Energy and Climate Change 5 (2024) 100144

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

Comparing net zero pathways across the Atlantic A model inter-comparison exercise between the Energy Modeling Forum 37 and the European Climate and Energy Modeling Forum

Luis Sarmiento[a,b,c,*], Johannes Emmerling[b,*], Robert Pietzcker[d], Vassilis Daioglou[e,f], Francesco Dalla Longa[g], Mark M. Dekker[e,f], Laurent Drouet[a,b], Amir Fattahi[g], Panagiotis Fragkos[h], Hauke T.J. Henke[i], Oliver Fricko[j], Leonard Göke[k], Volker Krey[j], Ellie Lochner[l], Gunnar Luderer[d], Nick Macaluso[m], Kowan T.V. O'Keefe[n], Kathleen M. Kennedy[n], Gokul Iyer[l], Renato Rodrigues[d], Eric Stewart[m], William Usher[i], Bob van der Zwaan[g,o,p,q], Detlef van Vuuren[e,f], Eleftheria Zisarou[h], Behnam Zakeri[j,r]

[a] RFF-CMCC European Institute on Economics and the Environment, Italy
[b] CMCC Foundation - Euro-Mediterranean Center on Climate Change, Italy
[c] Banco de Mexico, Mexico
[d] Postdam Institute for Climate Impact Research, Germany
[e] Copernicus Institute of Sustainable Development, Utrecht University, the Netherlands
[f] PBL Netherlands Environmental Assessment Agency, the Netherlands
[g] Netherlands Organization of Applied Scientific Research, the Netherlands
[h] E3 Modeling, Greece
[i] KTH Royal Institute of Technology, Sweden
[j] International Institute for Applied Systems Analysis, Austria
[k] ETH Zurich, Switzerland
[l] Pacific Northwest National Laboratory, USA
[m] Environment and Climate Change Canada, Canada
[n] Center for Global Sustainability, USA
[o] TNO, Energy Transition Studies (ETS), the Netherlands
[p] University of Amsterdam, Faculty of Science (HMS and IAS), the Netherlands
[q] John Hopkins University, School of Advanced International Studies, Italy
[r] Institute for Data, Energy, and Sustainability, Vienna University of Economics and Business (WU Wien), Austria

A R T I C L E I N F O

Keywords:
Net zero
Europe
United States
100 % renewables
Electrification
Energy Modeling Forum
European Climate & Energy Modeling Forum
Climate change mitigation
Renewable energy system models
Carbon dioxide removal (CDR)
Energy transition pathways

A B S T R A C T

Europe and North America account for 32 % of current carbon emissions. Due to distinct legacy systems, energy infrastructure, socioeconomic development, and energy resource endowment, both regions have different policy and technological pathways to reach net zero by the mid-century. Against this background, our paper examines the results from the net zero emission scenarios for Europe and North America that emerged from the collaboration of the European and American Energy Modeling Forums. In our analysis, we perform an inter-comparison of various integrated assessments and bottom-up energy system models. A clear qualitative consensus emerges on five main points. First, Europe and the United States reach net zero targets with electrification, demand-side reductions, and carbon capture and sequestration technologies. Second, the use of carbon capture and sequestration is more predominant in the United States due to a steeper decarbonization schedule. Third, the buildings sector is the easiest to electrify in both regions. Fourth, the industrial sector is the hardest to electrify in the United States and transportation in Europe.

Fifth, in both regions, the transition in the energy mix is driven by the substitution of coal and natural gas with solar and wind, but to a different extent.

* Corresponding authors.
E-mail addresses: luis.sarmiento@eiee.org (L. Sarmiento), johannes.emmerling@cmcc.it (J. Emmerling).

https://doi.org/10.1016/j.egycc.2024.100144

Available online 6 July 2024

Introduction

Understanding the pathways to net zero emissions across different regions is relevant for identifying bottlenecks, challenges, and opportunities on our way to a more sustainable future. This study explores the net zero pathways of Europe and the United States (US / USA) with a multi-model comparison exercise that includes more than 28 integrated assessment and bottom-up energy models from the Energy Modeling Forum 37 (EMF 37) and the European Climate and Energy Modeling Forum (ECEMF).[1] The goal is to compare the net zero mid-century pathways of both continents, in line with the 1.5° threshold of the Paris Agreement, under standardized scenarios across different modeling assumptions, research teams, technology projections, and implemented policies.

The Stanford Energy Modeling Forum (EMF) was established in 1976 to identify critical issues and share information and insights on energy, economics, and the environment. The European Climate and Energy Modeling Forum is a European Union (EU) funded project inspired by EMF and established in 2021 as a European network of climate and energy modeling groups and policymakers. Our comparison exercise examines the effects of the net zero transition on electrification, emissions, sectoral energy demand, and technological deployment. Our results can help identify the challenges and opportunities of the green transition in two of the world's largest single-energy markets. Fig. 1 shows the current and cumulative carbon dioxide emissions of different regions.

The United States and the European Union are jointly responsible for 22.8 % and 43.1 % of current and cumulative *Green-House-Gas* (GHG) emissions around the world. This large share of current emissions highlights the importance of studying their energy transition under standardized assumptions. Moreover, one could argue that Europe and the United States have an ethical responsibility to lead the global renewable transition by implementing efficient policies and new technologies (e.g., Berg et al. [3]), as they are responsible for a large share of historical cumulative emissions along with an established capacity to mitigate, as demonstrated by the large size of their economies and relatively high incomes per capita.

Trade, culture, policies, and environmental initiatives closely link the United States and Europe. Both regions have reduction pledges under the Paris Agreement to support the net-zero transition. That is, while Europe committed to net zero economy-wide GHG reductions with the European Green Deal (EGD) and has adopted the ambitious Fit-for-55 package based on a set of regulatory frameworks (e.g., the EU Energy Efficiency Directive, the Renewable Energy Directive, and the CO_2 Transport Standards), the

United States has passed legislation to support the energy transition with the Inflation Reduction Act (IRA). Among the central policies of the IRA are aggressive tax incentives for green vehicles, incentives for the electrification of buildings, and the acceleration of hydrogen deployment [4]. In particular, the Nationally Determined Contributions of the United States and the European Union pledge a 50 to 52 % reduction in CO_2 emissions by 2030 (w.r.t. 2005) for the United States and a reduction in domestic greenhouse gas emissions of 55 % by 2030 (w.r.t. 1990) for the EU [11].

This collaborative study between EMF 37 and ECEMF has three main objectives. First, understand the role of electrification under net zero (economy-wide) scenarios for the transportation, building, and industrial sectors; second, look at differences and similarities in technology pathways and lock-in effects for both regions; third, determine critical technologies to decarbonizing the energy system, such as renewables, storage, and carbon capture and storage. Although the current literature suggests that the power sector will be decarbonized first, there is a lack of consensus on the ultimate potential across energy sectors and the rate of implementation given technical, behavioral, economic, and deployment limits (e.g., infrastructure, workforce, supply chains, manufacturing). Furthermore, competition from other carbon mitigation and management options like carbon capture and storage, direct air capture, and clean hydrogen can affect the path toward electrification and change the technologies we need to redirect our limited resources.

This article contributes to the extensive literature on decarbonization

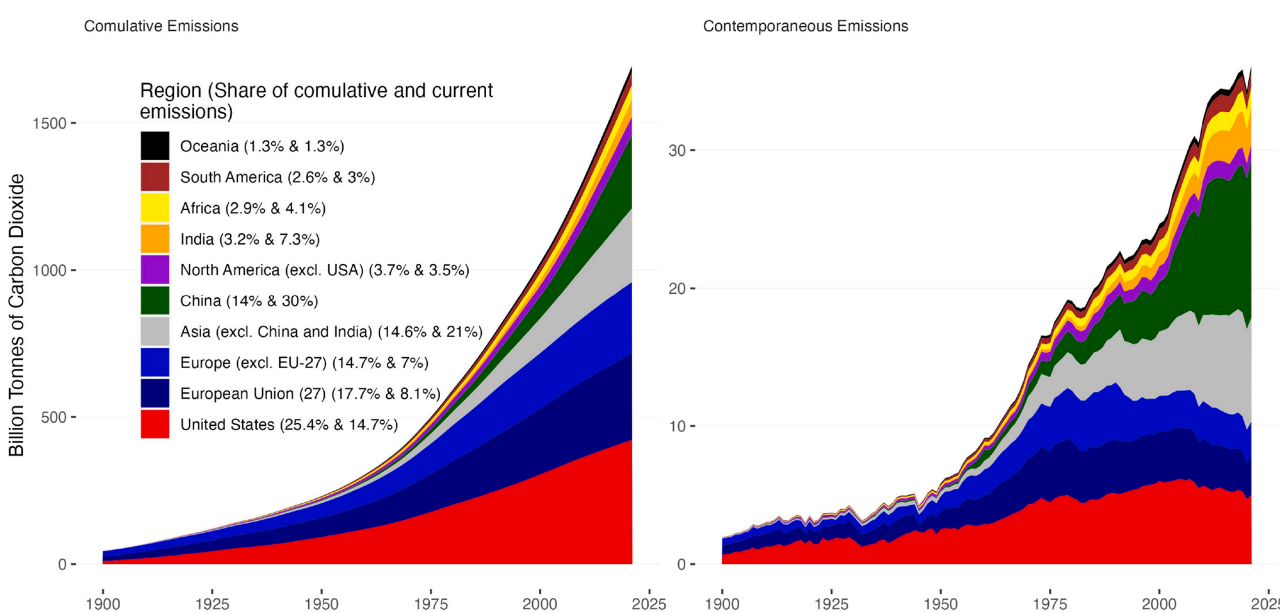

Fig. 1. Cumulative and current emissions for selected regions of the world
Notes: This figure presents 1750 onward cumulative (left) and annual (right) *carbon dioxide equivalent* (CO_2) emissions across the world. Source: Our World in Data [23] and the Global Carbon Project [27].

[1] Figs. A.1 and A.2 contain the spatial distribution of models for Europe and the United States.

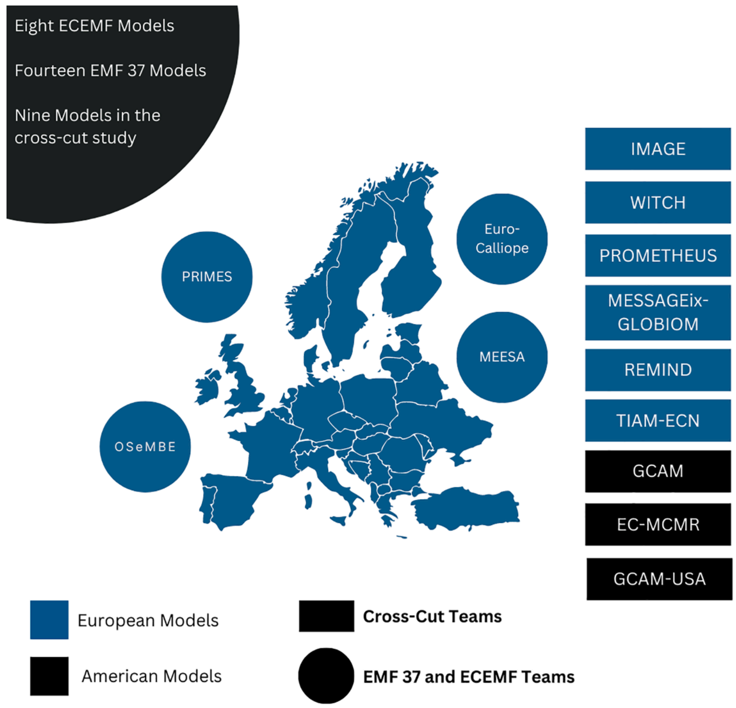

Fig. 2. Models participating in the cross-cut study.
Notes: We show models developed in Europe in blue and the United States in Black. The models in squares at the center of the figure represent the cross-cut teams who implemented Europe and US net zero pathways for this study. The circles around Europe and the United States show the models that only cover one region and whose results have been included in the analysis.

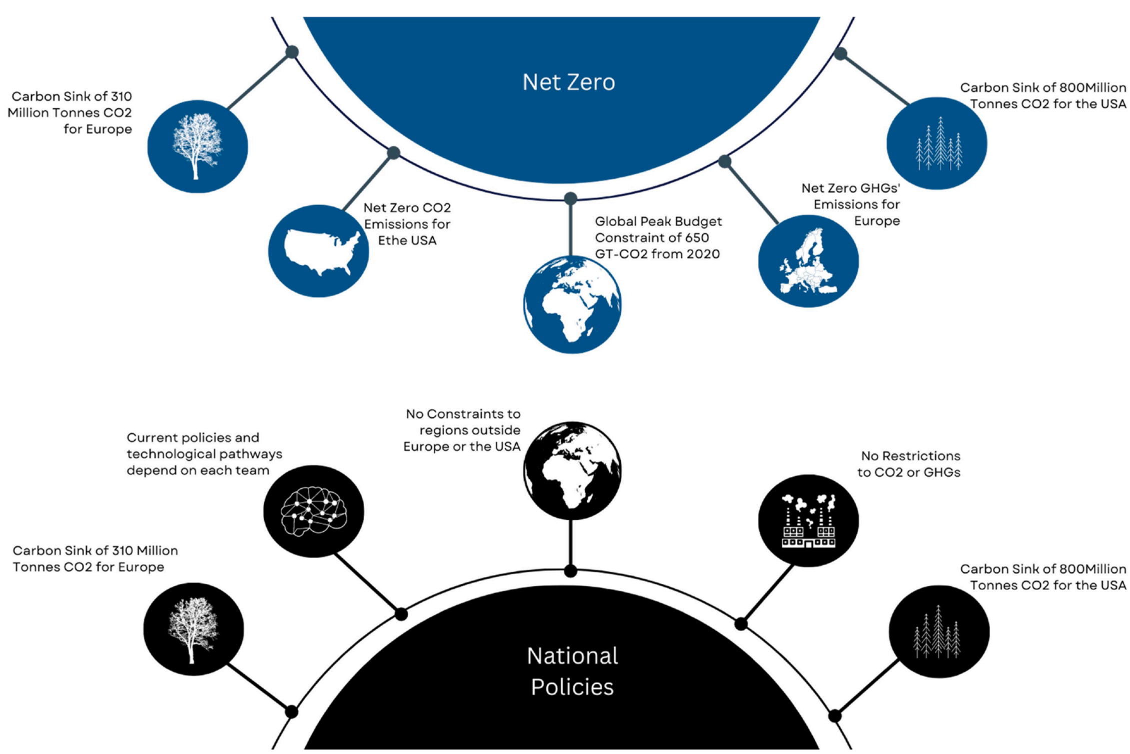

Fig. 3. Description of National policies and Net Zero scenarios.

studies including the IPCC AR6 database analysis at the global or macro levels [9] by providing a model inter-comparison exercise of net zero scenarios for the United States and Europe. As such, it builds on a growing number of deep decarbonization studies by providing a unique transatlantic comparison of net zero scenarios (see Williams et al. [28] for a review of current net zero studies in the United States).

Research design and scenario description

This article is based on the active participation of nine modeling

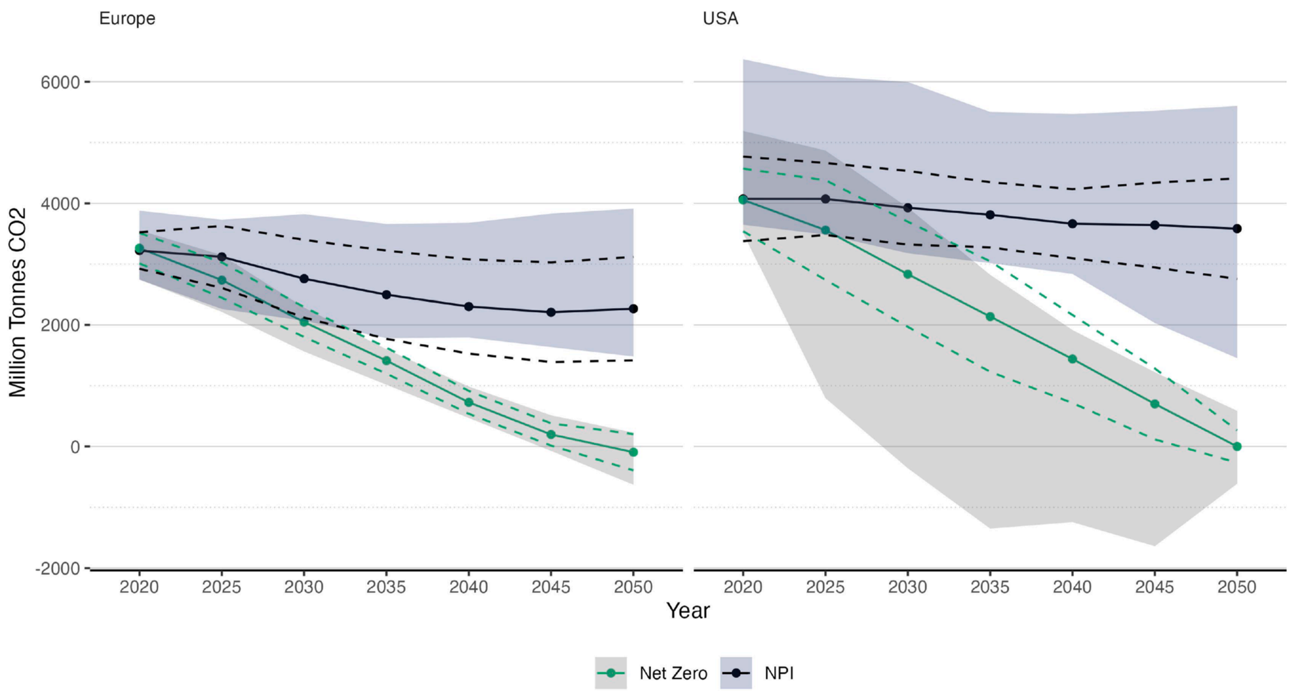

Fig. 4. Median Net CO_2 Emissions in Europe and the United States.
Notes: Net CO_2 emissions in Europe and the United States for the NPI and Net Zero scenarios. The solid line represents the median across models. The dotted lines are one-standard-deviation confidence bands. The colored ribbon shows the full interval of results. For Europe, the values come from ten different models: *EC-MSMR, GCAM-USA, GCAM, IMAGE, MESSAGEix, PRIMES, PROMETHEUS, REMIND, TIAM*, and *WITCH*. For the United States, the values come from 22 models: *ADAGE, AnyMOD, CTUS-NEMS, EC-MSMR, EPA-TIMES, EPS, FARM, FECM-NEMS, GCAM-USA, GCAM, gTECH, IMAGE, MARKAL, MESSAGEix, NATEM, PROMETHEUS, REMIND, TEMOA, TIAM, US-REGEN, ReEDS*, and *WITCH*.

teams, which implemented and provided scenarios for both the United States and Europe, as well as access to the results of fourteen additional models participating in the EMF 37 and ECEMF. Fig. A.3 lists the names, institutes, and countries of all models and whether they participated in this study, EMF 37 or ECEMF. In Fig. A.4, we include model characteristics such as spatial resolution, reported emissions, equilibrium approach, foresight, temporal granularity, and carbon management options. While the targets of the scenarios were defined for Europe and the United States, there are some differences in the regional scope of each team. For Europe, *TIAM-ECN, GCAM, PROMETHEUS*, and *IMAGE* present results for Europe excluding Turkey, *MESSAGEix* includes Turkey, and the rest of the modeling teams for EU27 + UK. For the United States, only one model (*MESSAGE*) reports values for North America rather than the United States. Fig. 2 presents a general outline of all the models in this study.

