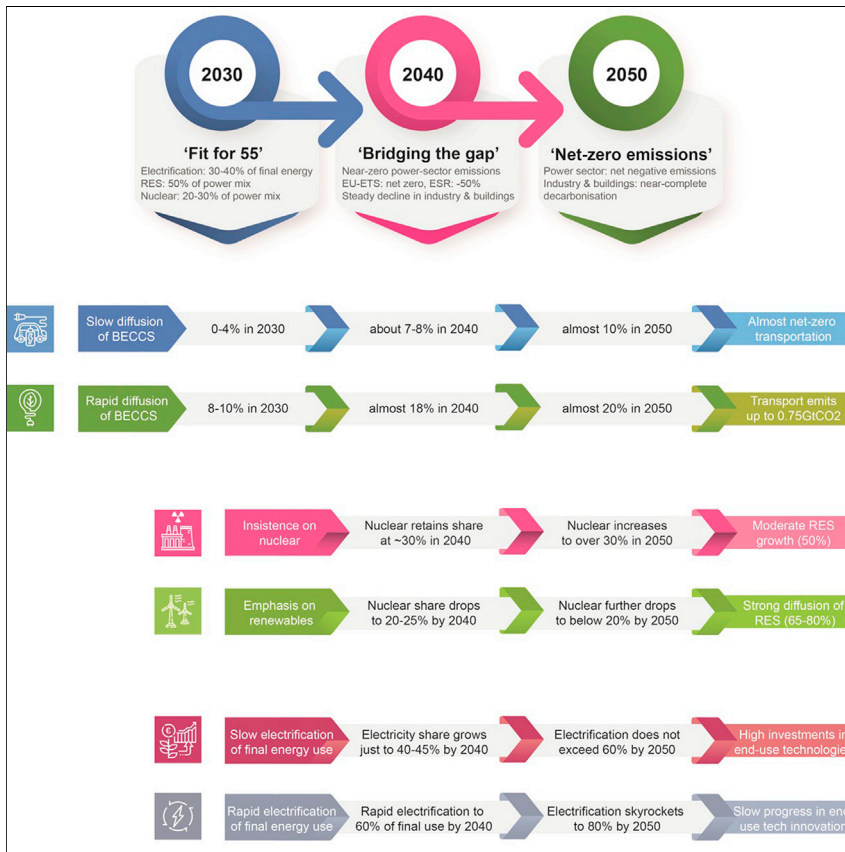


Article

# A multi-model analysis of the EU's path to net zero



The EU has formally introduced a net-zero target by 2050. However, delivering on the 2050 ambition will require exploiting a wide range of technological options and setting intermediate targets. We attempt to tackle this issue by using energy-economic modeling tools of diverse theoretical backgrounds. Getting from “Fit for 55” in 2030 to net zero by 2050 would entail total power-sector decarbonization by 2040 and rapid scale-up of a wide range of mitigation options, including renewables, bioenergy with carbon capture and storage, and electrification.

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Highlights

We examine the EU's cost-optimal timeline to net zero by 2050, using seven models

The bloc should phase out unabated coal and decarbonize its power sector by 2040

“Fit for 55” ETS and ESR targets are in line with the EU's 2050 net-zero ambition

Critical choices (e.g., RES vs. nuclear, BECCS vs. deep emissions cuts in transport)

Article

# A multi-model analysis of the EU's path to net zero

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## SUMMARY

The European Union (EU) recently ratcheted its climate ambition to net-zero emissions by 2050, with a milestone of 55% emissions cuts in 2030. This study carries out a model inter-comparison to assess the EU's path, from "Fit for 55" in 2030 to an intermediate milestone in 2040 and onto net zero in 2050, offering insights at sectoral and member-state levels. Our model results support the bloc's ambition for its Emissions Trading System and Effort Sharing Regulation sectors while pointing to the need for near-complete decarbonization of electricity by 2040, enabled by considerable deployment of renewables (45%–65% in 2030, to 60%–70% in 2040, and to 75%–90% in 2050 in electricity generation) and carbon capture and storage (0.5–2 GtCO<sub>2</sub>/year by 2050). We also highlight the trade-offs between supply-side and harder-to-abate sectors, assess the ambition of member states for net zero and timing of coal phaseout, and reflect on the economic implications of investment, technical, and policy needs.

