed data offer information on the total net power produced by source type at the point of generation, and that a discussion on the operational flexibility of the power system, although significant [51], is beyond the scope of this intercomparison. The models that consider low or no thermal power production technologies tend to assume that part of the power generated by intermittent renewable sources is stored in batteries or else used for synthesising hydrogen and/or other types of 'power to-x' solutions, which can in turn be used as carriers for electricity generation.

3.2.2. *Power generation related CO_2 emissions in Europe*

The CO_2 emissions from power generation (Fig. 5) reduce significantly in 2050 under both the Current Trends and Climate Neutrality scenarios (Figure B3 in Appendix B provides more disaggregated results). The values for Euro-Calliope and EnergyPLAN are calculated based on the reported fuel consumption (Figure B4 in Appendix B) and supply-side emission factors from the IMAGE model (Appendix C).

In 2015, EnergyPLAN, IMAGE, and PROMETHEUS report similar emissions for electricity generation, considering the different region definitions in which IMAGE and PROMETHEUS cover larger areas. The OFFICIAL scenario in 2015 shows higher emissions, and similar to REF2020, which additionally includes emissions form district heating. PyPSA-Eur on the other hand reports lower total emissions, but a fuel mix, like the ones from IMAGE and EnergyPLAN, although with almost no fossil liquids (Figure B4).

In the Current Trends scenario, power generation emissions decrease towards 2050, despite the increase of power generation. This is caused by a combination of efficiency improvements, a shift to renewables, and the use of CCS, which are results of cost reductions (especially wind and solar that have experienced drastic cost reductions in the last decade) and an increasing ETS carbon price. In 2030, Euro-Calliope reports higher emissions than IMAGE and PyPSA-Eur due to its reliance on coal for energy generation (see Section 3.2.1). However, by 2050, Euro-Calliope projects shows a steep decline, with only minimal residual emissions from natural gas. Emissions reduction by 2050 is also projected by EnergyPLAN, PROMETHEUS, PyPSA-Eur, and the official EU scenario. In this year, IMAGE projects the highest emissions, despite having the lowest electricity generation projections, and some negative emissions from BECCS; the reason behind this is the lower renewable share for IMAGE and the persistence of fossil fuels (especially natural gas) in the electricity mix.

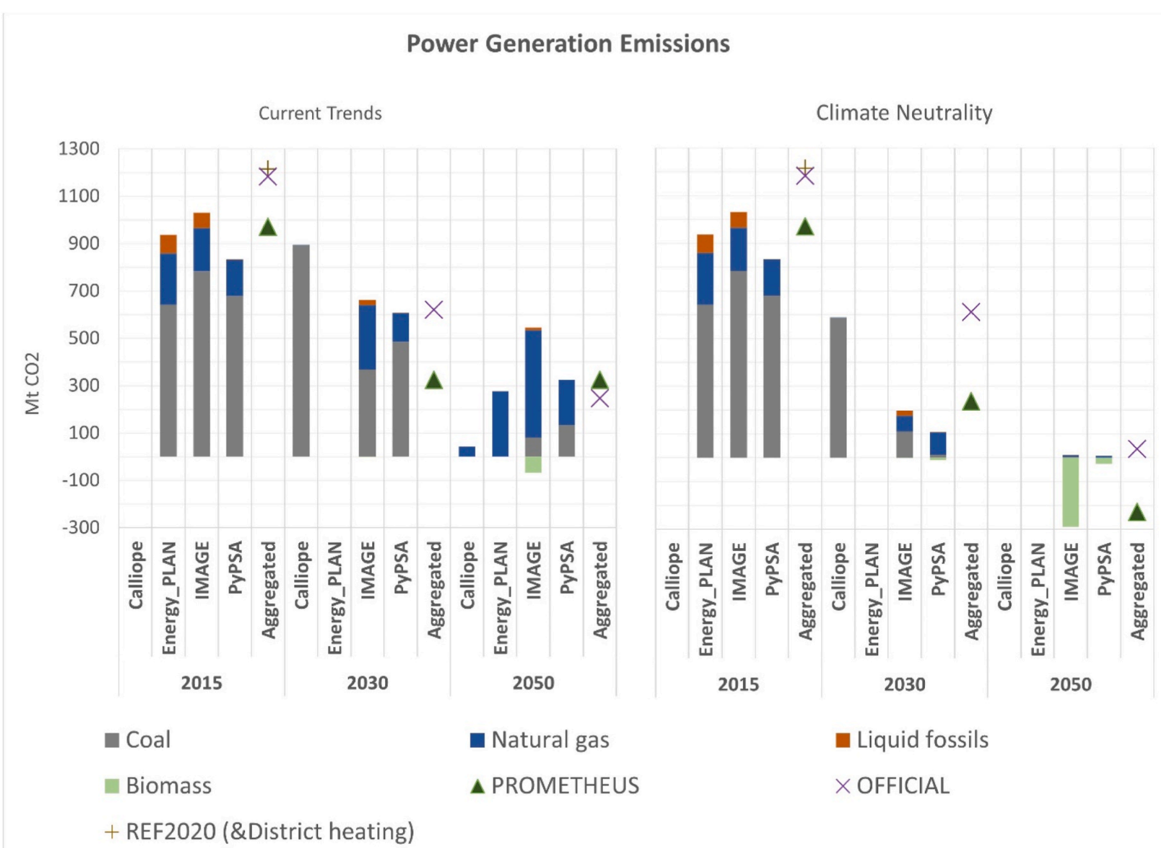

Fig. 5. CO_2 emissions from electricity generation for the Europe region under Current Trends and Climate Neutrality scenarios. "Aggregated" category refers to total CO_2 emissions provided by the official EU scenario, the REF2020 scenario, and PROMETHEUS.

In the Climate Neutrality scenario, emissions decrease significantly mainly due to the increased share of renewables, low-carbon fuels, and CCS. In 2030, Euro-Calliope and PROMETHEUS emissions projections decline by 34 % and 27 % compared to the Current Trends scenario, while IMAGE and PyPSA-Eur project more than double reductions. Notably, the OFFICIAL scenario projects similar CO_2 emissions in 2030 for both scenarios. By 2050, emissions from Euro-Calliope and EnergyPLAN decrease to zero, utilizing a combination of renewable energy sources (RES) and carbon-neutral gases. In contrast, IMAGE reports a smaller share of renewables. In the Climate Neutrality scenario, IMAGE employs CCS to reduce fossil fuel emissions almost to zero by 2050. Additionally, the negative emissions from BECCS further decrease CO_2 emissions from power generation in the IMAGE scenario. Other models that use BECCS are PROMETHEUS and, with a very limited use PyPSA-Eur. Together with IMAGE these models project the lowest emission values in the neutrality scenario. These findings highlight different approaches and technological options to achieve a net-zero electricity system. Some models deploy BECCS and sustainable imports of second-generation feedstocks, while others heavily rely on renewables.