The goal is to analyze two main scenarios: National Policies (NPI) and Net Zero 2050 emissions (Net Zero). Fig. 3 presents the characteristics of each scenario. In NPI, modeling teams implement current climate and energy policies while imposing no additional limits on GHG or CO_2 in Europe, the United States, or any other region. The specification of current policies and technological paths depends on each modeling team.[2] That is, each model is free to set all relevant techno-economic assumptions, such as fuel prices, cost curves, and energy losses, as the intention of the EMF and ECEMF exercises is not to standardize the underlying assumptions of all modeling groups but rather to study the range of different trajectories in key variables like emissions, energy consumption, and renewable deployment across models with different underlying parameters and assumptions. The only homogenizing assumption is an annual carbon sink for land use of 310 and 800 *million tonnes of carbon dioxide equivalent* (MT CO_2) in Europe and the US. The 310 carbon sink for Europe comes from the official 2030 goal of the EU.[3] The 800 land-use carbon sink for the United States aligns with the core assumptions of EMF-37 [8]. As discussed by Browning et al. [8], this provides 800 Mt CO_2 per year headroom for models to reach the net zero targets and translates into a maximum reduction of combustion and non-combustion CO_2 emissions of 87 % in 2050. The EMF-37 and ECEMF steering committees included this assumption because converting net emissions targets to gross values requires considering the full range of emission sources and GHG sinks. While in the medium to long term, carbon cycle feedback effects could significantly lower the carbon sink [10], this provides an upper bound for the study period (2020–2050). Of course, if the sink were to weaken significantly by the mid-century, reaching the net zero constraint in line with 1.5° would require additional effort.

In the Net Zero scenario, in addition to the annual carbon sink, all participating teams impose the following constraints: a global carbon budget of 650 GtCO2 from 2020 to 2050, net zero CO_2 emissions levels for the United States in 2050, and net zero GHG emissions levels for Europe in 2050. Note that the carbon budget was implemented as a *peak budget* or budget without overshoot. Therefore, once global emissions

[2] For the teams participating in the EMF 37, the models assume no new climate policy after the beginning of 2022, which excludes the Bipartisan Infrastructure Law [17] and the Inflation Reduction Act of 2022 [18]. To the extent practicable, the reference scenario includes all other federal and state policies (e.g., carbon emissions signatures, renewable portfolio standards, the Regional Greenhouse Gas Initiative, or California's Global Warming Solutions Act of 2006. For the ECEMF, the models only include currently implemented policies but not targets yet to be translated into policies at the end of 2022.

[3] The land use sink of 310 Mt CO2-eq/year was determined based on the available literature on the land use potential in the EU.

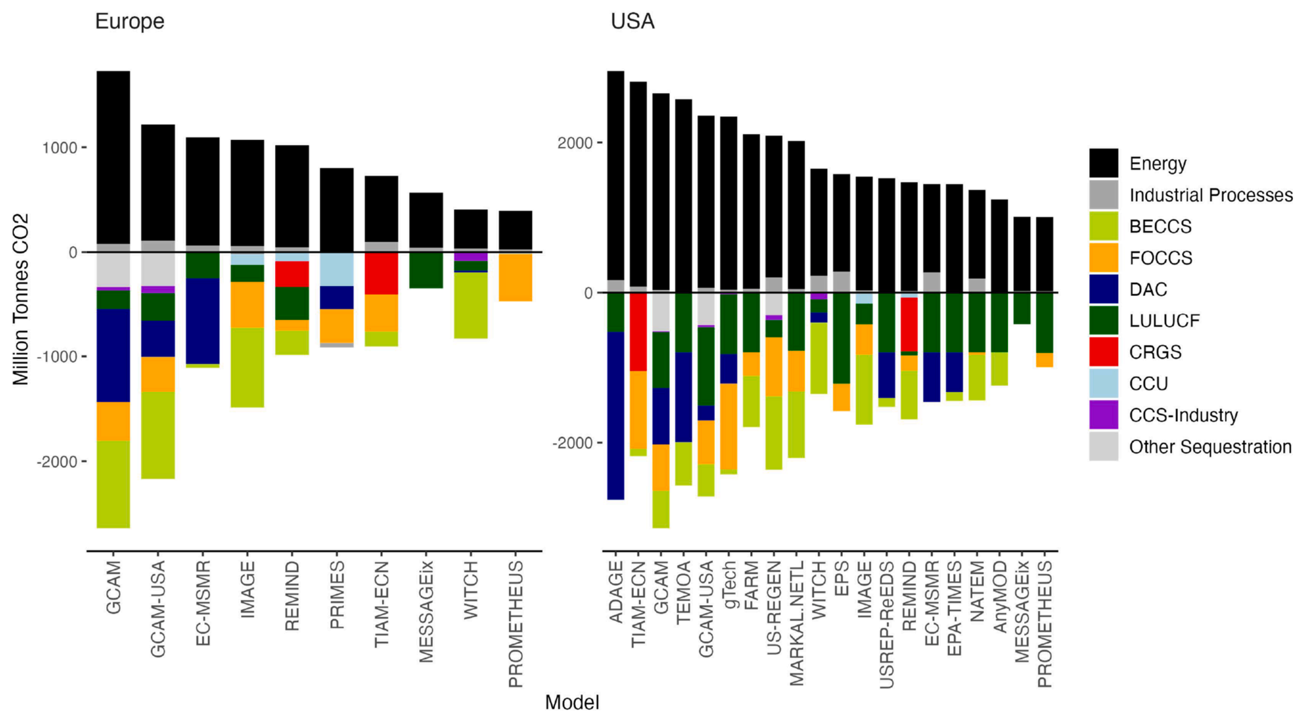

Fig. 5. Net Zero Difference in Sources of Emissions and Sequestration for Participating Models (2050).
Notes: Gross emissions and sequestration of CO_2. BECCS: Bioenergy with Carbon Capture and Sequestration. FOCCS: Fossil based with Carbon Capture and Storage. DAC: Direct Air Capture. LULUCF: Land Use, Land Use Change, and Forestry. CRGS: Carbon Removal and Geological Storage. CCU: Carbon Capture and Utilization. CCS Industry: Carbon Capture and Storage in the Industrial Sector.

reach the budget, they stabilize roughly at zero [24].[4] Net zero restrictions include the following sources, carbon capture, and sink categories: fossil fuel combustion, net emissions from non-energy use of fossil fuels, industrial process emissions, carbon dioxide removal (CDR) such as *Direct Air Capture* (DAC), and natural carbon management options like *Land Use, Land Use Change, and Forestry* (LULUCF). The difference in net zero goals between the United States and Europe (CO_2 versus GHGs) occurs due to different assumptions between the EMF 37 and ECEMF modeling projects. While the EMF 37 steering committee agreed on a carbon dioxide limit as its mid-century objective, ECEMF implemented the net zero target for all greenhouse gases, following the European policy target. Although in terms of total GHG emissions, this implies a difference for 2050, compared to 2020, the difference is limited. That is, we do not find a significant difference in the CO2 trajectory of the energy system when using either constraint. The additional European constraint would only require more negative CO2 emissions, as non-CO2 emissions are always positive, even in 2050. Actually, our results show that, in line with these heterogeneous constraints, while the net zero constraint for the USA leads to roughly zero emissions, the European GHG constraint leads to negative emissions of around 140 Mt CO2. Based on the results of individual modeling teams, we also found that the variation between models is similar to the difference between the CO_2 and GHG targets. Furthermore, some models do not model non-CO2 emissions (Euro-Calliope and PROMETHEUS), in which case there is no difference.[5]

It is important to note that the results of each model depend on specific parameterizations regarding resource allocation, technologies, and policies. For example, while some models assume exogenous energy demand, others estimate endogenous socioeconomic developments through different drivers such as population, economic growth, and energy efficiency. For the EMF 37, socioeconomic drivers like productivity and population were set independently by each modeling team [8]. For ECEMF, all models followed their implementation of the Shared Socioeconomic Baseline SSP2 *Middle of the Road* scenario [14]. As GDP and population are key drivers of energy demand and emissions, we present their time series by energy model and region in Figs. B.9 and B.11. Regarding economic costs, grid requirements, and other demand drivers such as population density or supply constraints, each model is calibrated and developed by its modeling team to capture real-world dynamics and constraints. That is, there were no semi-harmonized elements beyond the carbon sink and budget constraints. As such, the results across energy models are possible scenarios using a wide range of parametrizations following standardized scenarios and not the full range of potential outcomes.

Results

Emissions

Fig. 4 shows the emission trajectory of CO_2 in the United States and Europe for the NPI and Net Zero scenarios.

In 2020, average European emissions are around 79 % of the emissions in the United States. This value is similar to the one calculated by the Emissions Database for Global Atmospheric Research of the European Union [12]. According to current trends, technological pathways, and nationally determined contributions (NDC), median NPI emissions decrease by 35 % and 14 % in Europe and the United States between 2020 and 2050. The minimum and maximum percentage changes from

[4] For models not actively participating in the cross-cut exercise but with submitted results to the EMF 37 database, there is no global peak budget constraint requirement. Instead, its specification depended on each modeling team.

[5] These include FARM, FECM-NEMS, US-REGEN, gTech, TEMOA, AnyMOD, Euro-Calliope, PROMETHEUS, OSeMBE.

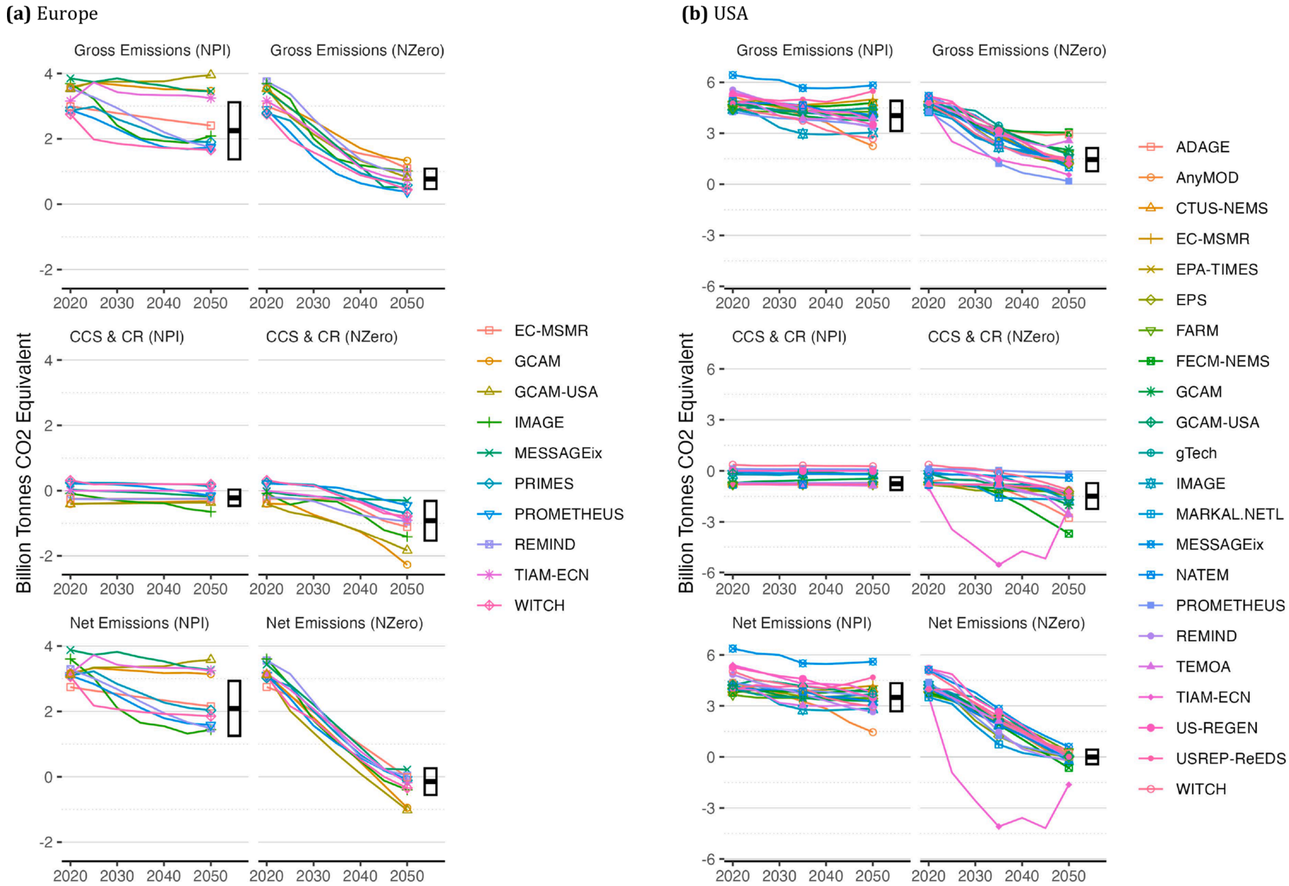

Fig. 6. contains the time series of gross, net, and captured emissions for both regions and each model.
Notes: This figure presents the 2020-2050 times series of gross emissions (top row), carbon capture storage and sequestration (middle row), and net emissions (bottom row) for Europe and the United States in the NPI and Net Zero scenarios. We add indicator shapes to identify each model in 2020 and 2050. We center the boxplot at the end of each panel around the median value and set its limits equal to the median plus and minus one standard deviation.

2020 to 2050 are reported by *IMAGE* (–60 %) and *GCAM-USA* (+14. 7 %) in Europe and *AnyMOD* (–66 %) and *ReEEDS* (+18.0 %) in the USA (see Fig. 6).[6] Regarding the Net Zero scenario, both continents reach net zero carbon dioxide (or GHG) emissions by the middle of the century. However, because the United States starts at a higher level of emissions than Europe, their period-wise emission reduction is slightly more significant.

The more considerable median reduction in gross emissions in Europe for the NPI scenario can arise from the larger number of environmental policies implemented on the continent from 2010 onward. Additionally, all modeling teams submitted the scenarios for the US before the Inflation Reduction Act (IRA), which would likely increase the NPI estimates of emission reduction. In a closely related project, Bistline et al. [5] use the EMF 37 results to analyze the impacts of the IRA on the power sector. Although they find substantial reductions in power sector emissions (around 50 % reduction w.r.t. 2005), they indicate that even with the IRA, the US would need additional policies to reach its mid-term climate targets, such as the Paris Agreement commitment to reduce GHG emissions across the economy by 50 % to 52 % below 2005 by 2030.

Fig. 5 shows the decomposition of gross emissions by model and emission source in the Net Zero scenario. Fig. A.5 presents the results for the NPI scenario.

For Europe, emissions come mainly from the energy sector, and although there are still around 900 MT CO_2 in 2050, it uses carbon capture and sequestration instruments to reach net zero. On average, Europe stores 1,180 MT CO_2 in 2050 to reach the net zero constraint. The main sink technologies used to achieve net zero are *Bio-Energy with Carbon Capture and Storage* (BECCS) (29.5 %), *Fossil Fuels with Carbon Capture and Storage* (FOCCS) (20.1 %), DAC (19.5 %), and LULUCF (13.7 %). For the United States, we can find similar patterns. Although the country emits 1,860 MT CO_2 in 2050, it uses carbon capture to achieve its net zero goals. The United States captures around 1900 MT CO_2 through a combination of LULUCF (34.1 %), BECCS (21.7 %), DAC (18.1 %), and FOCCS (16.7 %). Based on these numbers, it appears that the United States would require more than 50 % of the amount of carbon capture and removal than Europe to achieve the net zero constraint,

[6] We try to show the full range of possible results throughout the paper instead of relying solely on dispersion measures. For instance, Fig. 6 presents the full range of emission pathways for all participating models. Still, we sometimes use median values to compare pathways between scenarios, regions, and periods. Whenever we use median values, we often provide the complete set of results in either the main text or the Appendix. The issue of using measures of dispersion in multi-model exercises is not trivial. On the one hand, dispersion measures allow us to distill the information and identify aggregate trends. However, this implies that the set of results for any given modeled indicator forms a homogeneous and comparable set, which is unlikely, as any modeled indicator is intimately related to a given pathway projected by any given model (i.e., each indicator has context). As such, we might lose valuable information from outliers. Therefore, using dispersion measures raises several risks in interpreting results, such as flattening alternative pathways into contextless values. This means there is a trade-off between simplicity and information loss when using measures of dispersion instead of full ranges in multi-model approaches. In this paper, we try to find a healthy equilibrium where, while presenting some dispersion measures within the text, we try to show the complete set of results either in the main figures or the Appendix.

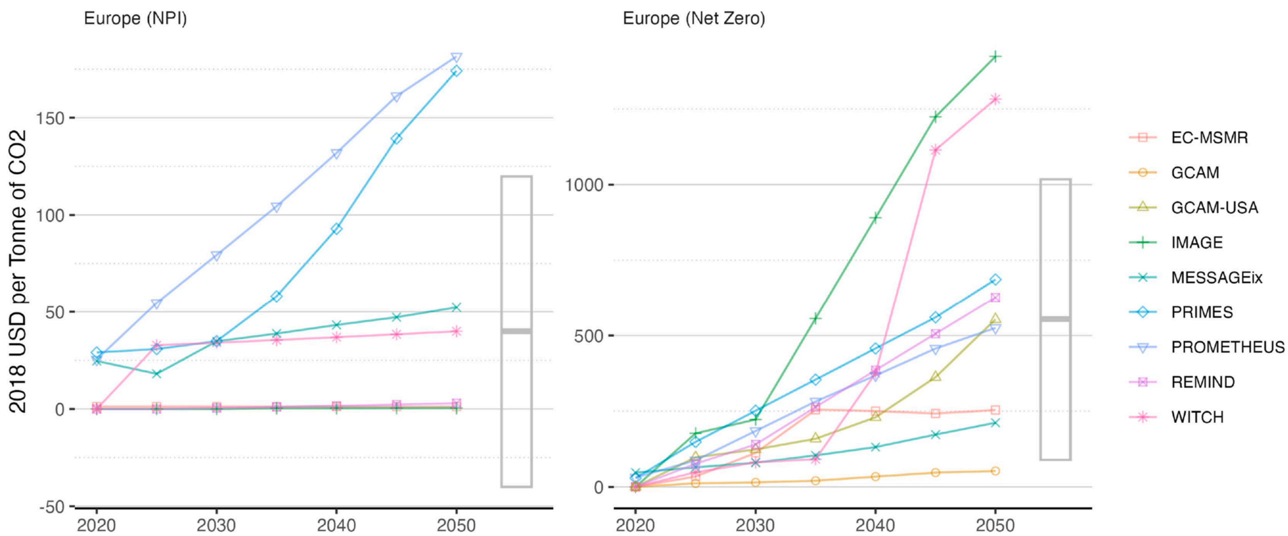

Fig. 7. Carbon prices in Europe in the NPI and Net Zero Scenarios for all participating models.
Notes: Time series of carbon prices between 2020 and 2050 for all participating European models. We separately present the marginal carbon price for the NPI and Net Zero scenarios. We center the boxplot at the end of each panel around the median carbon price and set its limits equal to the median plus and minus one standard deviation.

even when the European constraint requires net zero GHG. In fact, the United States is already pushing for the development and financing of carbon capture and storage through the 45Q tax credit included in the Inflation Reduction Act [15].