## INTRODUCTION

In pursuit of achieving the long-term temperature goals of the Paris Agreement, adopted in 2015, countries have agreed and submitted their nationally determined contributions (NDCs) and longer-term strategies with the aim to hold global mean temperature increase to well below 2°C. Since the first round of submissions, national policies and commitments have constantly been reinforced<sup>1</sup> yet not at the pace required to collectively align with the Paris temperature goals.<sup>2,3</sup> Notably, long-term national pledges now predominantly include plans for achieving net-zero emissions (NZE) by or around mid-century.<sup>4</sup> By the end of 2022, over 120 countries had submitted an NZE target, altogether covering more than two-thirds of global greenhouse gas (GHG) emissions.<sup>5</sup>

Traditionally a frontrunner in international climate efforts,<sup>6</sup> the European Union (EU) is on the verge of operationalizing its intention to become the first region to reach a net-zero GHG emissions balance by 2050. To pave the way, the bloc recently reinforced its climate target for 2030 too, as reflected in the European Green Deal and the "Fit for 55" proposal,<sup>7</sup> by aiming to cut its emissions by 55% by the end of this decade, compared with 1990. The new target comes as a bold upgrade to the previous –40% target,<sup>8</sup> which has been found attainable with the policies already in place but largely incompatible with the 2050 NZE target.<sup>9</sup> At the same time, as a supranational body with a collective set of climate pledges, the EU bears the additional challenge of appropriately disaggregating targets for its member states and successfully monitoring progress at both scales.<sup>10</sup> This means that any

## CONTEXT & SCALE

The EU has committed to becoming a net-zero economy by 2050, with many member states having integrated this goal into national strategies. However, the bloc's path toward achieving these targets remains unclear. We use five whole-system climate-economy models and two sectoral models to explore how the EU can keep net zero within reach by mid-century, offering insights into intermediate milestones and implications at sectoral and national levels. Our results indicate that a 62% emissions reduction in the Emissions Trading System and 40% in the Effort Sharing Regulation, compared with 2005 levels, are in line with cost-optimal paths toward the bloc's 55% emissions cuts target by 2030. Bridging the gap with net zero in 2050 entails near-complete decarbonization of ETS, total decarbonization of electricity, and complete phaseout of unabated coal power by 2040, as well as rapid scale-up of negative emissions technologies and an 80% diffusion of renewables in the EU electricity mix by 2050.

credible, actionable, and feasible way forward for the EU must be validated at the country level—considering the diversity in policy ambition, resource capacity and potentials, technological lock-ins and fossil-fuel intensity, societal perceptions/needs, and socioeconomic development across member states,<sup>11–15</sup> as also reflected in the level of ambition of member states' long-term strategies (see [Table S1](#)).

The development of the “Fit for 55” policy package is well underway—concretely via upgrades to key instruments of the bloc's energy and climate strategy. These include the EU Emissions Trading System (ETS),<sup>16</sup> the Effort Sharing Regulation (ESR),<sup>17</sup> and the regulation for land use, land use change, and forestry (LULUCF). To connect the dots between “Fit for 55” and NZE, the European Commission is also preparing to put forward a legislative proposal for an intermediate EU climate target for 2040 by early 2024, drawing from the best available and most recent scientific evidence and the use of energy-system, sectoral, and integrated assessment models (IAMs). Much like for other countries (e.g., India,<sup>18</sup> Japan,<sup>19</sup> USA,<sup>20–22</sup> Canada,<sup>23</sup> and China<sup>24</sup>) or broader regions<sup>25,26</sup> (see Bistline<sup>27</sup> for an exhaustive overview), the EU's transition to carbon neutrality is not an underexplored theme among studies based on such models.<sup>28,29</sup> But, apart from analyses of individual EU countries,<sup>30–34</sup> single-model studies,<sup>35,36</sup> and global-level analyses without sufficient regional detail,<sup>5,37–39</sup> there currently exist no multi-model studies of NZE pathways at the EU level with sufficient granularity, in terms of spatial representation, as well as representing a range of technologies and measures, to draw explicit and policy-relevant implications at the regional and member-state level.