3.3. Evaluating results against updated EU policy targets

Our study examines climate neutrality scenarios related to the EU Green Deal and the 2030 Climate Target Plan from the EC. Since our modelling runs, the Commission has published more recent directives that further update and strengthen the 2030 targets set by the Green Deal and the Fit for 55 package, providing more specific and binding targets as well as mechanisms to achieve these goals.

The revised Renewable Energy Directive (EU/2023/2413) [52] and the revised Energy Efficiency Directive (EU/2023/1791) [53] set updated 2030 targets for renewable energy share and energy consumption reduction, respectively. Directive (EU) 2023/2413, building on the REPowerEU Plan [54], aims to make the EU independent from Russian fossil fuels well before 2030. It proposes increasing the overall Union renewable energy target to 42.5 % of gross final energy consumption (GFEC) to significantly accelerate the deployment of renewable energy. Member States are encouraged to collectively strive for an even higher target of 45 %. Similarly, Directive (EU) 2023/1791 requires an additional level of effort compared to the measures currently in place or planned, raising the EU energy efficiency target by an additional 11.7 % reduction in energy consumption by 2030 (relative to the projections of the EU Reference Scenario 2020). This translates to a cap of 992.5 Mtoe for primary energy and 763 Mtoe for final energy demand.

Since we lack data for GFEC, we focus on the power sector for the RES target. While GFEC encompasses all energy consumed by end-use sectors, power supply specifically focuses on electricity generation. Although these are distinct metrics, comparing renewable power supply with the EU's GFEC-based renewable energy target remains relevant because electricity is a key driver of decarbonization. Power supply contributes significantly to GFEC and reflects progress in shifting to renewable energy sources, particularly in end-use sectors like transport and buildings, where electrification is crucial for meeting climate goals. In the absence of a specific target for power consumption, we assume the same percentage as a valid target for our comparison. For the energy efficiency target, we evaluate only our final energy demand modelling results, as primary energy demand is not part of the study.

When comparing our modelling results for the 2030 climate neutrality scenarios with the updated targets, we find that the models exceed the RES share target for 2030 but fall short of meeting the energy efficiency targets. The models project RES share in power production ranging from 50 % to 72 %, exceeding the 42.5 % GFEC target (Fig. 4). However, final energy demand results (Fig. 1) indicate projections higher than the 31.91 EJ (763 Mtoe) cap, ranging from 33 EJ (IMAGE) to 43 EJ (PyPSA). This suggests that models compensate for higher energy demand with greater RES deployment, emphasizing the interplay between energy efficiency and renewable energy targets. Achieving the updated efficiency targets would reduce the pressure to expand RES deployment, highlighting the importance of demand-side measures in balancing the EU's energy transition.

4. Discussion and conclusions

In this study, we have conducted a comprehensive model comparison, bringing together IAMs, IMAGE and PROMETHEUS, and bottom-up ESMs, DESSTINEE, EnergyPLAN, PyPSA-Eur, Euro-Calliope, and HEB (through interlinkages)), within a common scenario framework. The aim is to examine the recently strengthened 2030 EU climate target and the 2050 net-zero emission targets. These models exhibit different levels of geographic, temporal, technology, and sectoral aggregation. While these differences pose challenges for model comparison, they also provide the strength of this study by offering insights into different aspects of the energy transition.

4.1. Impact of assumptions on model projections

Considering both IAMs and ESMs offers us vital insights into specific sectors and the energy system as a whole. The model comparison provides a range of pathways for achieving policy goals. Furthermore, it allows us to identify similarities and differences between the models by examining key energy and emission indicators and how different assumptions and characteristics in the models influence projections for both Current Trends and Climate Neutrality scenarios. ESMs provide a more detailed evaluation of technology costs and performance, while IAMs offer a more aggregated yet comprehensive perspective. These two frameworks can complement each other: IAMs could expand their flexibility and technology inclusion, recognizing that flexibility is crucial in the energy transition. Meanwhile, ESMs could improve their integration of demand and supply sectors, incorporating dynamics such as sector coupling and feedbacks. Additionally, both frameworks could benefit from aligning with explicit policy targets for different sectors, enhancing their relevance to real-world policy objectives.

4.2. Energy consumption trends and electrification

Most participating models project an overall reduction in energy consumption relative to 2015 under both Current Trends and Climate Neutrality scenarios towards 2050. This reduction, ranging from 17 % to 30 % under Current Trends and 32 %–42 % under Climate Neutrality compared to 2015 levels, is primarily driven by accelerated electrification and energy efficiency improvements. Despite this decrease, the increased electrification of demand sectors leads to a higher share of electricity in total energy demand by 2050, ranging from 50 % to 57 % in Climate Neutrality scenarios.

4.3. Fossil fuel phase-out and renewable integration

Models depict varying pathways to achieve fossil fuel phase-out by 2050, primarily through increased electrification rates, renewable energy uptake, and incorporation of low-carbon alternatives like biomass, hydrogen, and e-fuels. IAMs such as IMAGE and PROMETHEUS, which assume fewer low-carbon fuel alternatives, illustrate less flexibility in transitioning rapidly to fully renewable energy systems compared to bottom-up ESMs. This underscores how different technology assumptions influence the feasibility and pace of decarbonization pathways.

4.4. Power generation and technology choices

Projections indicate an increase in power generation towards 2050 under both scenarios, with a significant shift towards renewables. Wind and solar power play pivotal roles, particularly in models emphasizing renewable energy integration. Euro-Calliope stands out with higher estimates driven by extensive use of green hydrogen and, together with EnergyPLAN and PyPSA-Eur, relies heavily on renewables to meet emission mitigation targets. Conversely, the examined IAMs, IMAGE and PROMETHEUS, align closely in their power generation projections and technology choices, employing CCS and BECCS to allow for residual fossil fuel use. This highlights diverse technological pathways to achieve climate neutrality.