Fig. 6: Emission Pathways for Europe and the US in the NPI and Net Zero Scenarios for all Participating Models

Gross emissions decrease substantially between the NPI and Net Zero scenarios. They go from a median of 2,245 to 770 MT CO_2 in Europe and from 4,022 to 1,451 MT CO_2 in the United States. These reductions imply a percentage decrease in gross emissions of 68 % and 73 %, respectively. Interestingly, two clusters emerge in the European NPI scenario, with four teams (GCAM-USA, GCAM, TIAM, and MESSAGE) predicting higher emissions than the rest. However, there seems to be less variation once we move to the

Net Zero scenario. The higher emissions in *MESSAGE* for the USA in the NPI scenario arise because *MESSAGE* reports emissions for North America. To reach the net zero constraint, the models rely on carbon capture and removal. For Europe, the models report a median value of carbon capture storage and removal of 924 MT CO_2 and for the United States of 1,485 MT CO_2. It is also noticeable how the GCAM teams require more CCS-CR to reach Europe's net zero greenhouse gas limit. Regarding net emissions, all teams roughly hit the net zero target in both the United States and Europe. For Europe, the median team reports carbon dioxide emissions of –145 MT CO_2 and roughly zero for the United States. This lower net value of CO_2 emissions for Europe in the net zero scenario is related to the stricter GHG constraint.

Figs. A.6 and A.7 present the decomposition of gross energy emissions by sector and scenario in Europe and the United States. By 2050, the European NPI (Net Zero) scenario reports median gross emissions of 288 (240) MT CO_2 in the transport sector, 358 (79) MT CO_2 in industry,

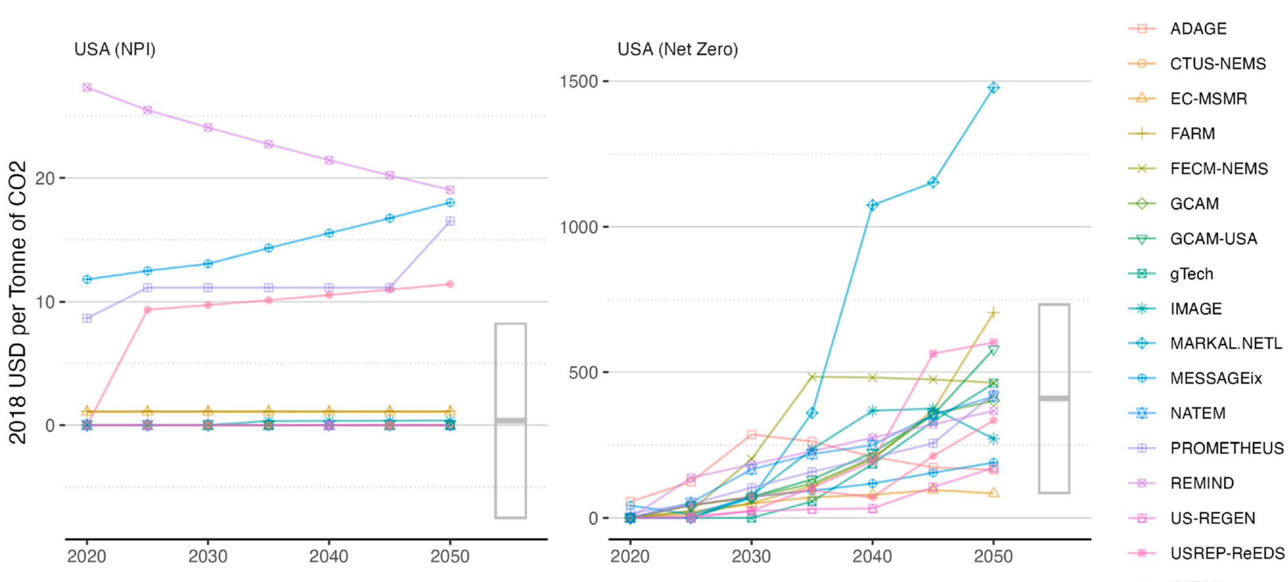

Fig. 8. Carbon prices in the United States in the NPI and Net Zero Scenarios for all participating models.
Notes: Time series of carbon prices between 2020 and 2050 for all participating models in the United States. We separately present the marginal carbon price for the NPI and Net Zero scenarios. We center the boxplot at the end of each panel around the median carbon price and set its limits equal to the median plus and minus one standard deviation.

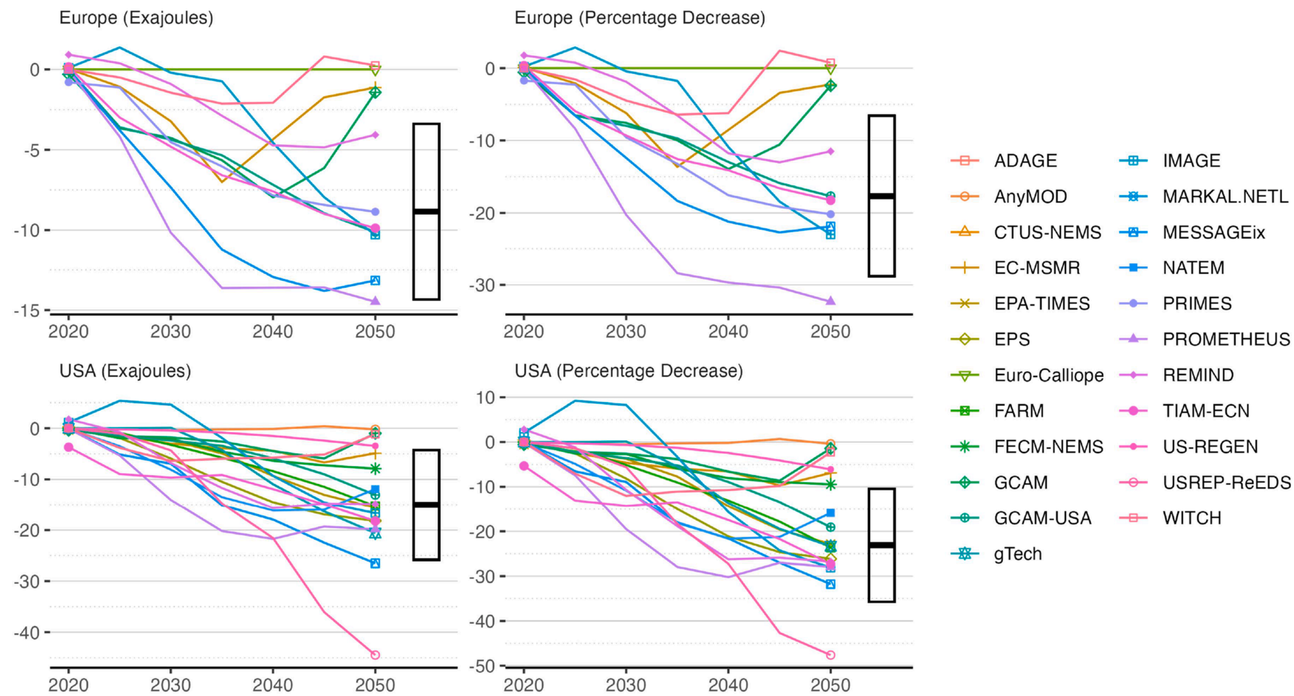

Fig. 9. Time Series of the Change in Final Energy Demand between the NPI and Net Zero Scenarios.
Notes: This figure presents the 2020–2050 time series of the difference in final energy demand between the NPI and Net Zero scenarios. The first column presents each period's raw difference (in exajoules). The second column shows the percentage decrease. We add indicator shapes to identify each model at the end of the time series in 2020 and 2050. The boxplot in each panel is centered around the median reduction in final energy demand, with its limits equivalent to plus and minus one standard deviation from the median.

446 (100) MT CO_2 in buildings, and 145 (48) MT CO_2 for other industrial processes. This implies relative reductions in the Net Zero scenario with respect to NPI of 65 %, 81 %, 76 %, and 59 %, respectively. For the USA, the gross sectoral emissions for the NPI (Net Zero) scenario are 1,294 (567) MT CO_2 in transport, 483 (249) MT CO_2 in buildings, 802 (459) MT CO_2 in industry, and 179 (103) MT CO_2 for other industrial processes. This implies relative reductions of 53 %, 49 %, 46 %, and 41 %. This relative abatement can be used as a summary statistic of how hard it is to reduce the emissions of a given sector from its reference. The lowest relative reduction is achieved for industrial processes in both regions, indicating that it is the most challenging sector to reduce emissions. The second sector that is hardest to abate is the industry sector in the US, while for Europe, transportation appears to be the second most difficult sector to decarbonize.

Carbon prices

ECEMF and EMF models reach mid-century Net Zero by setting CO_2 emission constraints with explicit or implicit carbon pricing. Fig. 7 shows the marginal abatement cost of CO_2 (or the carbon price) for Europe in the NPI and Net Zero scenarios for all reporting models. In the NPI scenario, Europe (where the current ETS is implemented along with associated target reductions) has a carbon price of around $45 (model median), with some model heterogeneity. EC-MSMR, IMAGE, and REMIND report almost zero carbon prices, WITCH and MESSAGE report prices around $50, and PROMETHEUS and PRIMES report higher carbon prices of around $200. For the Net Zero scenario, the median carbon price increases to $553. IMAGE reports the highest carbon price in 2050 at $1,423 and GCAM the lowest at $59.

Fig. 8 presents carbon prices for the United States. In the NPI scenario, most models report effective carbon prices close to zero, with only four European models, *REMIND, MESSAGE, PROMETHEUS*, and *WITCH* reporting carbon prices higher than $10. In the Net Zero scenario, carbon prices for the US grow substantially. The median Net Zero carbon price in 2050 is $410, with the highest prices reported by Markal ($1,477) and the lowest by EC-MSMR ($84). Despite different national policies and GHG targets for the Net Zero scenarios, these carbon prices show surprising similarities between both regions.

Another relevant analysis concerns energy prices. An increase in carbon prices could be passed on to consumers through higher energy prices with relevant implications for energy poverty [6], environmental justice [19], and industry competitiveness [13]. Although the models do not report a unified estimate of average energy prices, several models report the levelized cost of electricity. Fig. B.8 shows the difference between the NPI and Net Zero scenario in terms of electricity prices (typically reported by the levelized cost of electricity (LCOE). Positive values imply that the electricity price is higher in the Net Zero scenario than in the NPI scenario. The difference in median electricity prices between the NPI and Net Zero scenarios from 2020 to 2050 increases from essentially zero to 0.5 and 2.5 cents per kWh in Europe and the United States, respectively. These changes imply a percentage increase in median electricity prices of 10.3 % in Europe and 22.2 % in the United States. Naturally, these changes would have relevant implications throughout the economy in terms of firm competitiveness and energy poverty.

Another accompanying study looks at the effect of the Net Zero scenario on the equity distribution of the energy cost burden in the United States [6]. The authors find that net zero policy costs are unevenly distributed across income groups, with higher relative increases in energy expenditures for low-income families. However, they propose that recycled revenues from climate policies have countervailing effects when rebated on a per-capita basis, offsetting higher energy cost burdens and potentially even leading to net progressive outcomes.

Final energy demand

Fig. 9 presents the difference in final energy demand between scenarios in Europe and the United States. Negative values imply a lower

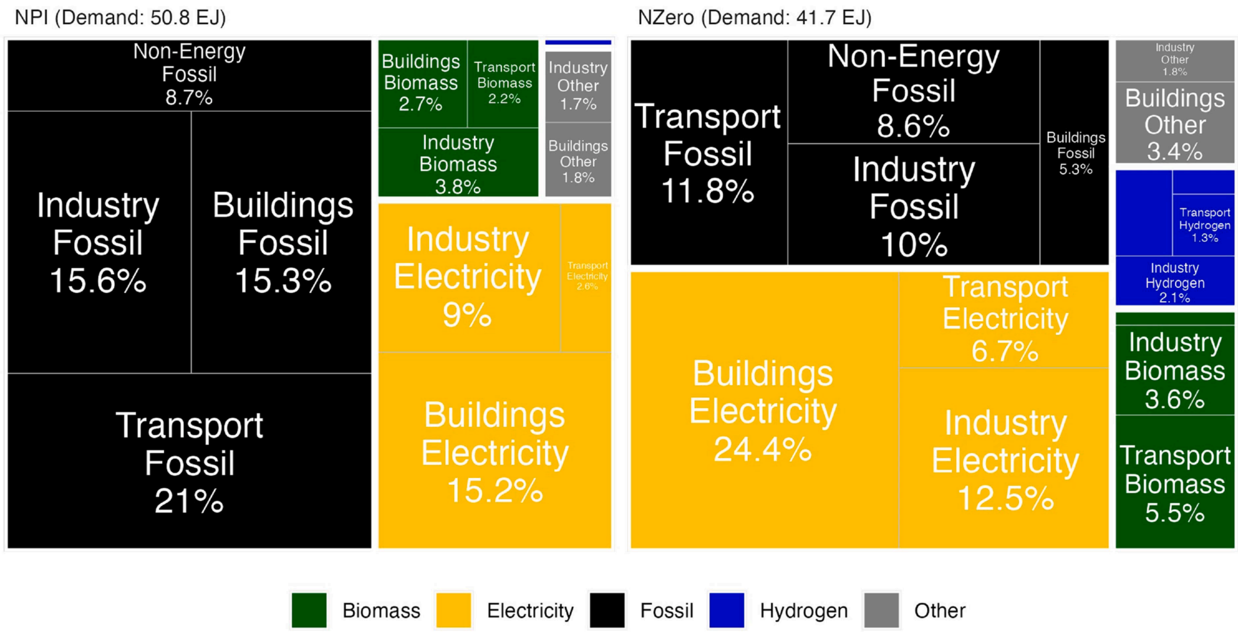

Fig. 10. Composition of final energy demand in Europe.
Notes: This figure presents the median composition of final energy demand in 2050 by source and sector for the NPI and Net Zero scenarios in Europe. To estimate these values, we calculate the median value of final energy demand for each scenario, sector, and source in Europe. After obtaining this value, we calculate the median percentage of final energy demand for each sector and source in each scenario by dividing its value by the sum of the median final energy demand across all sources and sectors.

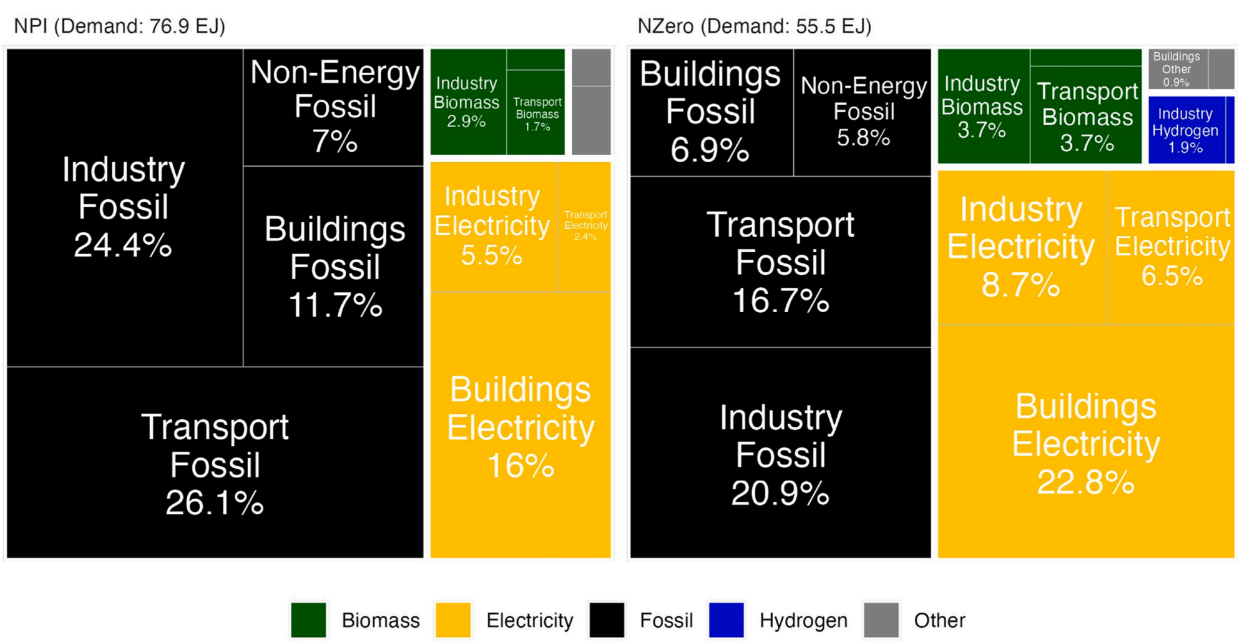

Fig. 11. Composition of final energy demand in the United States.
Notes: This figure presents the median composition of final energy demand in 2050 by source and sector for the NPI and Net Zero scenarios in the United States. To estimate these values, we calculate the median value of final energy demand for each scenario, sector, and source in Europe. After obtaining this value, we calculate the median percentage of final energy demand for each sector and source in each scenario by dividing its value by the sum of the median final energy demand across all sources and sectors.