In support of a credible intermediate 2040 climate target at the EU level, our study fills this critical gap by undertaking an NZE scenario analysis for the region, featuring the robustness of a multi-model assessment that brings different economic theories, granularity levels, and technological and policy representations to the table. As member states are revisiting their first National Energy and Climate Plans (NECPs), the cumulative emissions impact of which sits at a modest 41% emissions reduction by the end of this decade,<sup>40</sup> our regional analysis is complemented by insights into the individual countries' energy transformations, emissions projections, and economic impacts, aiming to offer research and policy takeaways regarding the sectoral and economic burdens of European decarbonization along the path to NZE by 2050.

## RESULTS

### Scenarios representing current policy ambitions

We exploit a diverse ensemble of seven models to explore how the EU can cover the ground from today to the –55% target in 2030, to an intermediate climate milestone in 2040, and onward to an NZE GHG economy by 2050. The use of this ensemble aims to enhance the robustness and confidence in the produced knowledge of the necessary sectoral and technoeconomic reconfigurations and burdens. On the one hand, we use three global IAMs: one partial equilibrium model (GCAM) and two computable general equilibrium (CGE) models (GEMINI-E3, ICES-XPS). On the other hand, we use four region-specific European models: of these, two are economy wide, including an energy-system model (EU-TIMES) and a macroeconomic model (NEMESIS), and two are sector-specific models, one for transport (ALADIN) and one for industry and buildings (FORECAST). See [model ensemble in experimental procedures](#) for a summary of the seven models, as well as [Table 1](#) for details on classification, coverage, and description. The seven models are

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**Table 1. Main features (type, team, version, EU geographical representation, and sectoral granularity) of each model in the analysis**

	ALADIN	EU-TIMES	FORECAST	GCAM	GEMINI-E3	ICES	NEMESIS	
Type of model	bottom-up sector perspective	energy-system model	bottom-up sector perspective	partial equilibrium	general equilibrium model	general equilibrium model	macroeconomic	
Research team (see also authors' affiliations)	Fraunhofer ISI	E4SMA s.r.l.	Fraunhofer ISI	BC3	EPFL	CMCC	SEURECO	
Version	–	E4SMA-EU-TIMES 1.0	–	GCAM-PR 5.3	GEMINI-E3 7.0	ICES-XPS 1.0	NEMESIS 5.1	
EU geographical disaggregation	30 regions: EU27 (each member state individually), United Kingdom, Norway, Switzerland	30 regions: EU27 (each member state individually), United Kingdom, Norway, Switzerland	30 regions: EU27 (each member state individually), United Kingdom, Norway, Switzerland	2 regions: EU15 (Sweden, Finland, Ireland, United Kingdom, Denmark, the Netherlands, Spain, Belgium, Portugal, France, Germany, Austria, Italy, Greece), EU12 (Estonia, Lithuania, Latvia, Poland, Czechia, Slovakia, Hungary, Slovenia, Romania, Bulgaria, Cyprus)	1 region (entire EU-27, United Kingdom)	12 regions: Germany, Benelux (Belgium, Holland, Luxembourg), Italy, Greece, Finland, Czechia, France, Spain, Poland, Sweden, United Kingdom, rest of EU (Estonia, Latvia, Lithuania, Denmark, Ireland, Portugal, Austria, Slovakia, Hungary, Slovenia, Croatia, Romania, Bulgaria, Cyprus)	30 regions: EU27 (each member state individually), United Kingdom, Norway, Iceland	
Sectoral granularity	macroeconomic	No	exogenous (as drivers)	exogenous (as drivers)	exogenous (as drivers)	yes	yes	yes
	agriculture	No	energy requirements only	no	detailed	as an economic activity with non-CO <sub>2</sub> emissions	as an economic activity	as an economic activity
	energy supply	No	very detailed	no	very detailed	detailed for power generation	detailed for power generation	detailed for power generation
	industry	No	detailed	very detailed	detailed	as economic activities	as economic activities	as economic activities
	transportation	very detailed	detailed	no	detailed	as economic activities and household expenditures	as economic activities and household expenditures	as economic activities and household expenditures
	buildings	No	no	very detailed	detailed	as economic activities and household expenditures	as economic activities and household expenditures	as economic activities and household expenditures
	land uses	No	no	no	yes	no	no	no