4.5. Nuclear energy and policy implications

Assumptions regarding nuclear energy vary significantly among models, with projected shares ranging from 1 % to 24 % by 2050. These differences underscore the importance of considering diverse technology portfolios in developing robust climate policies. Policymakers should prioritize strategies that enhance energy efficiency, promote electrification, and accelerate the deployment of renewable energy sources to achieve resilient and carbon-free energy systems. Additionally, the role of nuclear energy and effective carbon capture technologies should be considered to create a sustainable, low-emission energy landscape.

4.6. Future research directions

While this study has contributed to advancing our understanding of the energy transition and the associated challenges through a detailed model comparison, there are several areas where further research would be beneficial.

- Expand the model comparison alongside a well-defined scenario protocol: Enhance the comparison by incorporating a broader range of IAMs and ESMs. This approach would provide a more comprehensive understanding of the variations and uncertainties in model projections. Ensuring consistent scenario representation and addressing differences in model results would significantly improve the robustness of the findings and their relevance for policy recommendations.
- Enhancing system boundaries and assumptions: while less restricted system boundaries reflect the models varying scopes and design choices, future research should focus on refining system boundaries and assumptions in order to capture a more comprehensive view of the energy system. This includes addressing uncertainties related to feedstock/process emissions in the industry sector and incorporating more detailed representations of new and emerging technologies and fuels and a detailed representation of land use.
- Harmonisation of key indicators: by harmonising input data (e.g., techno-economic characteristics) between the models the degrees of freedom in the model calculation decrease making it easier to understand the origin of similarities and differences between the modelling results.
- Address uncertainties and sensitivity analysis: conduct sensitivity analyses to assess the impact of key uncertainties and assumptions on the model outputs. Similar to point above, this will help identify the sources of variations and provide insights into the robustness of the findings.
- Include policy updates: modelling pathways could be updated to more recently developed EU policy targets, for example REPowerEU Plan, introduced by the EC to tackle the energy market disruptions caused by Russia's invasion of Ukraine, or as in this study, the more recent revised Renewable Energy (EU/2023/2413) and Energy Efficiency (EU/2023/1791) Directives

In summary, our study has provided valuable insights into the diverse pathways toward climate neutrality in the EU. The model comparison exercise has highlighted the strengths and limitations of different modelling approaches and shed light on the challenges and opportunities associated with achieving the EU's climate neutrality goals. By continuing to advance research in these areas, we can improve the accuracy and reliability of model-based assessments and contribute to the successful realization of climate ambitions.

CRediT authorship contribution statement

Efstratios Mikropoulos: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mark Roelfsema:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Hsing-Hsuan Chen:** Methodology, Investigation, Data curation. **Iain Staffell:** Writing – review & editing, Software, Methodology, Investigation, Data curation, Conceptualization. **Gabriel Oreggioni:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dan Hdidouan:** Data curation, Investigation. **Jakob Zinck Thellufsen:** Writing – review & editing, Investigation, Formal analysis, data curation. **Miguel Antonio Chang:** Writing – review & editing, Investigation, Formal analysis. **Panagiotis Fragkos:** Writing – review & editing, Investigation, Formal analysis. **Anastasis Giannousakis:** Writing – review & editing, Investigation. **Souran Chatterjee:** Methodology, Investigation, Formal analysis. **Diana Ürge-Vorsatz:** Investigation, Formal analysis. **Stefan Pfenninger:** Writing – review & editing, Investigation. **Bryn Pickering:** Writing – review & editing, Investigation, Formal analysis. **Marta Victoria:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Tom Brown:** Investigation. **Detlef P. van Vuuren:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has received funding from the European Union's Horizon 2020 research and innovation programme (Grant agreement 837089, SENTINEL project).

Appendix A

Table A1
Framework and model synopsis.

Model	Starting point for scenarios	Scenario adjustments in line with model protocol	Model description	Model characteristics	Main model inputs	Documentation
DESSTINEE – demand module	DESSTINEE was updated for the SENTINEL project with technology incorporation defined to meet demand-related emissions in the European Commission's official Current Policies and Green Deal scenarios. "Current Trends" assumes no additional policy measures beyond those in 2023, "Climate Neutrality" aligns with achieving net-zero greenhouse gas emissions by 2050	The EU Reference 2020 figures were used to for trends in GDP, population growth, and demand drivers. Proposed EU-wide fuel baskets in official scenarios were nationally downscaled, based on econometric relationships with income and current deployment	A simulation model for future energy demand and European infrastructure requirements. Uses a scenario-based approach to project service demands and the energy vectors that supply them, disaggregated by sectors and countries. Final energy demand and resulting fossil CO_2 emissions are calculated	Geographical coverage: 40 countries in Europe & MENA. Energy vectors: 10 primary and secondary forms. Timespan: Annual energy demands and hourly electricity profiles, in 2015, 2030 and 2050. Coverage: road transport, aviation, shipping, residential & commercial buildings (heat, cool, appliances), light & heavy industries	Reference year calibration with country-level macroeconomic data and fuel consumption across final energy uses. Scenarios for growth in population, GDP, heating and cooling degree days. Scenarios for efficiency increase across end uses (e.g. building envelope improvement) and penetration of new technologies (e.g. heat pumps, electric and hydrogen vehicles)	Documentation inside the open source model spreadsheets, and via https://sites.google.com/site/2050desstinee/ Related publications: https://doi.org/10.1016/j.energy.2015.06.082 https://doi.org/10.1016/j.energy.2017.12.051
EnergyPLAN	Climate Neutral Europe, with offset in the PRIMES scenarios described in "A Clean Planet for All". Reference scenario is based on the Baseline scenarios in "A Clean Planet for All", whereas the Climate Neutral Scenarios is based on the carbon targets for the Energy System, defined in "A Clean Planet for All". The Climate Neutral Scenario is based on the concept of Smart Energy Systems. https://www.sciencedirect.com/science/article/pii/S2666955223000230		Sector coupled scenario of the European Energy System. The model includes electricity, heating, cooling, transport and industry. It includes renewable energy modelling, as well as district heating. It utilises sector coupling and smart energy system principles, including power to X, green fuel production and utilisation of waste heat The model is a simulation model, but the system has been designed to fufill demand in every single hour, across all sectors, limiting the use of biomass and ensuring demand can be fulfilled without imports to Europe	Europe is modelled as an aggregated model. Single year model with hourly resolution. Simulation model. The model covers EU + UK	Energy demands Energy capacities and efficiencies Time series for demands and production profiles from renewables Technology cost data	https://www.sciencedirect.com/science/article/pii/S2666955223000230 https://www.sciencedirect.com/science/article/pii/S2666955221000071
Euro-Calliope	"Current Trends" assumes no additional policy measures beyond those in 2023, "Climate Neutrality" aligns with achieving net-zero greenhouse gas emissions by 2050. Both scenarios were used to define percentage 1990 emissions reduction targets for 2030 and 2050. End-state (a.k.a. "greenfield") model with minimal initial conditions set for defining the supply system in 2030 or 2050. In 2030: - maximum capacity per country of conventional	2030 emissions reduction targets were set relative to only 1990 energy sector emissions. 2050 emissions reduction targets were set relative to 1990 energy and industry sector emissions (i.e. including feedstock emissions)	Sector-coupled energy system model comprising electricity, heating, land transport, industry (including industrial feedstock), shipping, and aviation. This includes direct air capture of CO2 and power-to-gas and power-to-liquids. The model is solved as a linear optimisation problem in which system-wide monetary costs are minimised in the	Geographical coverage: EU + UK, Norway, Switzerland, Iceland, Albania, Serbia, Bosnia & Herzegovina, North Macedonia, Montenegro. Final results limited to EU + UK. In 2030: imports of fossil fuels from beyond model boundaries permitted. In 2050: No imports/exports of energy or industry feedstocks permitted from beyond model boundaries.	Technology cost and efficiency Existing and planned transmission lines among countries. Demand for building-level services, industry (by subsector), land transport, aviation, and shipping (incl. international bunkers)	Main text & Supplemental Material: https://doi.org/10.1016/j.joule.2022.05.009