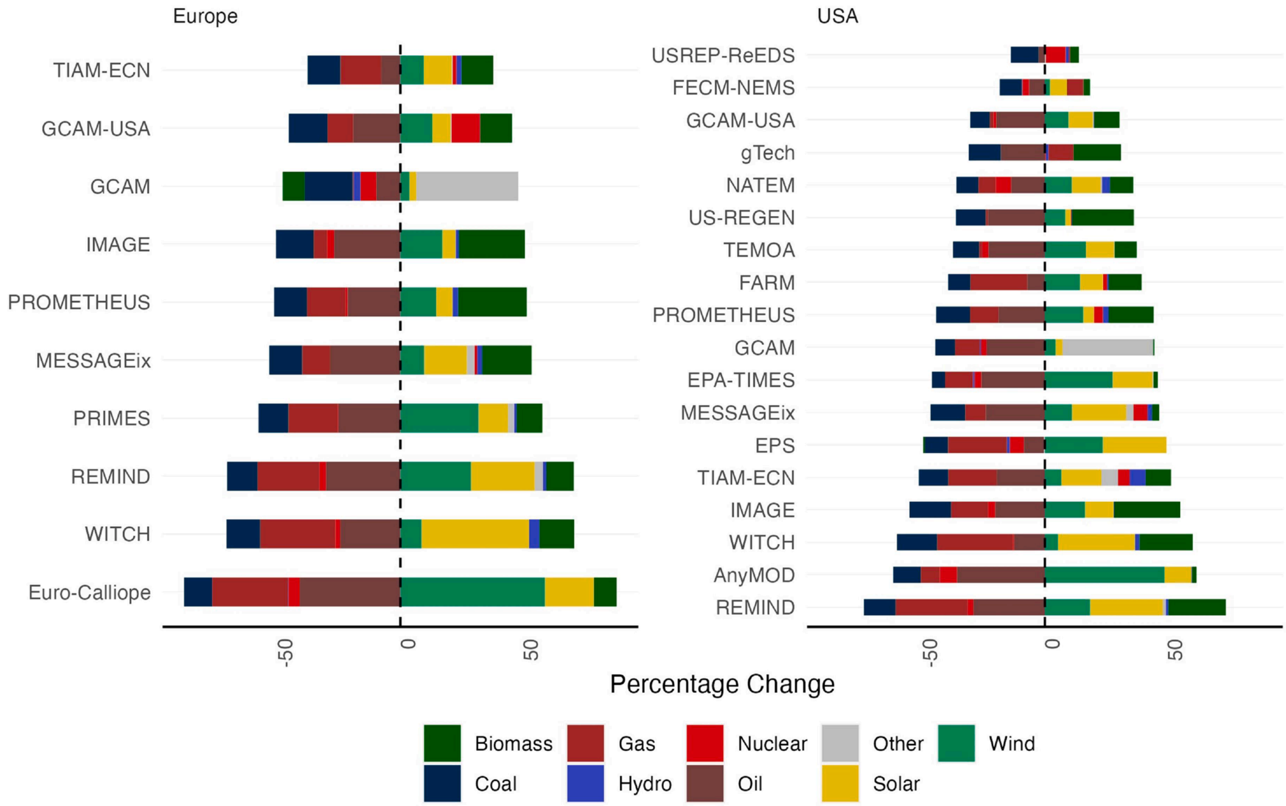

Fig. 12. Changes in primary energy demand for different sources.
Notes: Change in primary energy demand in 2050 between the NPI and Net Zero scenarios for all models, regions, sources, and sectors. Each panel refers to the region and sector. Panel rows represent the different models. The colors of the bar plots refer to the energy source.

final energy demand in the net zero scenario compared to NPI. We present the results in terms of net reduction in exajoules and percentage. The final energy demand is lower for both regions in the Net Zero scenario.[7] For Europe, the median reduction is approximately 9 EJ or 18 %. PROMETHEUS reports the highest decrease at 32 % and WITCH the lowest at around zero. For the US, the reduction seems slightly larger at 15 EJ or 23 %. ReEEDS reports the highest decrease (48 %) and AnyMOD the lowest (0.4 %).

Given the relevant reductions in final energy demand in the Net Zero scenario, we look at the effects of the Net Zero constraint on GDP and consumption. Fig. B.9 presents the time series of GDP by energy model between 2020 and 2050 in Europe and the United States. The median 2020 GDP of Europe and the US in both scenarios is around 20 trillion dollars. However, by 2050, there are slight deviations in the reported GDP values between both scenarios. In Europe, the Net Zero scenario reports a marginal reduction of around 1 % and in the US of around 1.7 %. These marginal reductions in the GDP of both regions align with previous results showing that the net zero constraint could lead to marginal economic losses [22,7]. For instance, according to scenarios developed by the Network of Central Banks and Supervisors for the Greening of the Financial System (NGFS), mid-century net-zero pathways could decrease global GDP by 1.8 % [21]. Fig. B.10 presents the consumption results. Note that fewer models report consumption measures. By 2050, the Net Zero scenario reports lower consumption in Europe and the United States. In Europe, the median model reports a 2050 drop of 355 billion dollars. In the United States, the reduction amounts to 1,475 billion dollars. These differences result in percentage reductions w.r.t. NPI of 1.7 % and 5.4 %, respectively, which, although relevant, do not fully account for the decrease between 20 % and 30 % in final energy demand. Section Energy and Carbon Intensitycontinues this analysis by looking at the relationship between emission reductions and intensity measures.

Fig. 10 presents the median composition of the final energy demand in Europe by sector and source in 2050 for the NPI and Net Zero scenarios. Total final energy demand for all sectors decreases from 50.8 EJ to 41.7 EJ between the NPI and Net Zero scenarios. Regarding the sources of final energy demand, fossil fuels decrease from 60.6 % to 35.8 %. This decrease comes hand in hand with an increase from 27 % to 44 % in electricity derived from clean energy sources, 8 % to 10 % in biomass, and 0.2 % to 6 % in hydrogen and synthetic fuels. In terms of sectors, the shares of final energy demand for the buildings (35 %), transport (26 %), industrial (30 %), and non-energy use (9 %) sectors under NPI change to 34 %, 25 %, 30 %, and 10 % in the Net Zero scenario. These numbers imply that, while there is a large shift in energy demand between energy sources, in line with previous research, there are no large changes in the sectoral composition of energy needs Lef̀evre et al. [see 22].

Fig. 11 presents the same decomposition for the United States. The most relevant energy sectors in the US for the Net Zero (NPI) scenario are industry with 35.6 % (33.9 %) of final energy demand, followed by buildings with 31.4 % (28.8 %), transport with 27.2 % (30.3 %), and non-energy uses with 7.02 % (5.83 %). Transportation is the sector with the most significant reductions in energy demand in the Net Zero scenario. This result contrasts with the estimates of European transport, which imply a slight increase of two percentage points. Regarding the sources of energy demand, there is a reduction of 47.6 % or 25 EJ in fossil fuels, an increase of 14.5 % or 2.7 EJ in electricity, a growth of 16 % or 0.6 EJ in biomass, and a rise of 1.2 EJ in energy production with

[7] It is worth noting that we did not obtain consistent information on useful energy shares and thus cannot effectively discern what share of the reduction in final energy demand comes from efficiency gains and what share comes from net reductions.

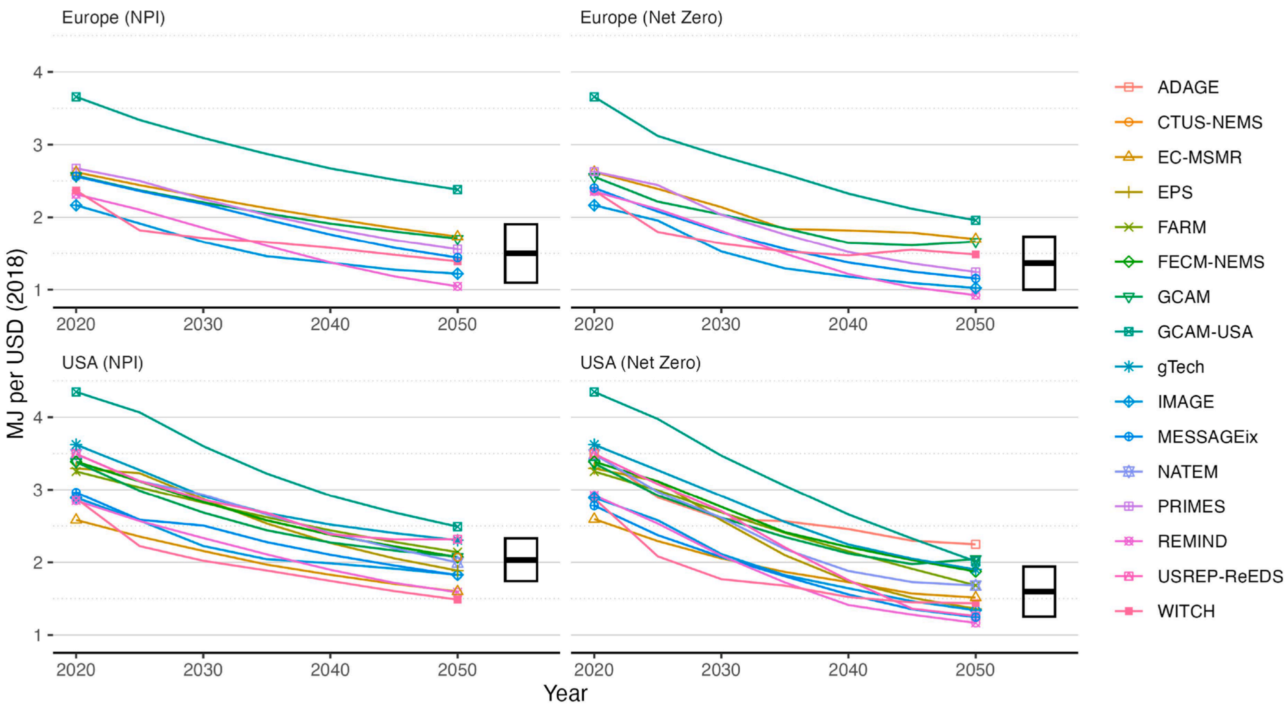

Fig. 13. Energy Efficiency in the NPI and Net Zero scenarios.
Notes: This picture presents the energy efficiency of the economy measured as final energy demand in mega joules per US dollar (2018) [MJ/$]. We present the efficiency measure for Europe in the first row and the United States in the second. For each region, we include the results of the NPI and Net Zero scenarios for all models that report GDP and the final energy demand. The box plot at the end of the line plots is centered around the median. Its limits represent one standard deviation above and below the median.

hydrogen and synthetic e-fuels.

To see the full range of possible results across all energy models, Fig. B.12 decomposes the previous exercise by analyzing the change with respect to NPI for each model. Although there are heterogeneous results on the use of electricity and biomass in the buildings sector, all models show a significant reduction in the demand for fossil fuels. Similar results hold for the industrial sector, with all European and US models reporting reductions in fossil fuels. However, contrary to the buildings sector, there seems to be a more generalized increase in the demand for energy from electricity and hydrogen. Concerning transportation, all models report relevant reductions in the use of fossil fuels and increases in hydrogen, synthetic fuels, and electricity.

Fig. 12 presents the percentage change in primary energy demand for each model between 2020 and 2050 for the Net Zero scenario. We present changes for Coal, Oil, Gas, Nuclear, Wind, Solar, Hydro, and Biomass. As expected, the high electrification of the power sector and the lower carbon intensity in electricity production lead to a significant decrease in the demand for fossil fuels. For gas, demand decreases by as much as 30 % in both Europe (Euro-Calliope) and the United States (Witch). For oil, the highest reduction is due to AnyMOD in the United States (36 %) and Euro-Calliope (41 %) in Europe. For coal, the greatest reduction occurs in Europe for GCAM (20 %) and in the United States for IMAGE (17 %). These reductions in fossil fuels are mainly compensated for by a higher demand for solar, wind, and biomass. The shift away from fossil fuels can have relevant implications for energy security on the

European continent given its low availability of fossil fuel resources, as evidenced by the effects of the Ukrainian war on European natural gas prices [20].[8] From a European perspective, the increase in energy security arising from a lower dependence on fossil fuels should be weighed against the consequences of higher dependence on rare earth minerals and special materials to decarbonize their energy system [1].

Energy and carbon intensity

Fig. 13 presents the energy intensity (MJ/$) of Europe and the United States in the NPI and Net Zero scenarios. In 2020, the energy intensity of Europe is lower than that of the US in both scenarios. That is, while Europe reported an energy intensity of about 2.5 MJ/$, the United States reported a median of 3.5 MJ/$. In the NPI scenario, the energy intensity of both regions decreased to 1.50 MJ/$ in Europe and 2.03 MJ/$ in the United States. These reductions are equivalent to around 60 % of the 2020 values. While differences in energy intensity between both regions persist in the NPI scenario, under Net Zero, midcentury efficiency improvements result in very similar energy intensities of around 1.5 MJ/$; that is, we expect the regional difference in energy intensity to decrease between both regions.

Regarding the carbon intensity of final energy demand, Fig. 14 shows the development across regions, models, and scenarios. Both regions show a very similar value of around 60 kgCO2/GJ in 2020, which, under the NPI scenario, is expected to decrease slightly to around 50 kgCO2/GJ. For the Net Zero scenario, the midcentury carbon intensity decreases to zero in the United States, while in Europe, given the inclusion of non-CO2 gases, it reaches –3 kgCO2/GJ using negative emission technologies like DAC and BECCS.

Fig. 15 presents the difference between the scenarios in the relationship between the annual rate of improvement in energy intensity and the annual rate of improvement in carbon intensity. We present the results separately for Europe and the United States to facilitate regional comparisons. Dashed lines mark the historical average energy and carbon intensity improvement rate between 1970 and 2010 [25]. The median improvement in energy intensity in the NPI scenario for Europe and the United States between 2020 and 2050 is 1.4 % and 1.3 %, respectively. This value is slightly higher than the historical

[8] This is less of a concern for the United States as the country does not need other nations to meet its current energy needs [26]

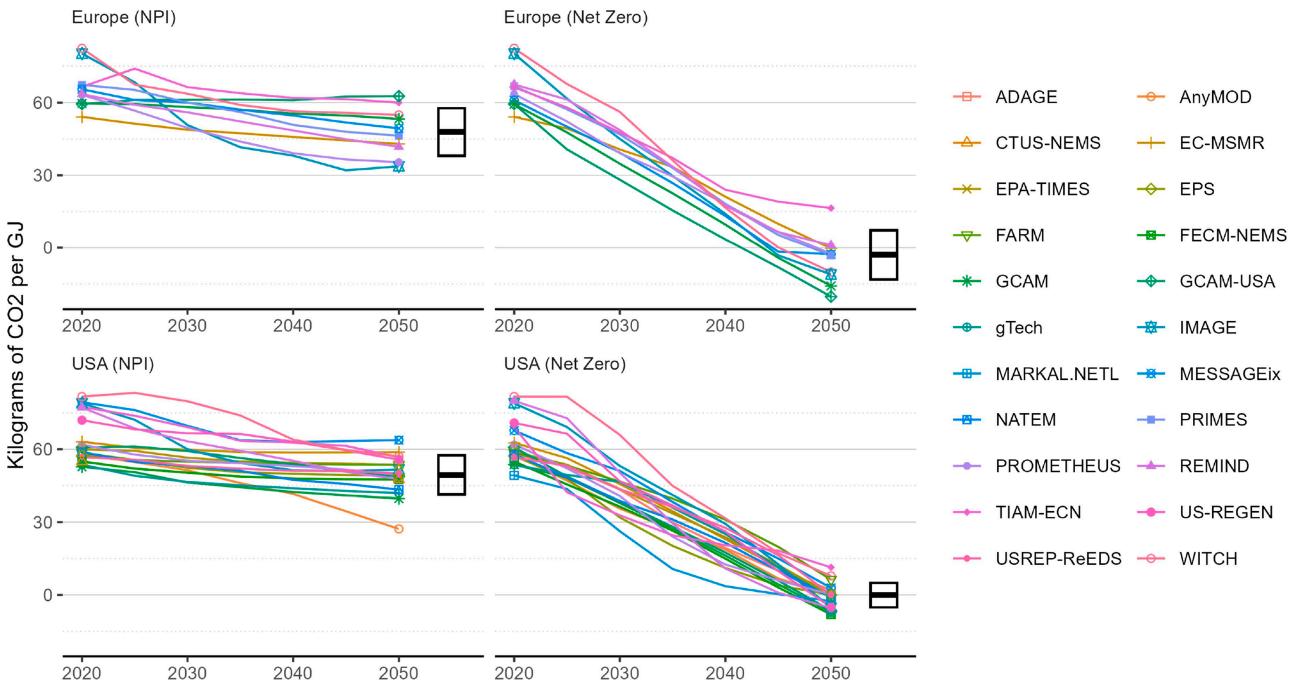

Fig. 14. Carbon Intensity in the NPI and Net Zero scenarios.
Notes: This picture presents the carbon intensity of the economy measured as emissions per unit of energy [kgCO2/GJ]. We present the intensity measure for Europe in the first row and the United States in the second. For each region, we include the results of the NPI and Net Zero scenarios for all models reporting emissions and the final energy demand. The box plot at the end of the line plots is centered around the median. Its limits represent one st.

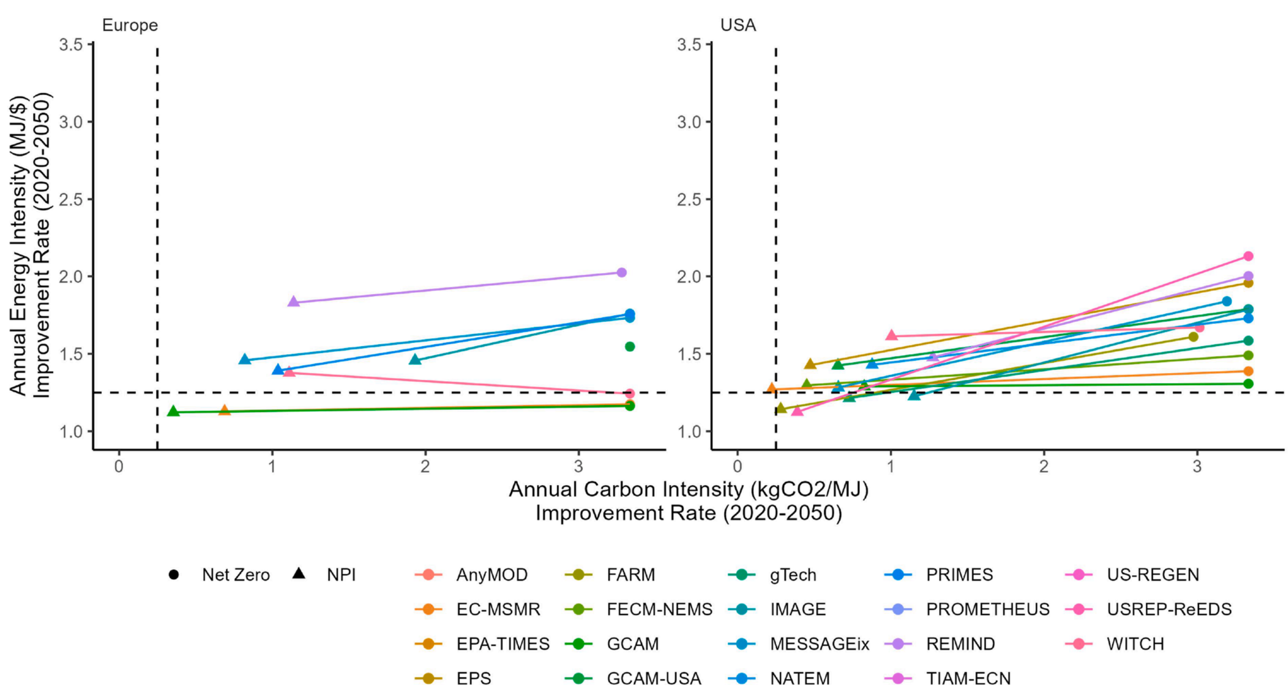

Fig. 15. Energy and Carbon Intensity average annual improvements.
Notes: This figure presents the difference between the NPI and Net Zero scenarios in the relationship between the annual rate of improvement in energy intensity and the annual rate of improvement in carbon intensity. We present the results separately for Europe and the United States to facilitate regional comparisons. Dashed lines mark the historical average energy and carbon intensity improvement rate between 1970 and 2010 [25].