**Table 2. Synthesis of the main GHG emissions reduction targets of the EU27 in the NZE scenarios**

	NZE Benchmark		NZE EU Policy Standard	
	2030	2050	2030	2050
GHG emissions change (w.r.t. 1990)	–55%	net-zero emissions	–55%	net-zero emissions
EU-ETS GHG emissions change (w.r.t. 2005)			–61%	adjusted to reach NZE EU-level target
ESR GHG emissions change (w.r.t. 2005)			–40% (without national targets)	–80%

harmonized to a set of shared socioeconomic and technoeconomic assumptions, allowing to constrain model response heterogeneity mainly to their structural/theoretical differences—for example, in the way carbon revenues are recycled among the three macroeconomic models (see [scenario design](#) and [recycling scheme of carbon revenues](#) in [experimental procedures](#)).

We then design two scenarios reflecting the EU's updated climate ambition, imposing emissions caps in 2030 and 2050 as follows ([Table 2](#)). In the first scenario, NZE Benchmark, each model is allowed to reach the 2030 –55% GHG target and subsequently the 2050 NZE target by taking its least-cost mitigation pathway (i.e., emissions are capped in 2030 and 2050 in line with the NDC and net-zero targets of the EU, linearly interpolating for the years in-between). Because not all seven models provide complete GHG emissions coverage, we define three sets of assumptions for the non-covered emissions by combining different levels of non-CO<sub>2</sub> and LULUCF emissions' contributions to GHG emissions reduction targets (low, medium, and high; see [Table 3](#) for an explanation of the assumptions underlying these scenarios). In the second scenario, NZE EU Policy Standard, the EU's 2030 emissions reduction targets additionally encompass an upgraded burden sharing of 61% (relative to 2005) for sectors covered by the EU-ETS and 40% for sectors covered by the ESR, as in the original "Fit for 55" proposal; for 2050, we impose an emissions cap of –80% in the ESR sectors and calculate the cap for the EU-ETS sectors. The multi-model exercise was carried out by September 2022, meaning that (1) the current policy baseline, against which the two scenarios are compared, implements EU climate change mitigation policies up to 2030 and as close as possible to legal text, as of June 2021—i.e., considering the EU's 2030 climate-energy framework with a GHG emissions reduction target of at least 40%, (2) the EU-ETS burden sharing of "Fit

**Table 3. Detailed emissions caps for the EU27 in the NZE Benchmark scenarios (in GtCO<sub>2</sub>equiv)**

	Historical data		Assumed contribution of non-CO <sub>2</sub> and LULUCF emissions to GHG mitigation					
	1990	2005	2030 Climate target plan (–55% w.r.t 1990)			2050 net-zero emissions		
			Low	Medium	High	Low	Medium	High
CO <sub>2</sub> (w/o LULUCF and w/ in't transport)	4.05	4.00	1.81	1.90	1.99	–0.27	0.01	0.22
CO <sub>2</sub> (w/o LULUCF and w/ intra-EEA aviation <sup>a</sup> )	3.91	3.79	–	–	–	–	–	–
Non-CO <sub>2</sub> (w/o LULUCF and w/ in't transport)	0.98	0.80	0.58	0.54	0.49	0.50	0.30	0.25
LULUCF	–0.21	–0.31	–0.23	–0.27	–0.31	–0.24	–0.31	–0.47
Total (w/ LULUCF and w/ in't transport)	4.82	4.48	2.17	2.17	2.17	0.00	0.00	0.00
Total (w/o LULUCF and w/ intra-EEA aviation <sup>a</sup> )	4.89	4.58	–	–	–	–	–	–

Source: historical values<sup>41</sup>; LULUCF emissions authors' calculation based on: 2030-low: current LULUCF regulation,<sup>42</sup> 2030-medium: average of low and high, 2030-high: new objectives from "Fit for 55,"<sup>43</sup> 2050-low: scenario "baseline,"<sup>44</sup> 2050-medium: *idem* 2030-high, and 2050-high: scenario "Life1.5LB"<sup>44</sup>; non-CO<sub>2</sub> emissions authors' calculation based on: 2030-low: scenario "Mix-50,"<sup>45</sup> 2030-medium: average of low and high, 2030-high: "All bank,"<sup>45</sup> 2050-low: EU reference scenario 2020,<sup>46</sup> 2050-medium: scenario "Combo,"<sup>44</sup> and 2050-high: scenario "Life1.5LB."<sup>44</sup>

Additional note: original data have been corrected for the UK where relevant.