(continued on next page)

Table A1 (*continued*)

Model	Starting point for scenarios	Scenario adjustments in line with model protocol	Model description	Model characteristics	Main model inputs	Documentation
	power plants (fossil fuel and nuclear) set at 2020 capacities. - International transmission capacity expansion limited to those currently under construction. In 2050: - maximum nuclear capacity per country limited to current levels minus those set for decommissioning. - International transmission capacity expansion limited to all those defined in the 2020 TYNDP. In 2030 & 2050: - Building & industry subsector demands scaled according to HEB and DESTINEE scenario-specific simulations		presence of a CO2 emissions budget (set per scenario and model year)	Single year optimisation model with hourly temporal resolution and national spatial resolution		
HEB	HEB model uses a bottom-up approach, integrating a performance-oriented perspective that incorporates detailed technological information on the building sector	HEB uses EU Reference 2020 values for increase trends for GDP, and population growth to align with model complementarity	Accounting based bottom-up model. Service energy demand covered: residential buildings (heating, cooling, and hot-water); commercial buildings (heating, cooling, and hot-water)	Service energy demand is calculated for three end uses namely space heating, cooling, and hot-water for each of the EU Member States and UK	HEB considers macroeconomic and sociodemographic parameters, such as population, urbanization rate, and floor area per capita for each of the EU Member States and UK	doi.org/10.1016/j.rser.2024.114827 doi.org/10.1016/j.erss.2024.103757 doi.org/10.1007/978-3-030-99177-7_7
PyPSA-Eur	Climate Neutrality: Transformation of the European energy system under a carbon budget corresponding to a temperature increase of 1.7 °C, with 67 % confidence. The share of the global carbon budget allocated to Europe is estimated assuming an equal per capita distribution. The available carbon budget is distributed throughout the path assuming an exponential decay and forcing net-zero CO2 emissions in 2050 https://doi.org/10.1016/j.joule.2022.04.016 Current trends: CO2 limit is not imposed	Run "Current trends" scenario which was not part of the original publication (https://doi.org/10.1016/j.joule.2022.04.016)	Sector-coupled energy system model comprising electricity, heating, land transport, industry (including industrial feedstock), shipping, and aviation, as we a detail carbon management. This includes power-to-gas and power-to-liquids, as well as energy consumed for carbon capture, use, and storage (CCUS). The model optimises generation, storge, transmission and energy conversion technologies together with their hourly operation to minimise system cost subject to a global CO2 constraint	Geographical coverage: EU + UK, Norway, Switzerland Each country ismodelled as a single node interconnected with others Temporal resolution: hourly resolution for a full year in each of the planning horizons Time horizon: 2020 to 2050 with a planning horizon every 5 years using myopic approach (For every planning horizon, the total system cost is minimised subject to a CO2 constraint determined by the exponential decay but without any information regarding the future)	Technology cost and efficiency Existing transmission lines among countries. Demand for land transport, aviation and shipping	Supplemental Materials in https://doi.org/10.1016/j.joule.2022.04.016 https://pypsa-eur.readthedocs.io/en/latest/
IMAGE	1.5C (SSP2-1.9) scenario from https://dspace.library.uu.nl/handle/1874/415178. Click or tap if you trust this link.">The 2021 SSP scenarios of the IMAGE 3.2 model Current trends baseline scenario	Harmonise socioeconomic inputs Introduce (additional) carbon price to further reduce CO2 emissions in Europe region in line with the targets	An integrated assessment model that simulates the environmental consequences of human activities worldwide. It represents interactions between society, the biosphere	Geographical coverage: Global, (26 regions), Western Europe and Eastern Europe are aggregated to Europe region Model type: Partial equilibrium (scenario model	Socio-economic parameters (GDP, population) Technology costs Learning parameters Resource depletion	https://sentinel.energy/model/image/ https://models.pbl.nl/image/Welcome_to_IMAGE_3.3_Documentation

(*continued on next page*)

Table A1 (*continued*)