improvement of 1.25 %. In the Net Zero scenario, the rate of improvement increases to 1.64 % in Europe and 1.73 % in the United States. These values are almost 30 % higher than historical values and suggest that the United States would have to reduce the intensity of the energy slightly faster than Europe. Regarding carbon intensity, the median improvement in the NPI scenario is 0.9 % and 0.7 % in Europe and the United States. This value is three to four times higher than the historical average of around 0.25 %, which is not entirely unlikely given the significant improvement in the costs and efficiency of clean energy sources [16]. For the Net Zero scenario, the carbon intensity improvement rate

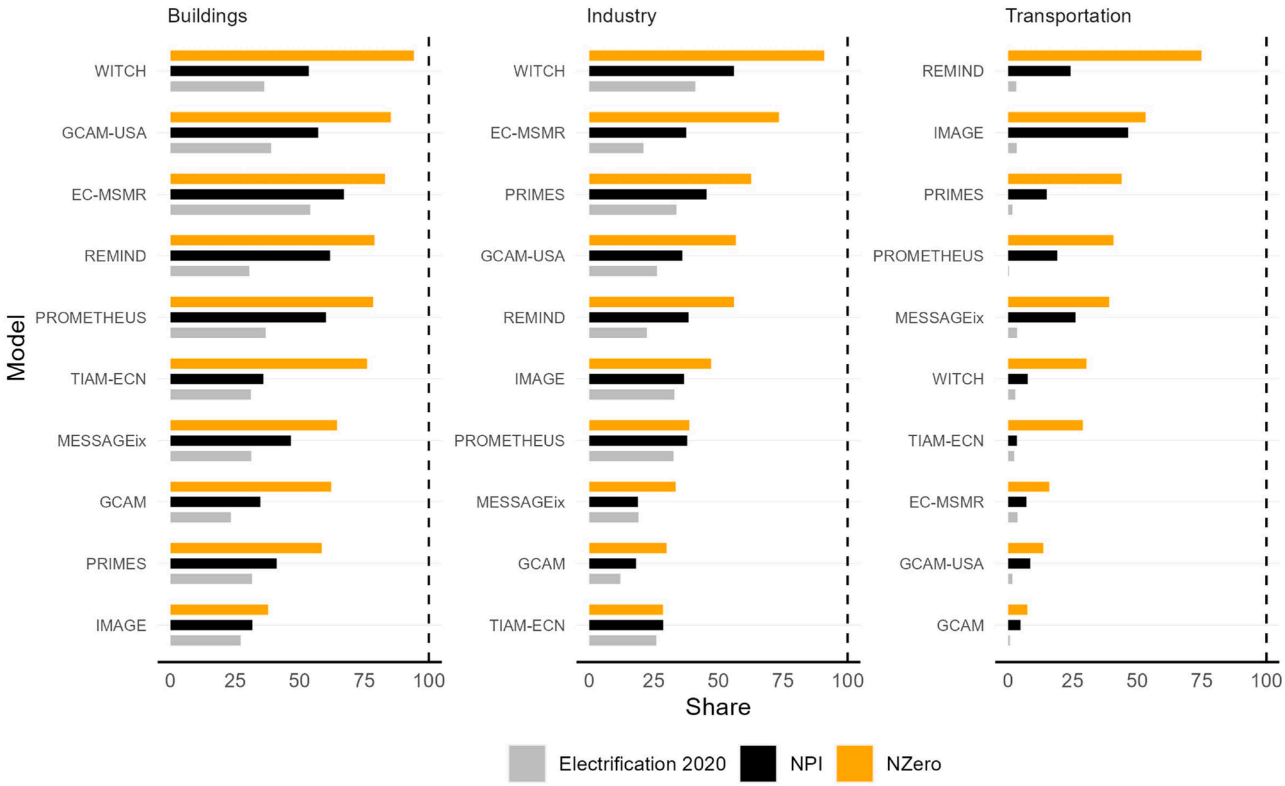

Fig. 16. Share of electricity in final energy demand in Europe.
Notes: Electrification shares in Europe's Buildings, Industry, and Transportation sectors across all models. Each panel presents the 2050 electrification for the NPI and Net Zero scenarios alongside the electrification rate in 2020. Note that only considers commercial buildings, not commercial and residential.

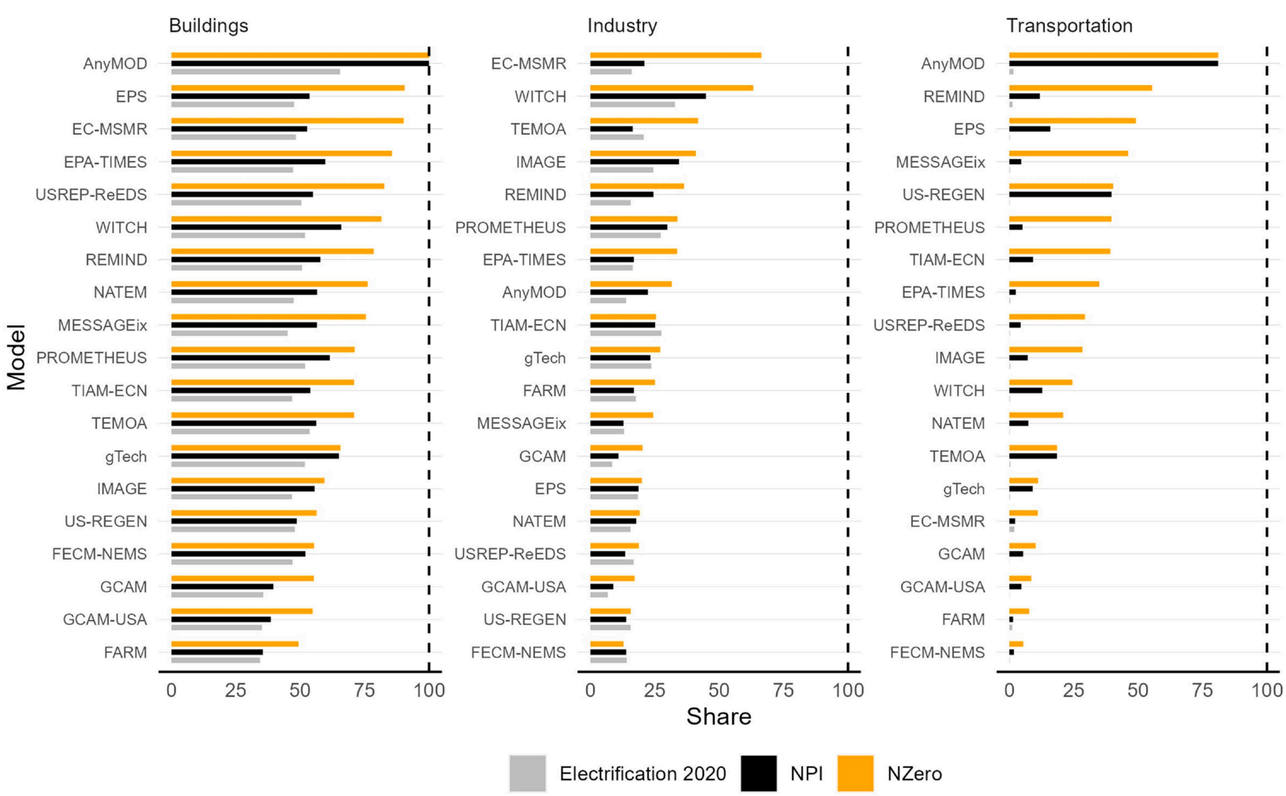

Fig. 17. Share of electricity in final energy demand across American models.
Notes: Electrification shares in the Buildings, Industry, and Transportation sectors in the United States across all models. Each panel presents the 2050 electrification for the NPI and Net Zero scenarios alongside the electrification rate in 2020. Note that only considers commercial buildings, not commercial and residential.

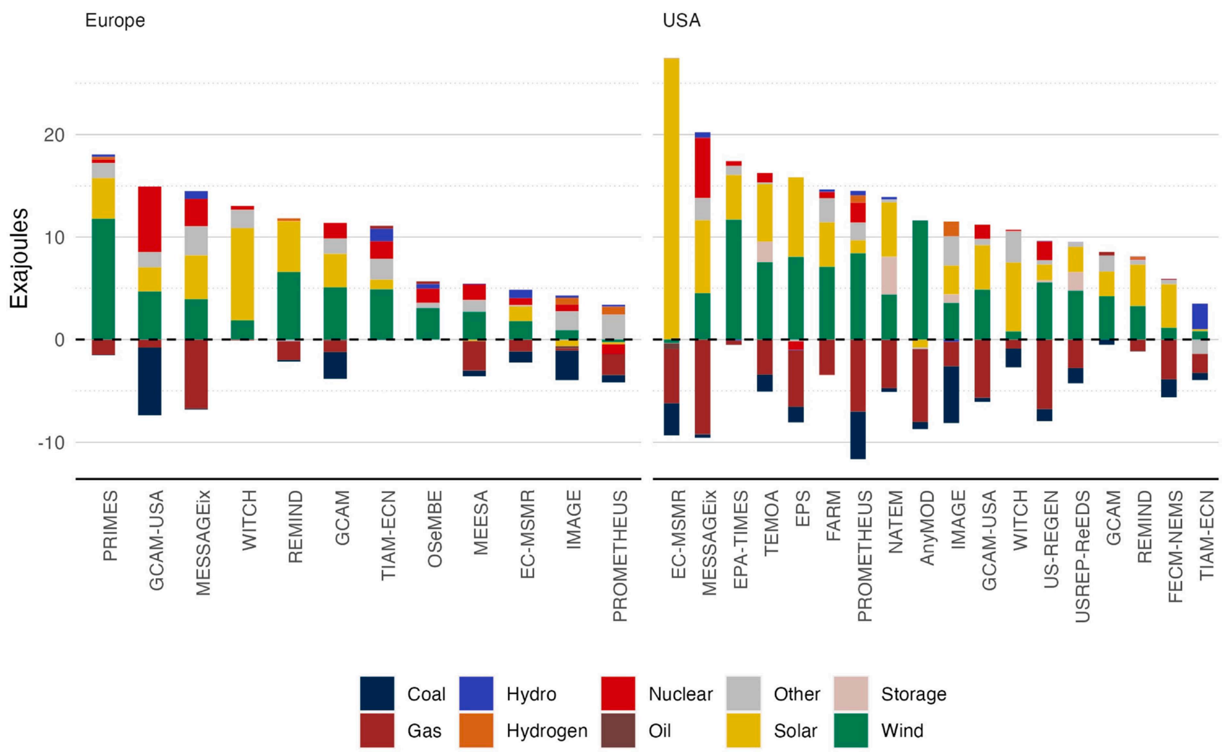

Fig. 18. Changes in the power-Mix in 2050 between the NPI and Net Zero scenarios across models.
Notes: This figure presents the difference in electricity generation between the NPI and Net Zero scenario across different technologies in 2050. We present the results for Europe on the left panel and the United States on the right panel. For each technology *t* and model *m*, we estimate the difference in power generation by simply estimating $\Delta Gen_{tm} = (Gen_{tm} \mid y = 2050 \ \& \ NPI)$ - $(Gen_{tm} \mid y = 2050 \ \& \ NZero)$.

increases dramatically to 3.3 % in both regions.

This value is more than ten times higher than the historical average of 0.25 %.

Electrification

The electrification of the energy sector and the reduction in fossil fuel demand lead to a reduction in final energy needs for both regions because electric end-use options are often more energy efficient than fossil fuel technologies. Fig. 16 shows the share of electricity in the final energy needs of Europe for all sectors, scenarios, and models. In the buildings sector, the share of electricity in the Net Zero scenario is highest for *WITCH* with 94 % and lowest for *IMAGE* with 38 %. The average share of electrification across all models is 71.9 %. For the industry sector, the model with the highest electrification is again *WITCH* with 91 %, while the lowest is now *TIAM-ECN* with 28.5 %. The average share across all models for the industrial sector is 51.7 %. For transport, the highest is *REMIND* with 75 % and the lowest *GCAM* with only 7.4 %. The average share of all models regarding transportation electrification is 34.8 %.

Fig. 17 shows the share of electricity in the final energy needs of the United States. On average, the Net Zero scenario implies that electricity would constitute 72.1 % of the final energy demand of buildings, 30.2 % of industry, and 29.5 % of transport. These shares represent a significant increase in electrification concerning 2020. That is, buildings (47.6 %), industry (18.1 %), and transportation (0.4 %). Across models, *AnyMOD* exhibits very aggressive electrification of transport and buildings, with more than 80 % of final energy coming from electric power in the transportation sector and almost 100 % in the buildings sector. On the other side of the spectrum, the electrification rate for buildings, industry, and transportation is lowest for *FARM* (49.3 %), *FECM-NEMS* (12.8 %), and *FECM-NEMS* (5.4 %). The high electrification of AnyMOD is mainly because renewables and electrification are already cost-effective for many applications in the NPI scenario without any cost or carbon limitation in their model. The model does not make any external assumptions or restrictions on the growth of electric vehicles. Furthermore, electric cars for passenger and freight road transport will become cost-competitive with internal combustion engine vehicles by 2025.

Prevailing limiting factors to greater electrification vary by model but include a lack of electric alternatives for some modes of transport or industrial processes, slow stock turnover, high cost of electric technologies for some applications or consumer segments, behavioral assumptions, and deployment limits. The added electrification from net zero constraints is higher for buildings, leading to almost full electrification in many models. Results for the transportation and industrial sectors also show increased electrification, although of smaller magnitudes than buildings

Power mix

In line with the electrification of end-use sectors, total power generation for both regions almost doubles between 2020 and 2050, increasing from 27 to 57 EJ. There are also relevant changes in the composition of the generation mix. The share of gas, coal, nuclear, hydro, and oil technologies decreases by 22, 20, 12, 4, and 1 percentage points. The models compensate for this significant reduction in traditional generation facilities with an increase of 25 percentage points in the use of solar and wind technologies (see Fig. B.13).

Fig. 18 shows the difference in electricity production between NPI

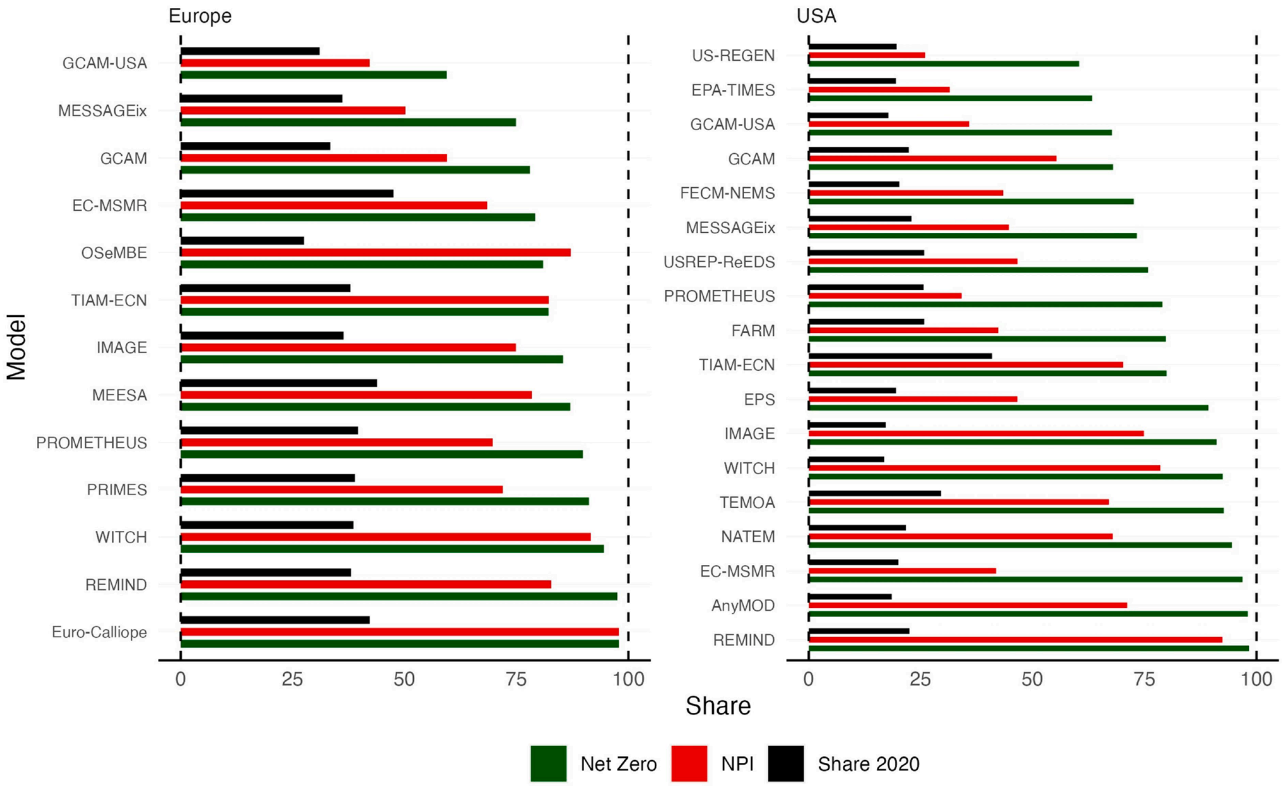

Fig. 19. Share of Renewables in the power sectors of Europe and the US across models.
Notes: This figure presents the share of electricity generation from renewable or clean energy sources in the NPI and Net Zero scenarios alongside the share in 2020. We present results for each energy model. The left panel shows results for Europe, and the right panel for the United States. We consider hydro, solar, wind, biomass, geothermal, and hydrogen as renewable energy options.

and Net Zero scenarios across technologies and models.[9] Throughout energy models, the generation from emission-free technologies, such as wind, solar, nuclear, and storage, increases significantly. The models with the highest growth in renewables generation are *PRIMES, GCAM-USA*, and *MESSAGEix-GLOBIOM* for Europe and *ECMSMR, MESSAGEix-GLOBIOM*, and *EPA-TIMES* in the USA. On the other hand, the models with the highest reduction in fossil fuels are *MESSAGEix-GLOBIOM, GCAM-USA*, and *IMAGE* in Europe and *EC-MSMR, MESSAGEix-GLOBIOM*, and *PROMETHEUS* for the USA.