<sup>a</sup>GHG emissions from intra-EEA aviation are assumed to represent 40% of total GHG emissions from international aviation in 1990 and 2005: the average value from 2015 to 2019 based on EEA.<sup>41,47</sup>

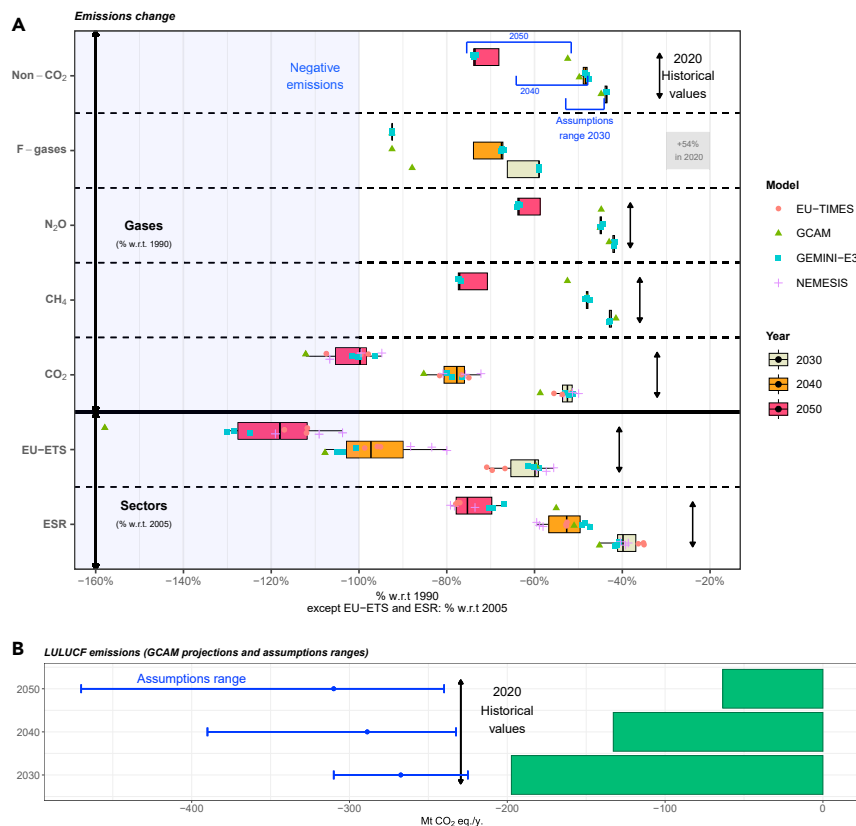
for 55" is assumed at 61% as in the original proposal and not 62% as eventually agreed by the European Commission, Parliament, and Council on December 18, 2022, (3) no assumptions are made as to the EU's response to the Russia-Ukraine war, and (4) the latest authoritative projections of fossil fuel prices available at the time did not include updates associated with the ongoing energy-supply crisis. For a complete description of the scenario logic and its implementation across models, see [scenario design](#) and [scenario implementation in each model](#) in [experimental procedures](#).