Model	Starting point for scenarios	Scenario adjustments in line with model protocol	Model description	Model characteristics	Main model inputs	Documentation
			and the climate system to assess sustainability issues such as climate change, biodiversity and human well-being. The objective of the IMAGE model is to explore the long-term dynamics and impacts of global changes that result from interacting socio-economic and environmental factors	Time horizon: 1971 to 2100		
PROMETHEUS	Socioeconomic assumptions follow SSP2 for non-EU regions and the EU Reference scenario for EU countries Current trends are included in the baseline scenario, while the net-zero CO2 target is imposed in the climate neutrality scenario	Use of EU Reference 2020 figures for increase trends for GDP, population growth, and demand drivers	PROMETHEUS is a global energy system model that simulates the complex interactions between energy demand and supply, energy prices and emissions. It is used to assess climate change mitigation pathways at global and regional scales, by quantifying the required low-carbon technology uptake and green financial needs focusing on the medium and long-term horizon	Geographical coverage: Global, (10 regions), Western Europe and Eastern Europe are aggregated to Europe region Model type: Energy market simulation (scenario-based model) Time horizon: 1981 to 2050	Socio-economic parameters (GDP, population, industrial production) Technoeconomic assumptions for energy-related technologies Energy and climate policies (differentiated by scenario) Learning parameters for low-carbon technologies Resource depletion for fossil fuels and renewable energy	Model manual: https://e3modelling.com/modelling-tools/prometheus/ https://www.i2am-paris.eu/detailed_model_doc/prometheus https://www.iamcdocumentation.eu/Model_Documentation_-_PROMETHEUS Related publications: https://link.springer.com/article/10.1007/s10666-015-9442-x?sa_campaign=email%2Fevent%2FarticleAuthor%2FonlineFirst https://onlinelibrary.wiley.com/doi/abs/10.1002/ente.202000395

Appendix B

Supplementary graphs for energy demand and supply.

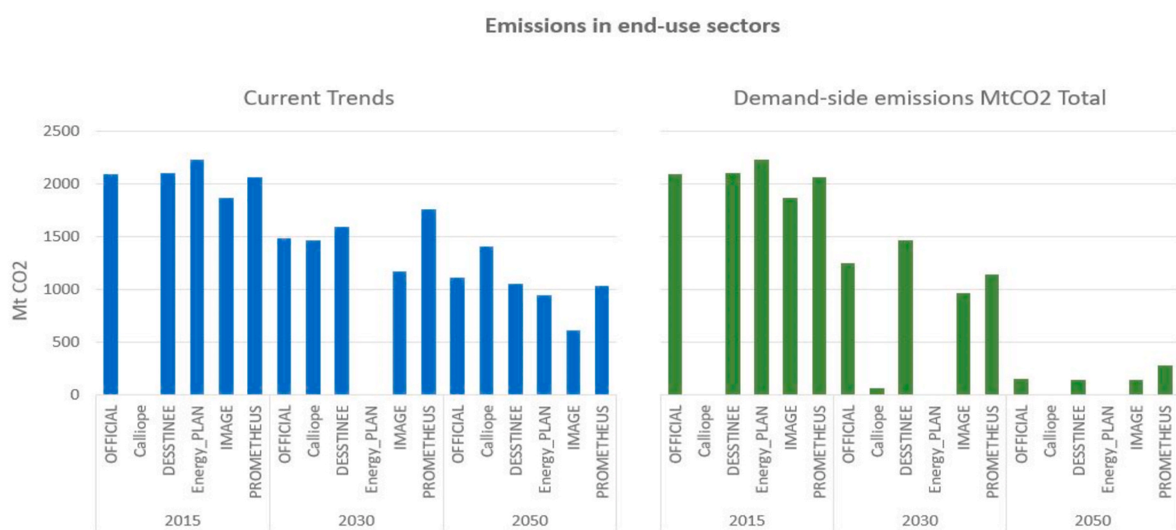

Fig. B1. Direct CO2 emissions for Europe region for industry (excluding emissions from industrial processes), transportation, and buildings sectors under the Current Trends and Climate Neutrality scenarios. For DEESTINEE the originally reported emissions are used (same as Fig. 2). For OFFICIAL and EnergyPLAN the emissions are approximated by multiplying the energy consumption with the carbon content of the corresponding carriers (Appendix C -Table C1); this is a simplified method that ignores factors like energy conversion efficiencies, transportation losses, and other considerations specific to the energy system.

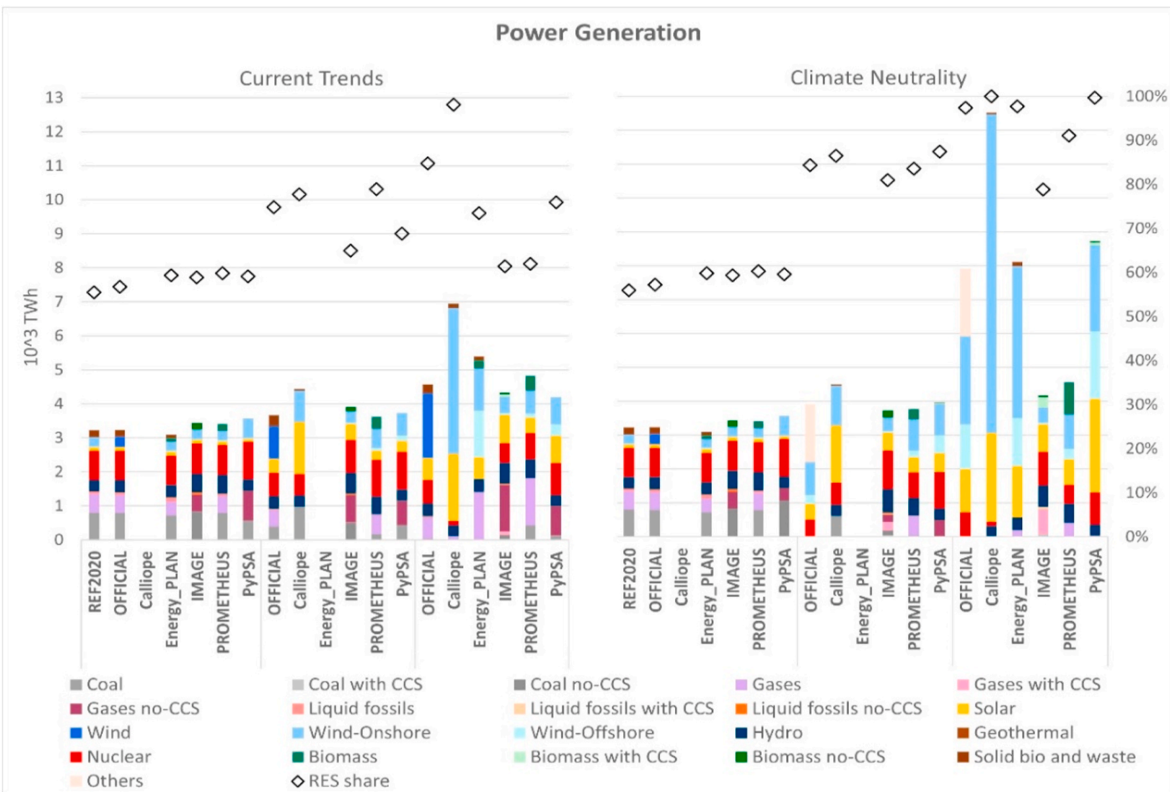

Fig. B2. Electricity production for the EUROPE region under Current Trends and Climate Neutrality scenarios. The official EU scenario incorporates data from 'A Clean Planet for all' and '2030 Climate Target Plan' (European Commission, 2018b, 2020b). "Others" category stands for other renewables for REF2020, and other renewables and fossils for the official EU scenario. Some models distinguish between carriers that are coupled with CCS and carriers that are not coupled to CCS.