Renewables

There has been a heated debate on the potential role of renewables in the power mix. Many recent studies have studied the feasibility and challenges of power systems based on 100 % renewable sources. For the US exemplary studies include Becker et al. [2], while for Europe, they include Zappa et al. [29]. Fig. 19 presents the share of generation with renewable energy sources for Europe and the United States. We consider hydro, solar, wind, biomass, geothermal, and hydrogen as renewable energy options. In Europe, the 2050 share in the NPI scenario ranges from 98 % in *Euro-Calliope* to 42 % in *GCAM-USA*, with a median share increasing from 38 % to 75 % between 2020 and 2050. In the Net Zero scenario, *GCAM-USA* still reports the smallest share, with 59 %, and Euro-Calliope reports the highest, with 98 %. The net zero median share grows in terms of NPI from 75 % to 85 %. For the United States, the models with the highest and lowest share of renewables in the NPI scenario are *REMIND* (92 %) and *US-REGEN* (26 %). The median share of renewables in the NPI for the US is significantly lower than in Europe. That is, 47 % vs 75 %. In the Net Zero scenario, *REMIND* still reports the highest share (98 %) and *US-REGEN* the lowest with 31 %. However, contrary to NPI, the Net Zero share of renewables in the United States is not too far away from Europe, i.e., 80 % ca. 85 %, respectively.[10]

Discussion and conclusion

Europe and North America account for 32 % of current carbon emissions. Due to distinct legacy systems, energy infrastructure, and potential lock-in effects, both regions likely have different policy and technological pathways to reach net zero targets by the mid-century. In this paper, we discuss the trajectory of CO_2 emission reductions, as well as related energy system developments in the United States and Europe, for the NPI and Net Zero scenarios based on a large number of European and American models. The NPI scenario allows teams to freely implement current climate and energy policies while imposing no additional GHG or CO_2 limits in Europe, the United States, or any other world region. In the Net Zero scenario, all teams impose the following constraints: a global peak budget constraint of 650, net zero CO_2 emissions for the United States in 2050, and net zero GHG emissions for Europe in 2050.

By 2050, the median emission reported by the energy models decreases by 35 % and 14 % (w.r.t. 2020) in Europe and the United States in the NPI scenario. Under Net Zero, both continents manage to reach

[9] Fig. B.14 complements Fig. 18 by showing the difference in percentage points in power generation between 2020 and 2050 for each technology in the Net Zero scenario. As expected, there is a significant decrease in traditional technologies such as coal, gas, nuclear, hydro, and oil across models, which is compensated by the higher electricity production with wind and solar.

[10] Fig B.15 presents the aggregate results when considering nuclear as renewable. When considering nuclear energy, the shares of zero-carbon technologies in the Net Zero scenario increase to 94 % and 96 %.

net zero CO_2 by 2050. To reach the highest rate of emissions reduction, the United States relies more heavily on carbon capture and sequestration to reach net zero than Europe. This is evident in the higher annual captured emissions for the United States by 2050. Industrial processes appear to be the hardest to decarbonize in Europe and the United States. The second most challenging sector to decrease emissions is industry in the United States and transport in Europe. There are also clear differences in carbon prices between models due to different assumptions. However, despite heterogeneous national policies and greenhouse gas targets for the Net Zero scenarios in Europe, both regions show relatively similar implicit or explicit carbon prices required to reach Net Zero targets. We also analyze the final energy demand by sector and source in Europe and the United States. The median final energy demand in 2050 decreases by 18 % and 23 % in Europe and the United States in the Net Zero scenario. Regarding the share of electricity in final energy needs in all sectors, scenarios, and models, the Net Zero scenario implies that electricity would comprise 73 % of the final energy demand of buildings, 24 % of industrial needs, and 24 % of transportation in the United States. For Europe, the numbers are quite similar for buildings and transport, while slightly higher for industry. That is, 71 %, 42 %, and 26 % of the final energy demand comes from electricity for the buildings, industrial, and transportation sectors. Despite the progress in reducing emissions and increasing electrification, prevailing limiting factors to greater electrification must be addressed, especially in specific industrial subsectors (such as cement) and transport modes (such as aviation and navigation).

Using a large number of energy systems and integrated assessment models, we explore the decarbonization pathways of two of the largest single-market regions in the world. Europe and the United States. We provide relevant diagnoses and insights for five main topics: Emissions, Carbon Prices, Final Energy Demand, Energy and Carbon Intensities, Electrification, and Renewable Electricity Generation. As such, we contribute to the burgeoning literature on the decarbonization of energy systems and the pathways towards a net zero economy.

Data availaibility

The two forums maintain open access databases which are available at https://data.ece.iiasa.ac.at/ecemf (for the ECEMF). For the EMF-37, the IIASA data base will become available after the special issue.

CRediT authorship contribution statement

Luis Sarmiento: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Johannes Emmerling:** Formal analysis, Methodology, Supervision, Writing – review & editing. **Robert Pietzcker:** Conceptualization, Data curation, Writing – review & editing. **Vassilis Daioglou:** Conceptualization, Data curation, Methodology, Writing – review & editing. **Francesco Dalla Longa:** Data curation. **Mark M. Dekker:** Data curation. **Laurent Drouet:** Data curation. **Amir Fattahi:** Data curation. **Panagiotis Fragkos:** Data curation, Writing – review & editing. **Hauke T.J. Henke:** Data curation. **Oliver Fricko:** Data curation. **Leonard Göke:** Data curation. **Volker Krey:** Data curation. **Ellie Lochner:** Data curation. **Gunnar Luderer:** Data curation. **Nick Macaluso:** Data curation. **Kowan T.V. O'Keefe:** Data curation. **Kathleen M. Kennedy:** Data curation. **Gokul Iyer:** Data curation. **Renato Rodrigues:** Data curation. **Eric Stewart:** Data curation. **William Usher:** Data curation, Writing – review & editing. **Bob van der Zwaan:** Data curation. **Detlef van Vuuren:** Data curation. **Eleftheria Zisarou:** Data curation. **Behnam Zakeri:** Data curation.

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.

Acknowledgments

We want to thank the steering committee of the Stanford Energy Modeling Forum and the European Climate and Energy Modeling Forum for the opportunity to participate in these relevant scientific endeavours aimed at comprehending the decarbonization of our energy system. Particularly, we want to thank John Weyant and Will Usher for their valuable insights and continuous work in the field. Luis Sarmiento gratefully acknowledges the financial support from the H2020 ERC Starting Grant funded by European Commission (#853487) . Panagiotis Fragkos and Elefteria Zisarou would like to thank the NDC ASPECTS project part of the European Union's Horizon 2020 Research and Innovation Programme under grant agreement no 101003866. The contribution of Behnam Zakeri was in part supported by the Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation, and Technology (BMK) under the BMK-endowed professorship for Data-Driven Knowledge Generation: Climate Action. This work was supported by the European Climate and Energy Modelling Forum (ECEMF, H2020 grant agreement No 101022622).

Appendix A. Appendix

A.1. Introduction and methodology

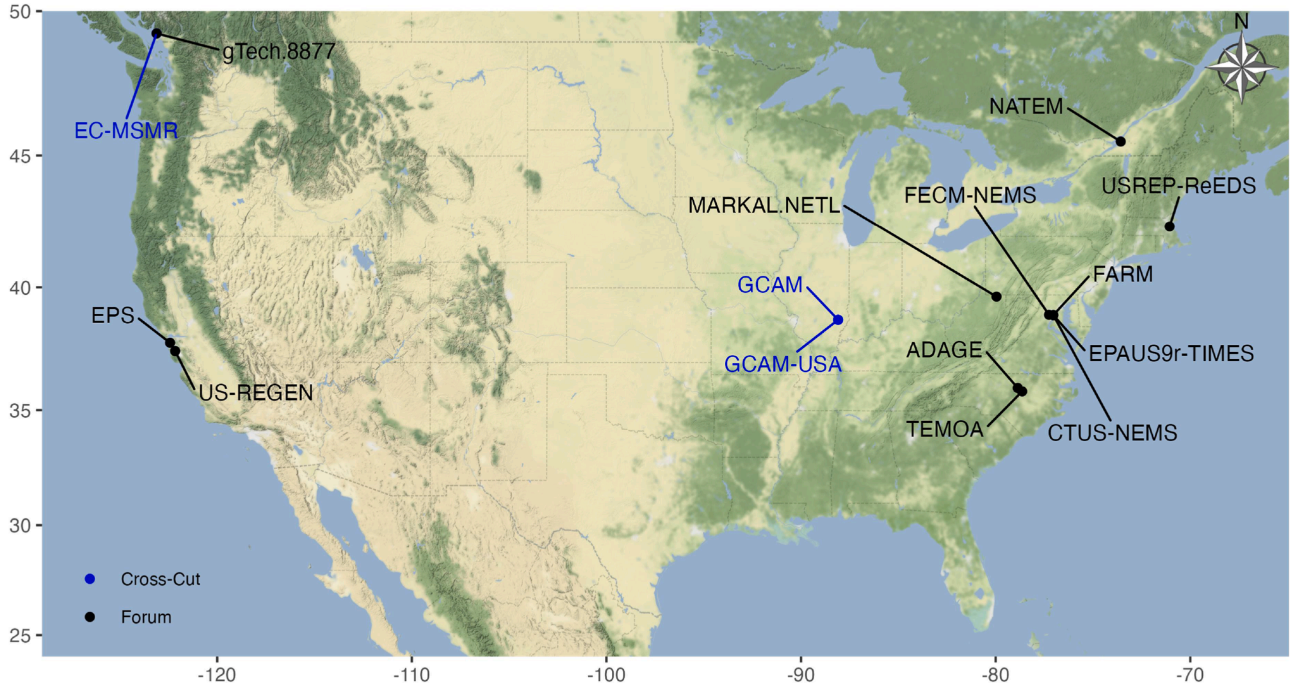

Fig. A.1. Study's models across North America

Fig. A.2. Study's models across Europe

MODEL	VERSION	ACRONYM	INSTITUTE	COUNTRY	CROSS-CUT	EMF	ECEMF	US RESULTS	EUROPEAN RESULTS
ADAGE	1.0	ADAGE	RTI International		No	Yes	No	Yes	No
AnyMOD	0.1.6	AnyM	Berlin Institute of Technology		No	Yes	No	Yes	No
CTUS-NEMS	1.0	CTUS	U.S. Department of Energy		No	Yes	No	Yes	No
EC-MSMR	20220822	ECMS	Environment and Climate Change Canada		Yes	Yes	No	Yes	Yes
EPAUS9r-TIMES	20.5.1	EPA-T	Environmental Protection Agency		No	Yes	No	Yes	No
EPS	3.2.1	EPS	Energy Innovation		No	Yes	No	Yes	No
Euro-Calliope	2	Euro-C	Polytechnical Institute of Zurich		No	No	Yes	No	Yes
FARM	4.1	FARM	United States Department of Agriculture		No	Yes	No	Yes	No
FECM-NEMS	1.0	FECN	OnLocation		No	Yes	No	Yes	No
GCAM	5.3	GCAM-US	Pacific Northwest National Laboratory		Yes	Yes	No	Yes	Yes
GCAM-USA	5.3	GCAM	Pacific Northwest National Laboratory		Yes	Yes	No	Yes	Yes
IMAGE	3.2	IMG	Netherlands Environmental Assessment Agency		No	No	Yes	No	Yes
MARKAL.NETL	2021 1.0	MRK	National Energy Technology Laboratory		No	Yes	No	Yes	No
MEESA	1.1	MSA	Center for Climate and Energy Analysis		No	No	Yes	No	Yes
MESSAGEix-GLOBIOM	1.2	MSG-G	International Institute for Applied Systems Analysis		Yes	No	Yes	Yes	Yes
NATEM	1.0	NATEM	Esmia Consultants		No	Yes	No	Yes	No
OSeMBE	1.0.0	OSMB	KTH Royal Institute of Technology		No	No	Yes	No	Yes
PRIMES	2022	PRMS	E3Modelling		Yes	No	Yes	No	Yes
PROMETHEUS	1.2	PRMTH	E3Modelling		Yes	No	Yes	Yes	Yes
REMIND	2.1	RMND	Postdam Institute for Climate Impact Research		Yes	No	Yes	Yes	Yes
TEMOA	1.0	TEMOA	North Carolina State University		No	Yes	No	Yes	No
TIAM-ECN	1.2	TIAM	Netherlands Organization for Applied Scientific Research		Yes	No	Yes	Yes	Yes
US-REGEN	5.0	REGEN	Electric Power Research Institute		No	Yes	No	Yes	No
USREP-ReEDS	22.1.0	ReEDS	MIT-NREL		No	Yes	No	Yes	No
WITCH	5.0	WITCH	European Institute on Economics and the Environment		Yes	No	Yes	Yes	Yes
gTech	8877	gTech	Navius Research		No	Yes	No	Yes	No

Fig. A.3. List of participating Models

MODEL	SPATIAL RESOLUTION	GAS COVERAGE	EQUILIBRIUM APPROACH	BASE-END YEARS; TIMESTEP;	CARBON MANAGEMENT OPTIONS
ADAGE	US+7 global regions	CO2 & non-CO2	General; Myopic	2010-2050; 5-year time steps; CES	DAC, Biofuels
AnyMOD	US, Canada, and Mexico	CO2 only	Partial; Perfect	2020-2050; 5-year time steps; LP	BECCS, DAC, H2
EC-MSMR	Canada, Mexico, US + 13 other regions	CO2 & non-CO2	General; Myopic	2014-2050, 5-year time steps; CES	BECCS (Electricity only), DAC, Green H2, Biofuels, Renewable Natural Gas
EPA-TIMES	9 US regions	CO2 & non-CO2	Partial; Perfect	2010-2050, 5-year time steps; LP	BECCS (Electricity only), DAC, H2, Biofuels
EPS	US	CO2 & non-CO2	Partial; Myopic	2020-2050, 1-year time steps; Logit	DAC, H2, Biofuels
FARM	US, Canada + 11 other world regions	CO2 only	General; Myopic	2011-2101, 5-year time steps; Mixed: Logit for electricity generation shares; CES otherwise	BECCS, Biofuels
FECM-NEMS & OP-NEMS	US; subnational aggregation varies by submodule	CO2 only	General; Myopic	2021-2050; 1-year time steps; Mixed: LP in power and liquid fuels; MIP for CO2 pipeline and storage; Logit in demand models	BECCS (electricity only), DAC, CCS for ethanol, natural gas processing, H2 in refineries, and cement; liquid biofuels
GCAM	50 US states, Canada, Mexico+29 other regions	CO2 & non-CO2	Partial; perfect	2015-2100; 5-year time step; New investment: logit based on expected profitability; Existing technologies must cover operating costs.	BECCS (electricity, biofuels, H2 with CCS), DAC, H2 in end-use, liquid biofuels, biogas
GCAM-USA	Canadian Provinces + US	CO2 & non-CO2	Partial; Myopic	2015-2100; 5-year time step; New investment: logit based on expected profitability; Existing technologies must cover operating costs.	BECCS (electricity, biofuels, H2 with CCS), DAC, H2 in end-use, liquid biofuels, biogas
MARKAL-NETL	13 Canadian regions; 9 US Census regions + CA, TX, NY; Mexico	CO2 & non-CO2	General; Myopic	2005-2075; 5-year time steps; LP	BECCS, DAC, H2, Biofuels, Synthetic Gas & Liquids
NATEM	9 US regions	CO2 & non-CO2	Partial; Perfect	2016-2060; 2- to 5-year time steps; LP	BECCS, DAC, H2, Biofuels, Synthetic Gas & Liquids
TEMOA	16 US regions	CO2 only	Partial; Perfect	2020 to 2050; 5-year time steps; LP	BECCS (electricity only), DAC, H2, Biofuels, Synthetic fuels
US-REGEN	USREP: 12 US regions	CO2 & non-CO2	Partial; Perfect	2015-2050; 5-year time steps; Mixed; LP in electric and fuels sectors, logit in end-use sectors	BECCS, DAC, H2, Biofuels, Synthetic Gas & Liquids, Ammonia
USREP-ReEDS	ReEDS: 134 balancing areas	CO2 & non-CO2	General; Myopic	2017-2050; 5-year time steps; Mixed; CES in USREP; LP in ReEDS	BECCS (Electricity only), DAC, Biofuels, Industrial CCS
gTech	9 US Census regions	CO2 & non-CO2	Partial; Myopic	2015-2050; 5-year time steps; CES	DAC, BECCS, H2, Biofuels

Fig. A.4. Model characteristics for EMF 37

A.2. Emissions

Notes: Gross emissions and sequestration of CO_2 across models, regions, and sources in the NPI scenario. BECCS: Bioenergy with Carbon Capture and Sequestration. FOCCS: Fossil-based with Carbon Capture and Storage. DAC: Direct Air Capture. LULUCF: Land Use, Land Use Change, and Forestry. CRGS: Carbon Removal and Geological Storage. CCU: Carbon Capture and Utilization. CCS Industry: Carbon Capture and Storage in the Industrial sector.

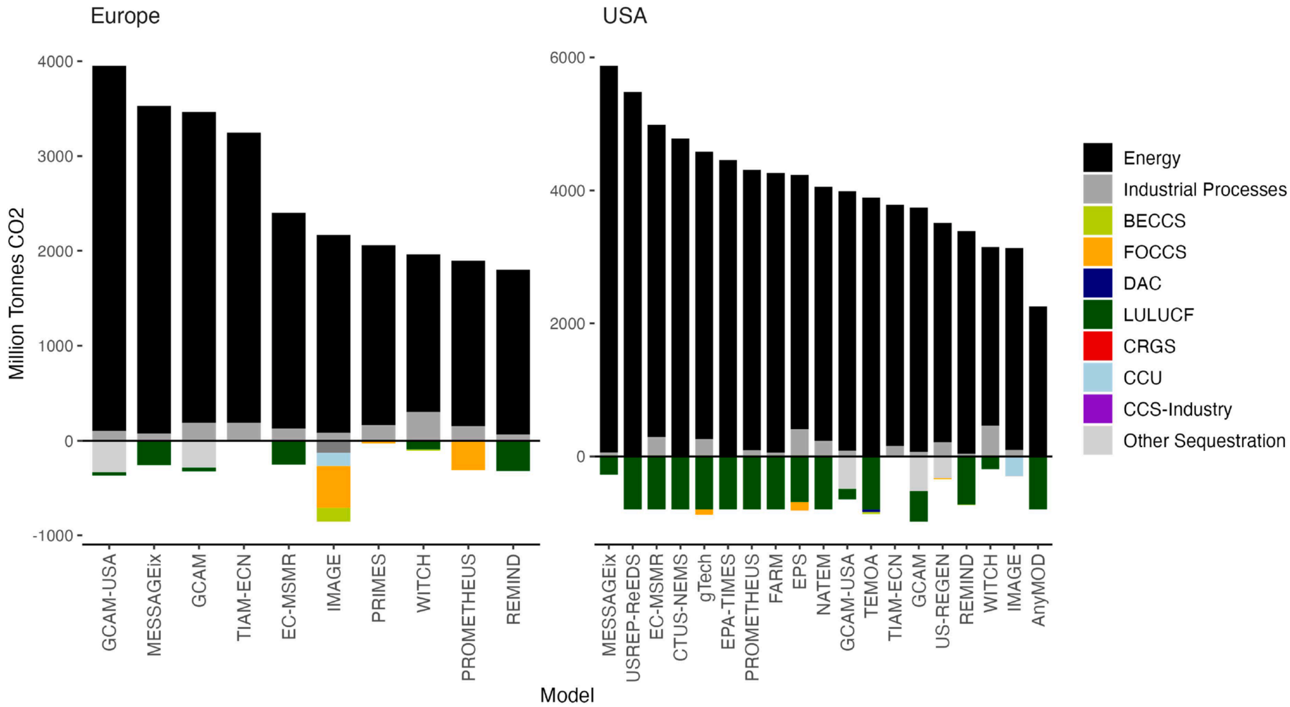

Fig. A.5. NPI difference in sources of emissions and sequestration for participating models (2050)
Notes: Gross emissions of CO_2 across models, sectors, and scenarios in Europe. Transportation includes Bunkers. The text in parenthesis is the sum of emissions for all four sectors.