### **Emission outcomes and effort sharing between EU-ETS and ESR sectors**

Post-2030, the EU would need to continue reducing its GHG emissions at a linear yearly reduction rate of 5% (4.5%–6.5% for CO<sub>2</sub> emissions depending on assumptions regarding non-CO<sub>2</sub> and LULUCF emissions) to reach NZE by 2050. Emissions burden sharing between the EU-ETS and ESR sectors is a key question for EU policy-makers. Before the region's ratcheting of climate ambition, the 2030 targets for the EU-ETS and ESR were –43% and –30%, respectively, in comparison to 2005, corresponding to an overall GHG emissions reduction of 40% compared with 1990. With the increased ambition of at least a 55% emissions reduction in 2030 compared with 1990,<sup>48</sup> in its original "Fit for 55" proposal, the European Commission proposed to cap the EU-ETS and ESR emissions at –61% and –40%, respectively, in 2030 compared with 2005 levels.<sup>49,50</sup> In the NZE Benchmark scenarios, by 2030, the modeled GHG emissions reductions in the EU-ETS sectors range from 56% to 71% and in the ESR sectors from 35% to 45% across models, with median values (60% and 40%, respectively) being in line with the emissions caps set between the EU-ETS and ESR in the European Commission's proposal ([Figure 1](#)). In 2040 and 2050, models show greater divergences. In 2040, the EU-ETS would be almost carbon-neutral with about 97% (80%–108%)<sup>51</sup> median emission reductions across models, whereas the mitigation effort in the ESR is lower, at around –53% (–47% to –59%) relative to 2005; in 2050, mitigation in the EU-ETS further increases, reaching a median value of –118% [–104% to –158%], largely fueled by bioenergy with carbon capture and storage (BECCS)—especially in GCAM—whereas mitigation in the ESR sector reaches a median value of –75% [–55% to –79%].

Two of the global IAMs, GCAM and GEMINI-E3, which can endogenously calculate a broad range of GHG emissions, appear to be conservative in the exploitation of non-CO<sub>2</sub> emissions reductions in 2030 and 2040, getting close to the pessimistic set of assumptions considered in the low NZE Benchmark scenario ([Figure 1](#)). Across NZE Benchmark scenarios, we see significant variations in non-CO<sub>2</sub> emission cuts in 2050 compared with 1990 levels among models, with non-CO<sub>2</sub> emissions being around 550 and 305 [303–310] MtCO<sub>2</sub>equiv/year in GCAM and GEMINI-E3, respectively, in the range of the assumptions for all other models (290–560 MtCO<sub>2</sub>/year).

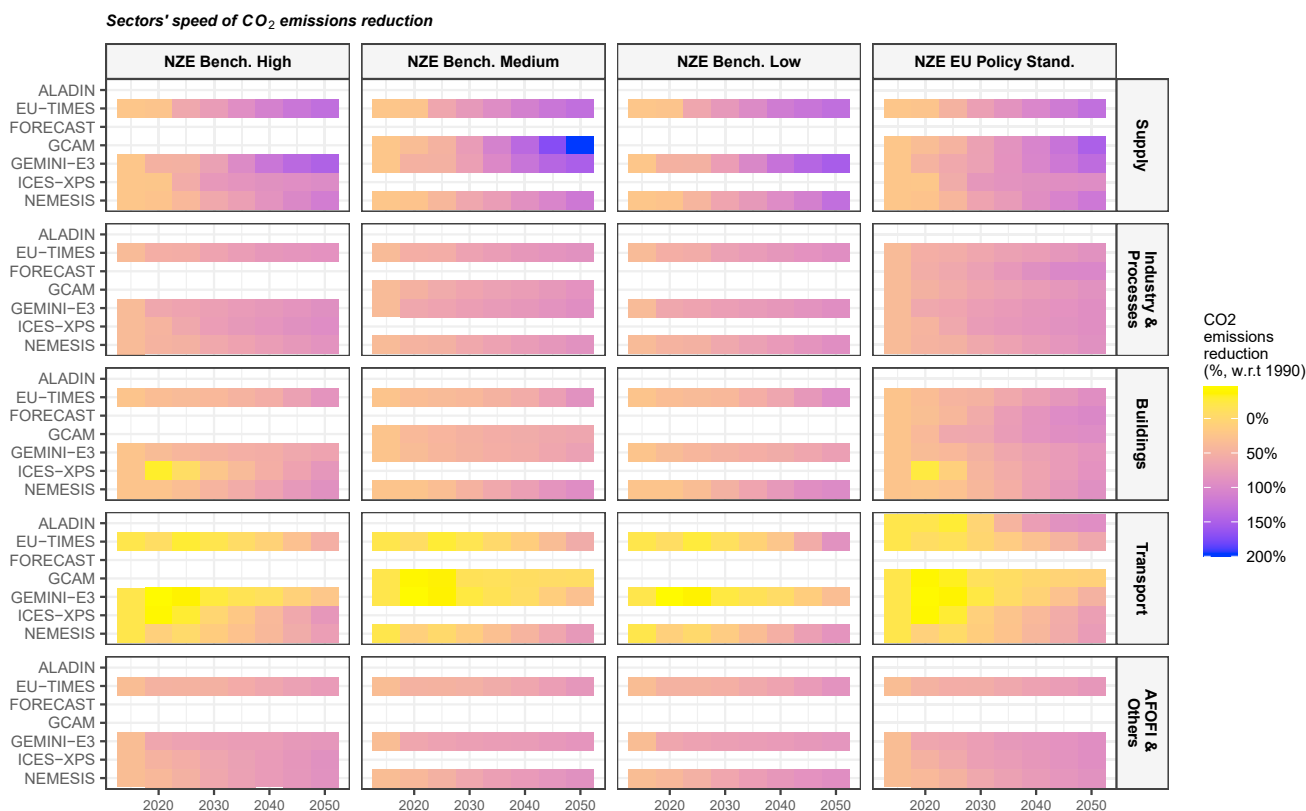
Similarly, the role that the LULUCF sector could play in achieving NZE is also highly uncertain but tilting toward lower contributions. GCAM (with endogenous representation of LULUCF) shows a decline in the EU's carbon sink from 200 MtCO<sub>2</sub>equiv/year in 2030 to 65 MtCO<sub>2</sub>equiv/year in 2050, as bioenergy consumption rises in the next two decades. These results are lower than the set of assumptions considered for the other models, which in fact see increasing potential between 2030 and 2050 ([Table 3](#)). This could in fact reflect optimism in our assumptions on non-CO<sub>2</sub> emissions (drawn directly from official European Commission data) and/or pessimism in the two models with endogenous representation (GCAM and GEMINI-E3).