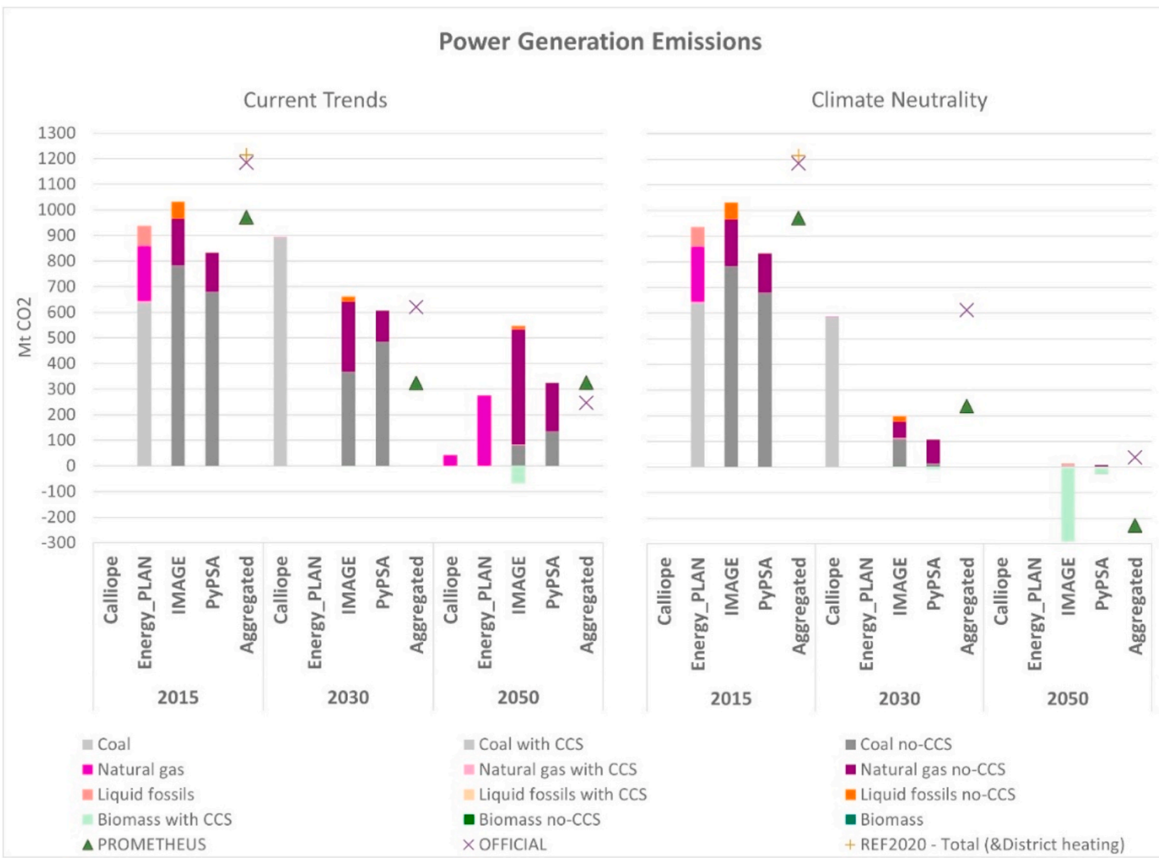

Fig. B3. CO2 emissions from electricity generation for the Europe region under Current Trends and Climate Neutrality scenarios. The official EU scenario contains data from 'A Clean Planet for all' and '2030 Climate Target Plan' (European Commission, 2018b, 2020b). "External" category refers to data from the official EU scenario and the REF2020 scenario. Some models distinguish between carriers that are coupled with CCS and carriers that are not coupled to CCS.