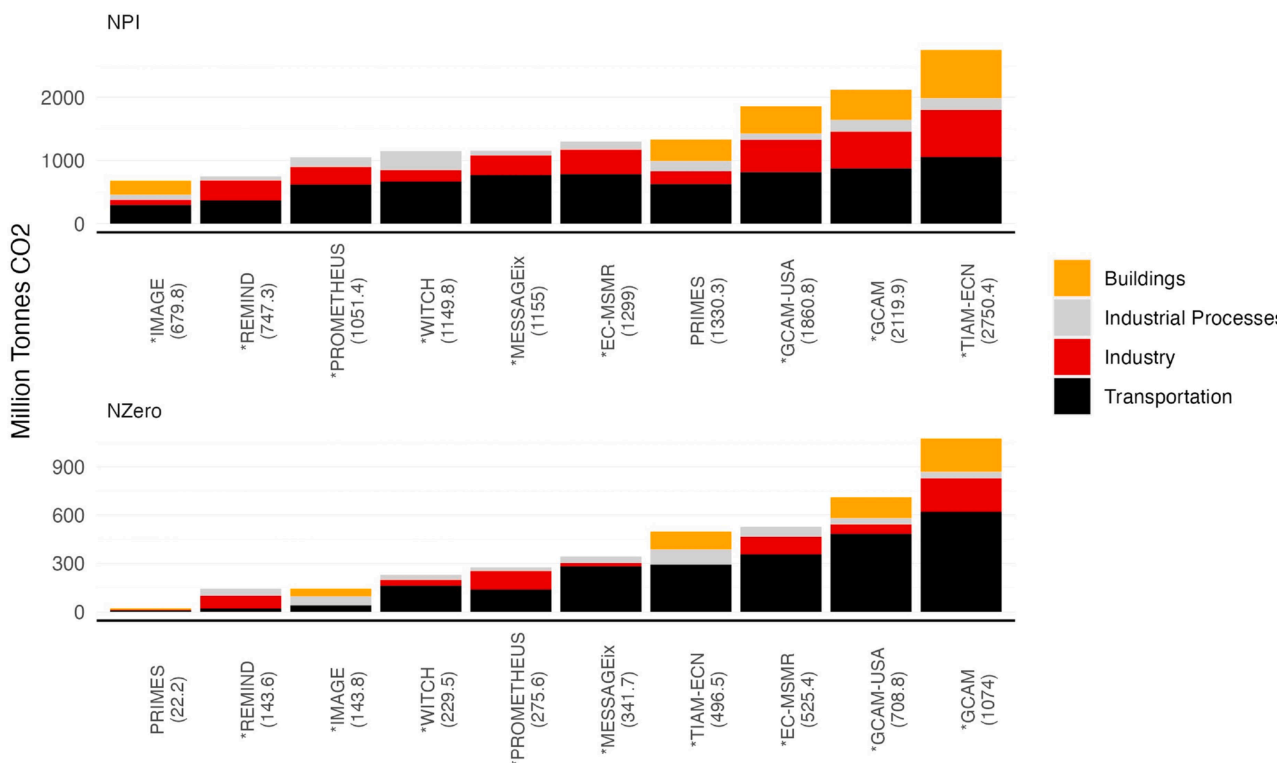

Fig. A.6. Gross CO_2 emissions across models and energy sectors in Europe (2050)
Notes: Gross emissions of CO_2 across models, sectors, and scenarios in the United States.

Transportation includes Bunkers. The text in parenthesis is the sum of emissions for all four sectors.

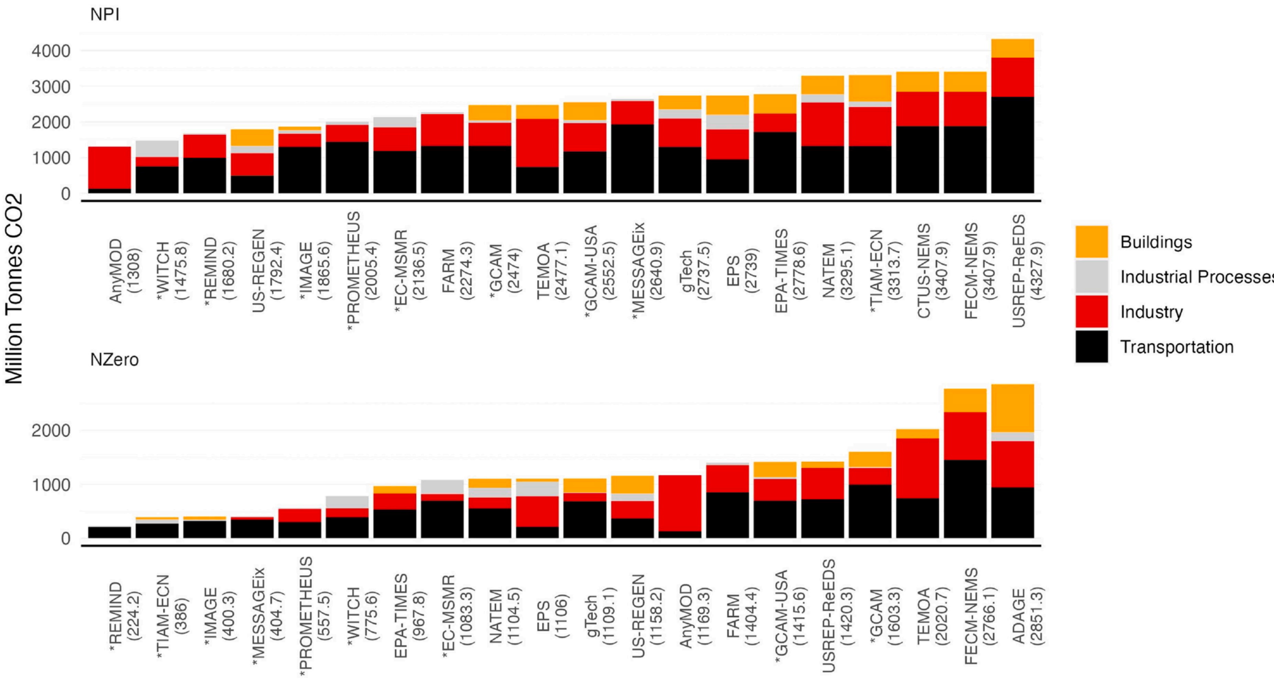

Fig. A.7. Gross CO_2 emissions across models and energy sectors in the USA (2050)

Appendix B. Carbon prices

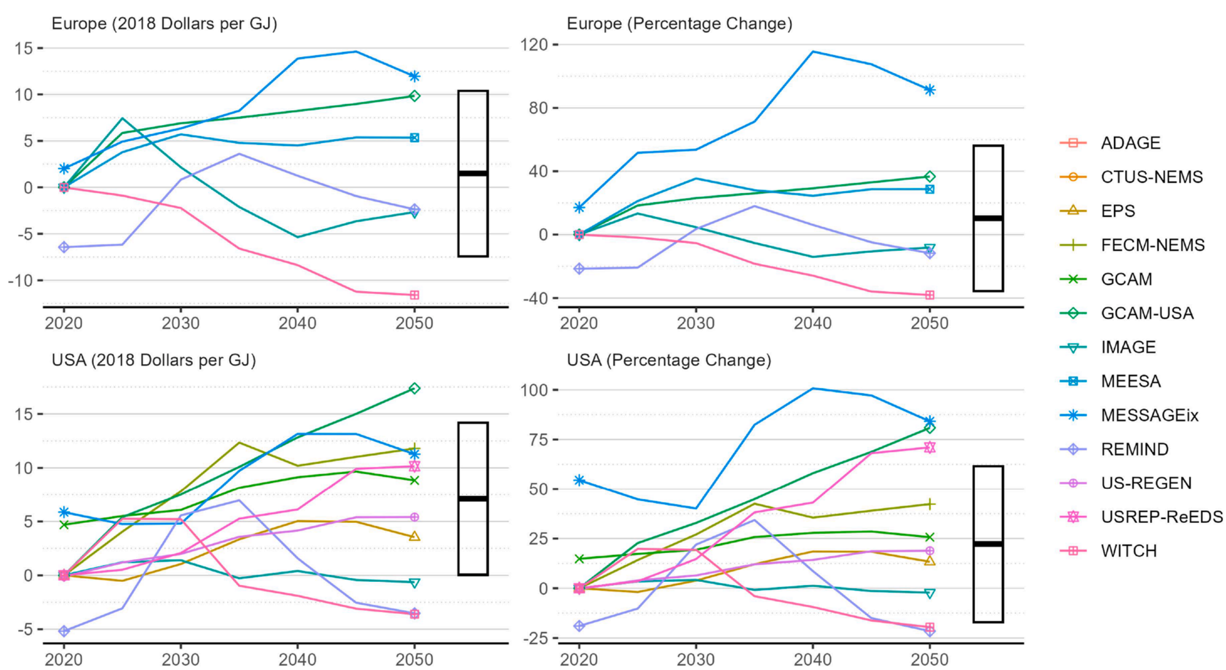

Fig. B.8. Time Series of the Change in the LCOE Between the NPI and Net Zero Scenarios

Notes: This figure presents the 2020–2050 time series of the difference in the levelized cost of electricity (LCOE) between the NPI and Net Zero scenarios. The first column presents each period's raw difference (in 2018 Cents per kWh). The second column shows the percentage decrease in the LCOE in the Net Zero scenario concerning NPI. We add indicator shapes to identify each model in 2020 and 2050. The boxplot in each panel is centered around the median reduction in prices, with its limits equivalent to plus and minus one standard deviation from the median

B.1. Final energy demand

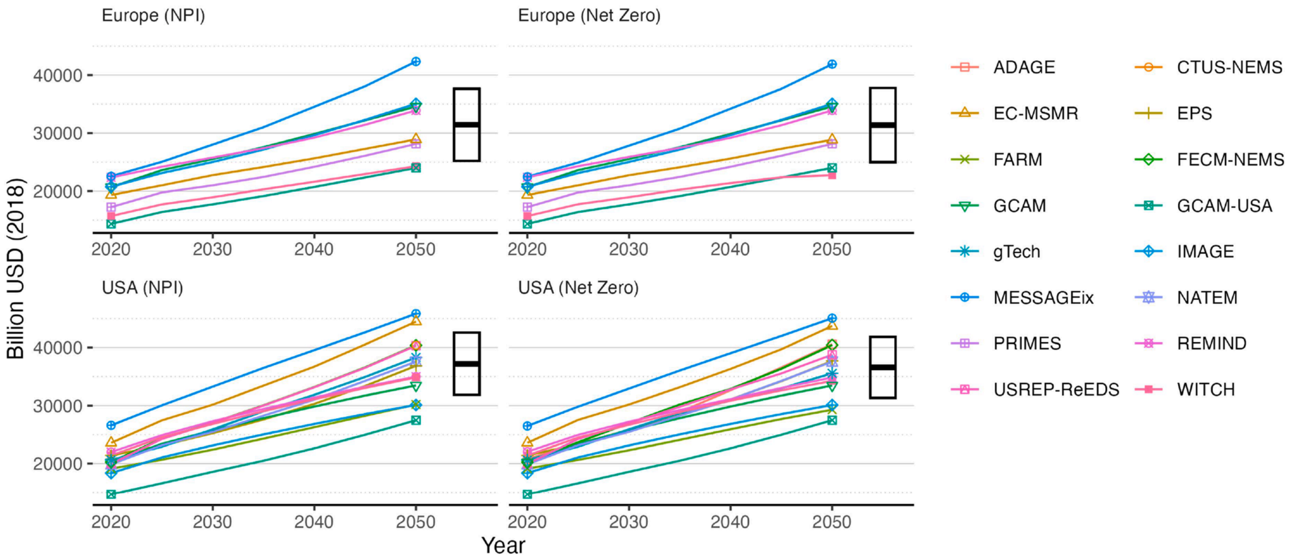

Fig. B.9. GDP across models, regions, and scenarios
Notes: Gross domestic product in Europe and the United States for the NPI and Net Zero scenarios. Values reported in billion USD (2018)

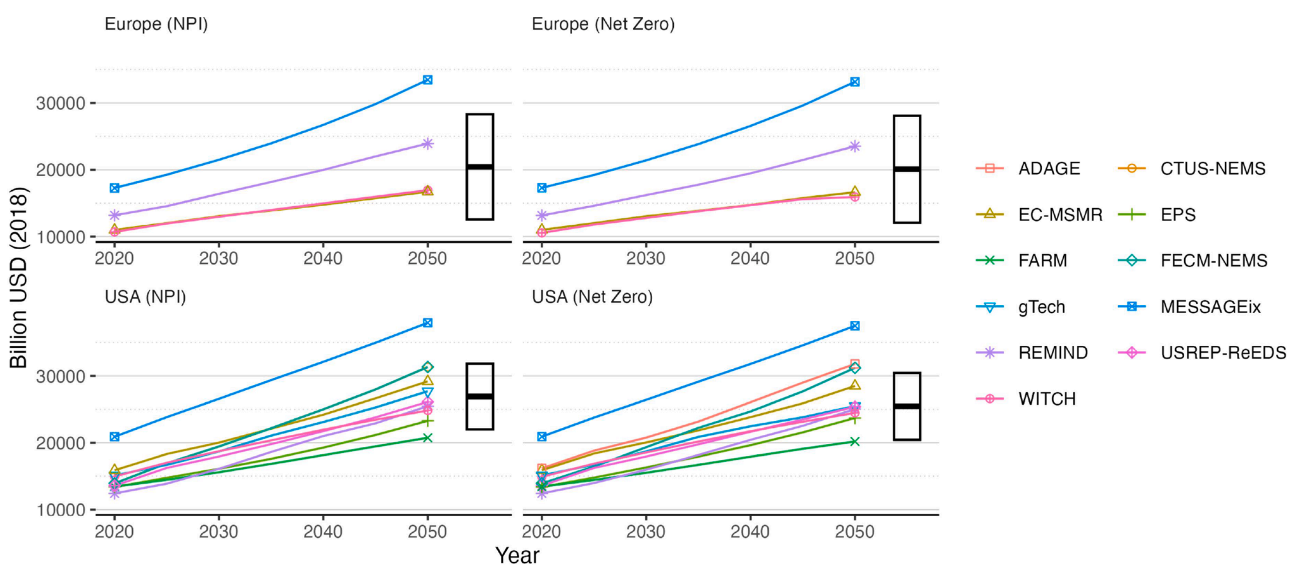

Fig. B.10. Total consumption across models, regions, and scenarios
Notes: Total consumption in Europe and the United States for the NPI and Net Zero scenarios. Values reported in billion USD (2018)

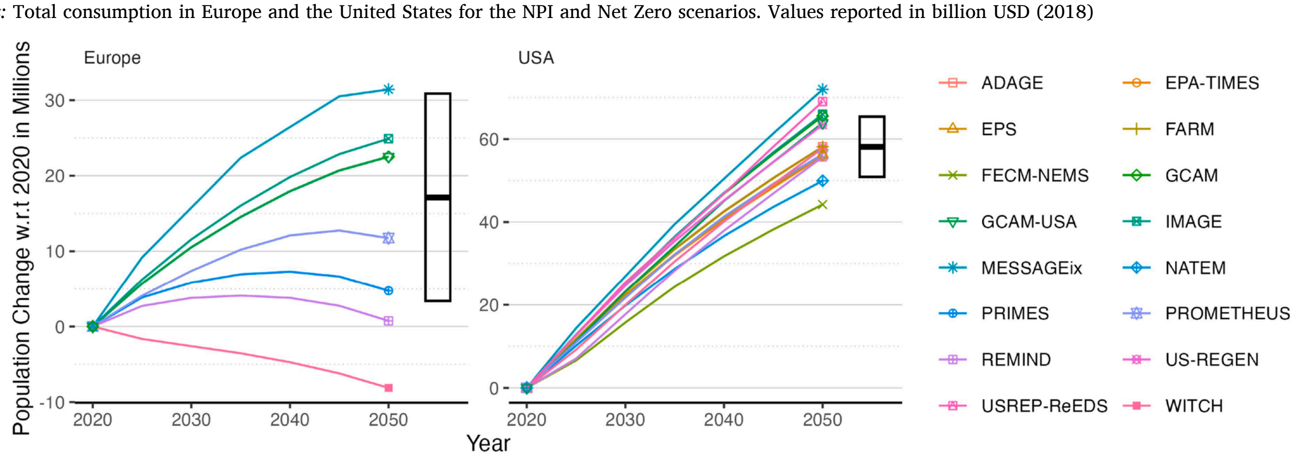

Fig. B.11. Population across models, regions, and scenarios
Notes: Change in the population in Europe and the United States concerning 2020. Values reported in million inhabitants. there are some differences in the regional scope of each team. For Europe, *TIAM-ECN, GCAM, PROMETHEUS*, and *IMAGE* present results for Europe excluding Turkey, *MESSAGEix* includes Turkey, and the rest

of the modeling teams for EU27 + UK. For the United States, only one model (*MESSAGE*) reports values for North America rather than the United States.