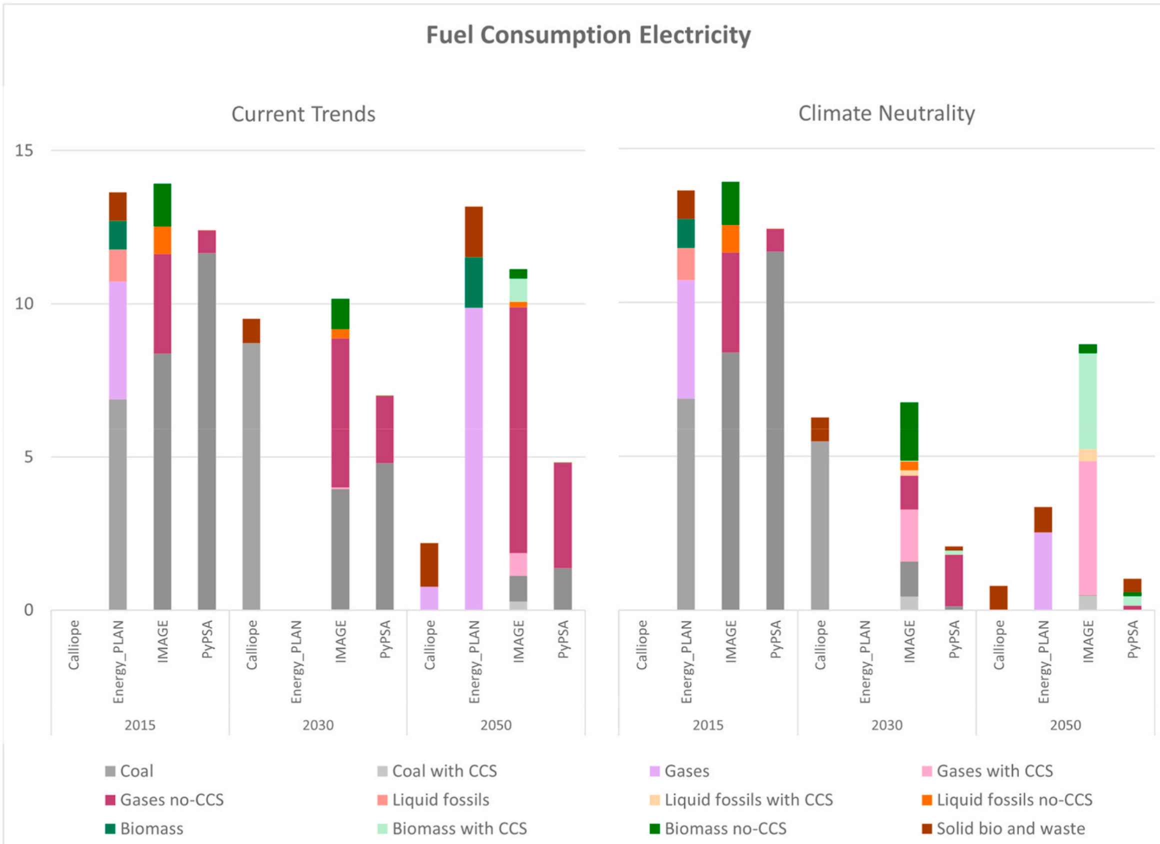

Fig. B4. Fuel consumption for electricity production for Europe region under Current Trends and Climate Neutrality scenarios. "Other" category, used by the IMAGE model, presents the total of other means/carriers used for electricity production.

Appendix C

Power generation CO2 emissions for Euro-Calliope and EnergyPLAN

CO_2 emissions from power generation for Euro-Calliope and EnergyPLAN are based on the reported fuel consumption (Figure B4) and supply-side emission factors from the IMAGE model (Table C1). The reported carrier "gases" for these two models are considered to be natural gas under the Current Trends scenario, and a combination of carbon-neutral gases (e.g., e-gases, gasified biomass, and biogas) under the Climate Neutrality scenario. Finally, the "solid bio and waste" category was grouped together with "biomass" (assuming emissions from waste burning are relatively insignificant), and an emission factor of zero was used, assuming net biomass emissions are zero compliant with IPCC reporting guidelines. This approach for biomass is used in the IMAGE model which allocates the biomass emissions to the land use sector, and thus, are not accounted for in the power sector.

Table C1
Power generation emission factors from IMAGE.

Emission factors for energy generation (Mtg CO2/EJ input)					
Year	Solid	Heavy Liquid Fuel	Light Liquid Fuel	Gas	Biofuel
		(Diesel, residual fuel oil, and crude oil)	(LPG and gasoline)	(Natural gas and gasworks gas)	(Liquid, solid, and gas)
2015	93.5	74.8	65.63	56.1	0
2030	93.5	74.8	65.63	56.1	0
2050	93.5	74.8	65.63	56.1	0

Data availability

Data will be made available on request.

References

[1] European Commission. The European green deal. 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. Brussels, Belgium. 2019.

[2] European Commission. Stepping up Europe's 2030 climate ambition: Investing in a climate-neutral future for the benefit of our people. COM(2020) 562 final. 2020. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0562.

[3] European Commission. Fit for 55": delivering the EU's 2030 Climate Target on the way to climate neutrality. COM(2021) 550–final. 2021. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550.

[4] European Commission. EU reference scenario 2020 : energy, transport and GHG emissions : trends to 2050. Publications Office; 2021. https://doi.org/10.2833/35750.
[5] European Commission. IN-DEPTH analysis in support of the commission communication COM(2018) 773. In: A Clean Planet for all. A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy; 2018.
[6] Hainsch K, et al. Energy transition scenarios: what policies, societal attitudes, and technology developments will realize the EU Green Deal? Energy 2022;239:122067.
[7] Auer H, et al. Development and modelling of different decarbonization scenarios of the European energy system until 2050 as a contribution to achieving the ambitious 1.5 ∘C climate target—establishment of open source/data modelling in the European H2020 project openENTRANCE. E I Elektrotechnik Inf 2020;137:346–58.
[8] Rybak A, Rybak A, Joostberens J, Kolev SD. Cluster analysis of the EU-27 countries in light of the guiding principles of the European green deal, with particular emphasis on Poland. Energies 2022;15:5082.
[9] Steininger KW, Williges K, Meyer LH, Maczek F, Riahi K. Sharing the effort of the European Green Deal among countries. Nat Commun 2022;13:3673.
[10] Maris G, Flouros F. The green deal, national energy and climate plans in Europe: member States' compliance and strategies. Adm Sci 2021;11:75.
[11] Fallahnejad M, et al. The economic potential of district heating under climate neutrality: the case of Austria. Energy 2022;259:124920.
[12] Montanarella L, Panagos P. The relevance of sustainable soil management within the European Green Deal. Land Use Policy 2021;100.
[13] Kougias I, Taylor N, Kakoulaki G, Jäger-Waldau A. The role of photovoltaics for the European Green Deal and the recovery plan. Renew Sustain Energy Rev 2021;144:111017.
[14] Fortes P, et al. How sensitive is a carbon-neutral power sector to climate change? The interplay between hydro, solar and wind for Portugal. Energy 2022;239:122106.
[15] Daioglou V, et al. Bioenergy technologies in long-run climate change mitigation: results from the EMF-33 study. Clim Change 2020;163:1603–20.
[16] Riahi K, Bertram C. Long-term economic beneets of stabilizing warming without overshoot-the ENGAGE model intercomparison. Nat Clim Change 2021. https://doi.org/10.21203/rs.3.rs-127847/v1.
[17] van de Ven DJ, et al. A multimodel analysis of post-Glasgow climate targets and feasibility challenges. Nature Climate Change 2023 2023;13(6 13):570–8.
[18] Edelenbosch OY, et al. Decomposing passenger transport futures: comparing results of global integrated assessment models. Transp Res D Transp Environ 2017;55:281–93.
[19] Priesmann J, Nolting L, Praktiknjo A. Are complex energy system models more accurate? An intra-model comparison of power system optimization models. Appl Energy 2019;255:113783.
[20] Nikas A, et al. Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison. Sci Total Environ 2021;793:148549.
[21] Rodrigues R, et al. Narrative-driven alternative roads to achieve mid-century CO2 net neutrality in Europe. Energy 2022;239:121908.
[22] Boitier B, et al. A multi-model analysis of the EU's path to net zero. Joule 2023;7:2760–82.
[23] Krey V, et al. Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. Energy 2019;172:1254–67.
[24] IMAGE. IMAGE integrated model to assess the global environment. IMAGE framework 2022. https://models.pbl.nl/image/IMAGE_framework.
[25] Vuuren D van, et al. The 2021 SSP scenarios of the IMAGE 3.2 model. 2021. https://doi.org/10.31223/X5CG92.
[26] Staffell I, Pfenninger S. The increasing impact of weather on electricity supply and demand. Energy 2018;145:65–78.
[27] Bobmann T, Staffell I. The shape of future electricity demand: exploring load curves in 2050s Germany and Britain. Energy 2015;90:1317–33.
[28] Chang M, et al. Smart energy approaches for carbon abatement: scenario designs for Chile's energy transition. Smart Energy 2023;10:100098.
[29] Wu F, Muller A, Pfenninger S. Strategic uses for ancillary bioenergy in a carbon-neutral and fossil-free 2050 European energy system. Environ Res Lett 2023;18:014019.
[30] Chatterjee S, Kiss B, Ürge-Vorsatz D, Teske S. Decarbonisation pathways for buildings. Achieving the Paris Climate Agreement Goals : Part 2: Science-based Target Setting for the Finance industry — Net-Zero Sectoral 1.5°C Pathways for Real Economy Sectors 2022:161–85. https://doi.org/10.1007/978-3-030-99177-7_7/TABLES/8.
[31] PROMETHEUS. Prometheus model 2018 model description E3-modelling. http://www.e3modelling.gr; 2018.
[32] Fragkos P, Kouvaritakis N. Model-based analysis of intended nationally determined Contributions and 2 °C pathways for major economies. Energy 2018;160:965–78.
[33] Victoria M, Zeyen E, Brown T. Speed of technological transformations required in Europe to achieve different climate goals. Joule 2022;6:1066–86.
[34] Oreggioni G, Roelfsema M, Mikropoulos S, Van Vuuren DP, Staffell I. Model intercomparison database for climate-neutral European energy scenarios. Deliverable 8.2. Sustainable energy transitions laboratory (SENTINEL) project. London: Imperial College London (ICL); 2022. https://sentinel.energy/results/deliverables/.
[35] IMAGE. Region classification map - IMAGE. https://models.pbl.nl/image/index.php/Region_classification_map; 2018.
[36] Fricko O, et al. The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century. Glob Environ Change 2017;42:251–67.
[37] European Commission. Stepping up Europe's 2030 climate ambition. Investing in a climate-neutral future for the benefit of our people. SWD(2020) 176 final. 2020. https://eur-lex.europa.eu/resource.html?uri=cellar:749e04bb-f8c5-11ea-991b-01aa75ed71a1.0001.02/DOC_1&format=PDF.
[38] UK Climate Change Committee. Policies for the sixth carbon budget and net zero. 2020.
[39] Roelfsema M, Oreggioni G, Mikropoulos S, Staffell I, Van Vuuren DP. SENTINELIntercomparisonprotocol.Deliverable8.1. SustainableEnergyTransitionsLaboratory(SENTINEL)Project. Utrecht: UtrechtUniversity(UU); 2021. https://sentinel.energy/results/deliverables/.
[40] European Commission. 2050 long-term strategy. https://ec.europa.eu/clima/eu-action/climate-strategies-targets/2050-long-term-strategy_en; 2020.
[41] Grassi G, et al. Critical adjustment of land mitigation pathways for assessing countries' climate progress. Nat Clim Change 2021;11:425–34.
[42] Roelfsema M, et al. Developing scenarios in the context of the Paris Agreement and application in the integrated assessment model IMAGE: a framework for bridging the policy-modelling divide. Environ Sci Pol 2022;135:104–16.
[43] Dafnomilis I, den Elzen M, van Vuuren DP. Achieving net-zero emissions targets: an analysis of long-term scenarios using an integrated assessment model. Ann N Y Acad Sci 2023;1522:98–108.
[44] Victoria M, Zeyen E, Brown T. Speed of technological transformations required in Europe to achieve different climate goals. Joule 2022;6:1066–86.
[45] Thellufsen JZ, et al. Beyond sector coupling: utilizing energy grids in sector coupling to improve the European energy transition. Smart Energy 2023;12:100116.
[46] Bistline J, et al. Emissions and energy impacts of the inflation reduction Act. Science 2023;380:1324–7. 1979.
[47] Chatterjee S, et al. Integration of demand model results into system planning models. Deliverable 3.3. Sustainable energy transitions laboratory (SENTINEL) project. European Commission; 2021. https://sentinel.energy/wp-content/uploads/2022/05/3.3-EC.pdf.
[48] European Environment Agency. National emissions reported to the UNFCCC and to the EU greenhouse gas monitoring mechanism. https://www.eea.europa.eu/en/datahub/datahubitem-view/3b7fe76c-524a-439a-bfd2-a6e4046302a2; 2023.
[49] IEA. Greenhouse gas emissions from energy. https://Www.Iea.Org/Data-and-Statistics/Data-Product/Greenhouse-Gas-Emissions-from-Energy; 2023.
[50] Eurostat. Air emissions accounts by NACE Rev. 2 activity 2023. Eurostat. Retrieved from, https://ec.europa.eu/eurostat/databrowser/view/env_ac_ainah_r2__custom_11890494/default/table?lang=en.
[51] Golombek R, Lind A, Ringkjøb HK, Seljom P. The role of transmission and energy storage in European decarbonization towards 2050. Energy 2022;239:122159.
[52] European Union. Directive (EU) 2023/2413 of the European parliament and of the council of 18 october 2023 amending directive (EU) 2018/2001, regulation (EU) 2018/1999 and directive 98/70/EC as regards the promotion of energy from renewable sources. Official Journal of the European Union 2023;L 2413:1–77. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023L2413.
[53] European Union. DIRECTIVES DIRECTIVE (EU) 2023/1791 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast). Official Journal of the European Union; 2023.
[54] European Commission. REPowerEU plan. COM/2022/230 final. https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0230; 2022.