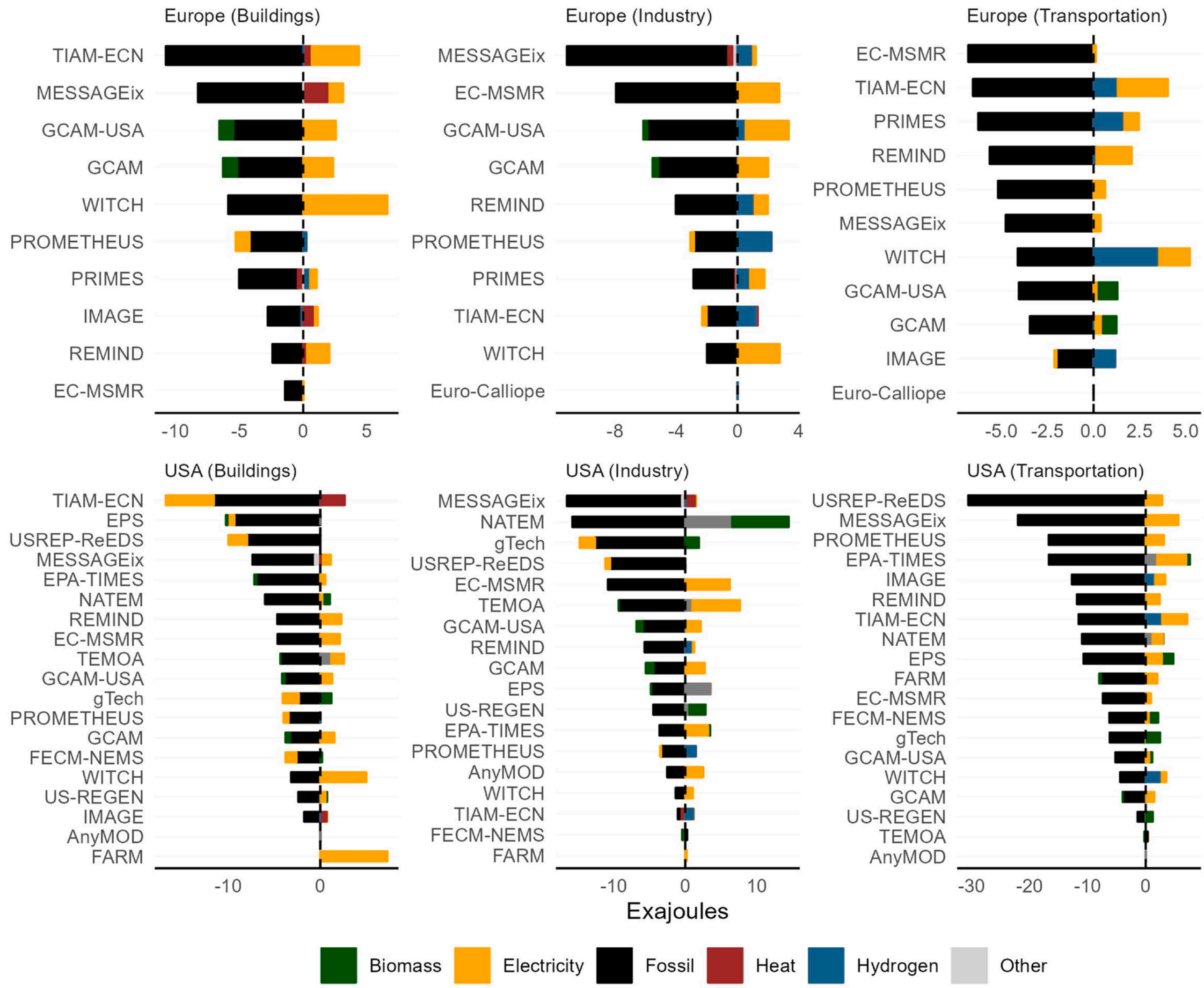

Fig. B.12. Change in final energy demand by model, sector, and source
Notes: Change in final energy demand in 2050 between the NPI and Net Zero scenarios for all models, regions, sources, and sectors. Each panel refers to the region and sector. Panel rows represent the different models. The colors of the bar plots refer to the energy source.

B.2. Power mix

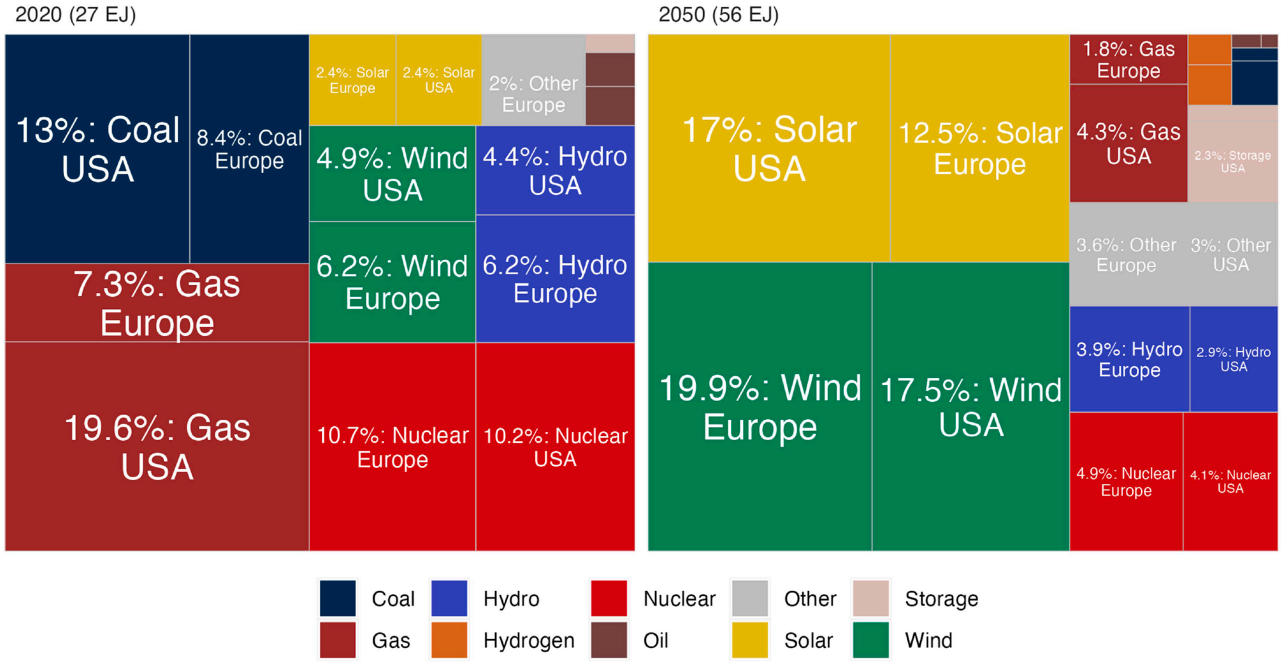

Fig. B.13. Share of electricity in final energy demand

Notes: This figure presents the 2020 and 2050 power mix for the Net Zero scenario in both Europe and the United States. Each panel presents the mix for one period, and each color refers to one of twelve generation technologies.

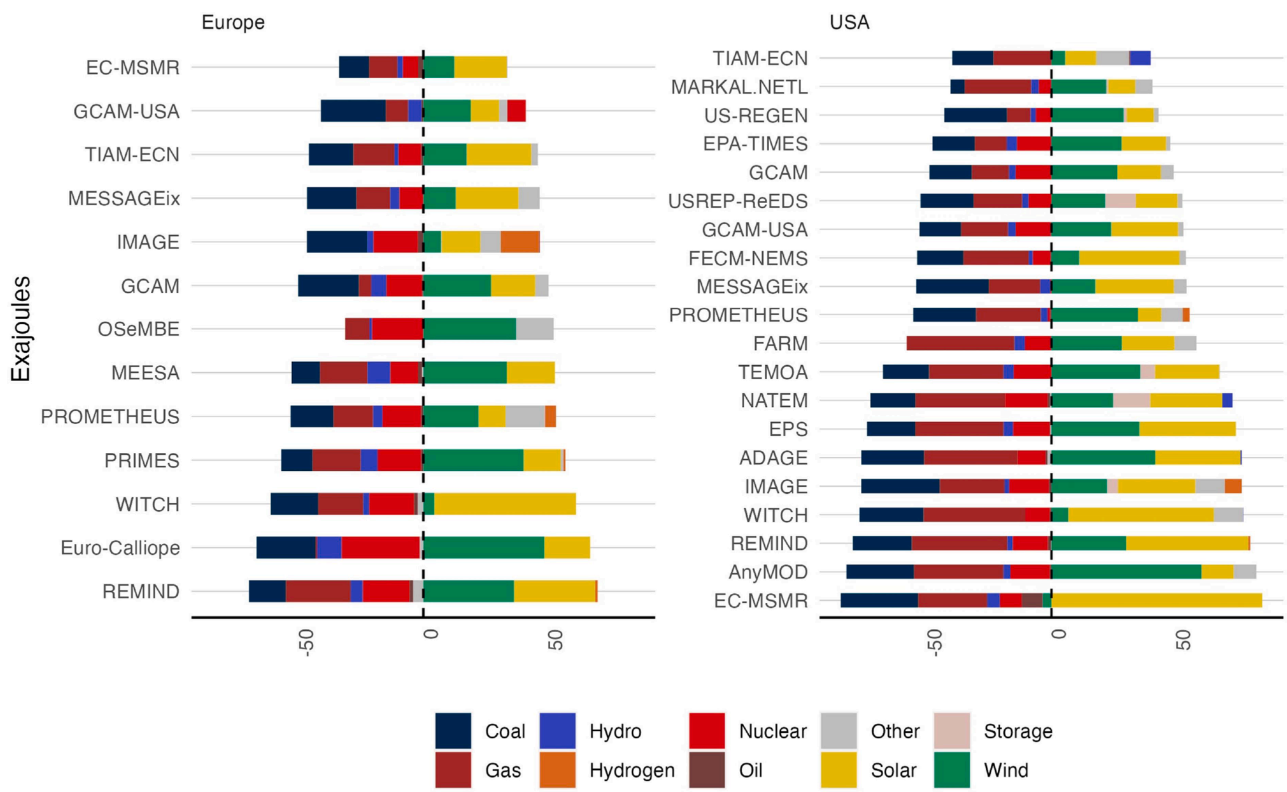

Fig. B.14. Changes in the power-Mix for the Net Zero scenario between 2020 and 2050 across models

B.3. Renewables

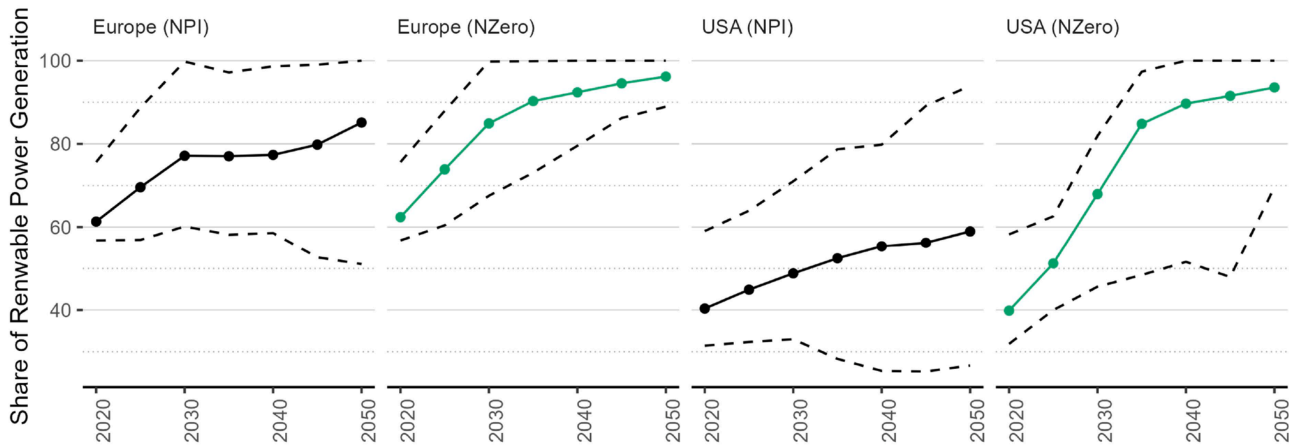

Fig. B.15. Share of Renewables including Nuclear in the power sector of Europe and the US
Notes: Average share of electricity production with renewable resources in Europe and the United States. Each line is the average across all models for that region and scenario. The collared ribbons report a one standard deviation confidence band.

References

[1] P. Alves Dias, S. Bobba, S. Carrara, B Plazzotta, The Role of Rare Earth Elements in Wind Energy and Electric Mobility, European Commission, Luxembourg, 2020, p. 16.
[2] S. Becker, B.A. Frew, G.B. Andresen, T. Zeyer, S. Schramm, M. Greiner, M. Z. Jacobson, Features of a fully renewable US electricity system: optimized mixes of wind and solar PV and transmission grid extensions, Energy 72 (22) (2014) 443–458.
[3] N.J. Van den Berg, H.L. van Soest, A.F. Hof, M.G. den Elzen, D.P. van Vuuren, W. Chen, L. Drouet, J. Emmerling, S. Fujimori, N. Höhne, et al., Implications of various effort-sharing approaches for national carbon budgets and emission pathways, Clim. Change 162 (4) (2020) 1805–1822.
[4] J. Bistline, G. Blanford, M. Brown, D. Burtraw, M. Domeshek, J. Farbes, A. Fawcett, A. Hamilton, J. Jenkins, R. Jones, et al., Emissions and energy impacts of the Inflation Reduction Act, Science 380 (6652) (2023) 1324–1327, 4.
[5] J.E. Bistline, M. Brown, M. Domeshek, C. Marcy, N. Roy, G. Blanford, D. Burtraw, J. Farbes, A. Fawcett, A. Hamilton, et al., Power sector impacts of the Inflation Reduction Act of 2022, Environ. Res. Lett. 19 (1) (2023) 014013, 9.
[6] J. Bistline, C. Onda, M. Browning, J. Emmerling, G. Iyer, M. Mahajan, J. McFarland, H. McJeon, R. Orvis, F.R. Fonseca, et al., Equity implications of net-zero emissions: A multi-model analysis of energy expenditures across income classes under economy-wide deep decarbonization policies, Energy Clim. Change 5 (12) (2024) 100118, 13.
[7] B. Boitier, A. Nikas, A. Gambhir, K. Koasidis, A. Elia, K. Al-Dabbas, Ş. Alibaş, L. Campagnolo, A. Chiodi, E. Delpiazzo, H. Doukas, A. Fougeyrollas, M. Gargiulo, P. Le Mouël, F. Neuner, S. Perdana, D.-J. Van De Ven, M. Vielle, P. Zagamé, S Mittal, A multi-model analysis of the EU's path to net zero, Joule 7 (12) (2023) 2760–2782, 14.
[8] M. Browning, J. McFarland, J. Bistline, G. Boyd, M. Muratori, M. Binsted, C. Harris, T. Mai, G. Blanford, J. Edmonds, et al., Net-zero CO2 by 2050 scenarios for the United States in the Energy Modeling Forum 37 study, Energy Clim. Change 4 (6) (2023) 100104, 7.
[9] E. Byers, V. Krey, E. Kriegler, K. Riahi, R. Schaeffer, J. Kikstra, R. Lamboll, Z. Nicholls, M. Sandstad, C. Smith, K. van der Wijst, A. Al Khourdajie, F. Lecocq, J. Portugal-Pereira, Y. Saheb, A. Stromman, H. Winkler, C. Auer, E. Brutschin, M. Gidden, P. Hackstock, M. Harmsen, D. Huppmann, P. Kolp, C. Lepault, J. Lewis, G. Marangoni, E. Müller-Casseres, R. Skeie, M. Werning, K. Calvin, P. Forster, C. Guivarch, T. Hasegawa, M. Meinshausen, G. Peters, J. Rogelj, B. Samset, J. Steinberger, M. Tavoni, D. van Vuuren, AR6 Scenarios Database, 2022. November. 4.
[10] V.R. Chimuka, C.-M. Nzotungicimpaye, K Zickfeld, Quantifying land carbon cycle feedbacks under negative CO_2 emissions, Biogeosciences 20 (12) (2023) 2283–2299. PublisherCopernicus GmbH. 6.
[11] Climate Action Tracker, CAT Climate Target Update Tracker, 2023, p. 4. https://climateactiontracker.org/climate-target-update-tracker-2022/ [Online; accessed 11-June-2023].
[12] European Comission, Emissions Data Base for Global Atmpsheric Research, 2022, p. 8 [Online; accessed 11-November-2022].
[13] I. Faiella, A. Mistretta, Bank of Italy Temi diDiscussione (Working Paper) No, 1259, 2020, p. 12.
[14] O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Strubegger, H. Valin, M. Amann, T. Ermolieva, N. Forsell, M. Herrero, C. Heyes, G. Kindermann, V. Krey, D.L. McCollum, M. Obersteiner, S. Pachauri, S. Rao, E. Schmid, W. Schoepp, K Riahi, The marker quantification of the Shared Socioeconomic Pathway 2: a middle-of-the-road scenario for the 21st century, Glob. Environ. Change 42 (7) (2017) 251–267.
[15] A. Goddard, OIES Paper, 2023. CM. 10.
[16] F. Gotzens, H. Heinrichs, J.-F. Hake, H.-J Allelein, The influence of continued reductions in renewable energy cost on the European electricity system, Energy Strat. Rev. 21 (18) (2018) 71–81.
[17] 117th Congress, House Bill 5376, 2021, p. 6. Available online: https://www.congress.gov/bill/117th-congress/house-bill/5376/text.
[18] (2021b) Build Back Better Act. 117th Congress, House Bill 5376, Available online: https://www.congress.gov/bill/117th-congress/house-bill/5376/text. 6.
[19] R. Khosla, J. Lezaun, A. McGivern, J. Omukuti, Can 'Net Zero'still be an instrument of climate justice? Environ. Res. Lett. 18 (6) (2023) 12.
[20] P. Kotek, A. Selei, B.T. Tóth, B Felsmann, What can the EU do to address the high natural gas prices? Energy Policy 173 (16) (2023) 113312.
[21] M. Krishnan, B. Hamid Samandari, J. Woetzel, S Smit, The Net-Zero Transition, 2022, p. 14.
[22] J. Lefèvre, T. Le Gallic, P. Fragkos, J.-F. Mercure, Y. Simsek, L Paroussos, Global socioeconomic and climate change mitigation scenarios through the lens of structural change, Glob. Environ. Change 74 (14) (2022) 102510. , 15.
[23] Our World in Data, CO and Greenhouse Gas Emissions, 2023, p. 3. https://ourworldindata.org/co2-and-greenhouse-gas-emissions [Online; accessed 11-May-2023].
[24] K. Riahi, C. Bertram, D. Huppmann, J. Rogelj, V. Bosetti, A.-M. Cabardos, A. Deppermann, L. Drouet, S. Frank, O. Fricko, S. Fujimori, M. Harmsen, T. Hasegawa, V. Krey, G. Luderer, L. Paroussos, R. Schaeffer, M. Weitzel, B. van der Zwaan, Z. Vrontisi, F.D. Longa, J. Després, F. Fosse, K. Fragkiadakis, M. Gusti, F. Humpenöder, K. Keramidas, P. Kishimoto, E. Kriegler, M. Meinshausen, L. P. Nogueira, K. Oshiro, A. Popp, P.R.R. Rochedo, G. Unlü, B. van Ruijven, J. Takakura, M. Tavoni, D. van Vuuren, B Zakeri, Cost and attainability of meeting stringent climate targets without overshoot, Nat. Clim. Change 11 (12) (2021) 1063–1069. Number: 12 Publisher: Nature Publishing Group. 7.
[25] K. Riahi, D.P. Van Vuuren, E. Kriegler, J. Edmonds, B.C. O'neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, et al., The shared socioeconomic pathways and their energy, land use, and greenhouse gas emissions implications: an overview, Glob. Environ. Change 42 (18, 19) (2017) 153–168.
[26] L. Sarmiento, A. Molar-Cruz, C. Avraam, M. Brown, J. Rosellón, S. Siddiqui, B. S. Rodríguez, Mexico and US power systems under variations in natural gas prices, Energy Policy 156 (16) (2021) 112378.
[27] The Global Carbon Project (2023) . https://www.globalcarbonproject.org/, [Online; accessed 11-May-2023]. 3.
[28] J.H. Williams, R.A. Jones, B. Haley, G. Kwok, J. Hargreaves, J. Farbes, M.S. Torn, Carbon-neutral pathways for the United States, AGU Adv. 2 (1) (2021) 4, e2020AV000284.
[29] W. Zappa, M. Junginger, M. Van Den Broek, Is a 100 % renewable European power system feasible by 2050? Appl. Energy 233 (22) (2019) 1027–1050.