**Figure 1. EU emissions reductions and LULUCF emissions projections in the “NZE Benchmark” scenarios**

(A) Emissions reductions by gas (% w.r.t. 1990) and by sector (EU-ETS and ESR—% w.r.t. 2005). (B) GCAM LULUCF emissions projections. Black vertical arrows show 2020 historical values, and blue horizontal intervals show the range of assumptions for non-CO<sub>2</sub> and LULUCF emissions used by the models not covering them—see [experimental procedures](#) for additional information. Historical values come from the European Environmental Agency (EEA).<sup>41,47</sup> Sectoral models are not presented here because they do not cover the entire economy. ICES-XPS is not presented either because it includes only CO<sub>2</sub> emissions from energy. Exogenous assumptions are detailed in [Table 3](#).

At the member-state level, countries with an important existing carbon sink potential from the LULUCF sector, such as Sweden, Finland, Bulgaria, Lithuania, or Romania, which could reach NZE early (in some cases earlier than committed), show conservative ambition in their targets, whereas others with smaller natural carbon sinks and a carbon-intensive power generation sector may reach NZE later (in some cases post-2050). This indicates that it might not be cost-effective for some member states, such as Germany, Czechia, Ireland, or Poland, to achieve their NZE commitments by 2050 (see [Figure S1](#)). Overall, our results show that most member states are broadly in line with their NZE targets, as reflected in legally binding commitments or proposals (see [Table S1](#)). However, of the 27 EU member states, four (Austria, Greece, Ireland, and the Netherlands) do not reach their NZE commitments in any scenario, whereas three (Cyprus, Denmark, and Germany) appear to do so only in some scenarios; the 20 remaining countries achieve their commitments in most scenarios. Regarding member states not hitting their NZE targets, non-CO<sub>2</sub> emissions appear to constitute the largest chunk of any remaining emissions, mainly followed by transport CO<sub>2</sub> emissions; moreover, despite some heterogeneity in their residual emissions, we find that there is no one-size-fits-all approach and these countries should take



**Figure 2. EU sector reduction of CO<sub>2</sub> emissions from energy and industrial processes (w.r.t. 1990)**

The ICES-XPS model does not cover CO<sub>2</sub> emissions from industrial processes and does not include CCS as a mitigation technology. The two sectoral models only output sectoral data (ALADIN: transport; FORECAST: industry and processes, buildings) and only for the NZE EU Policy Standard scenario; GCAM was not run for the high and low variants of the NZE Benchmark scenario; ICES-XPS was not run for the medium and low variants of the NZE Benchmark scenario. AFOFI, agriculture, forestry, and fisheries (only energy-related emissions).

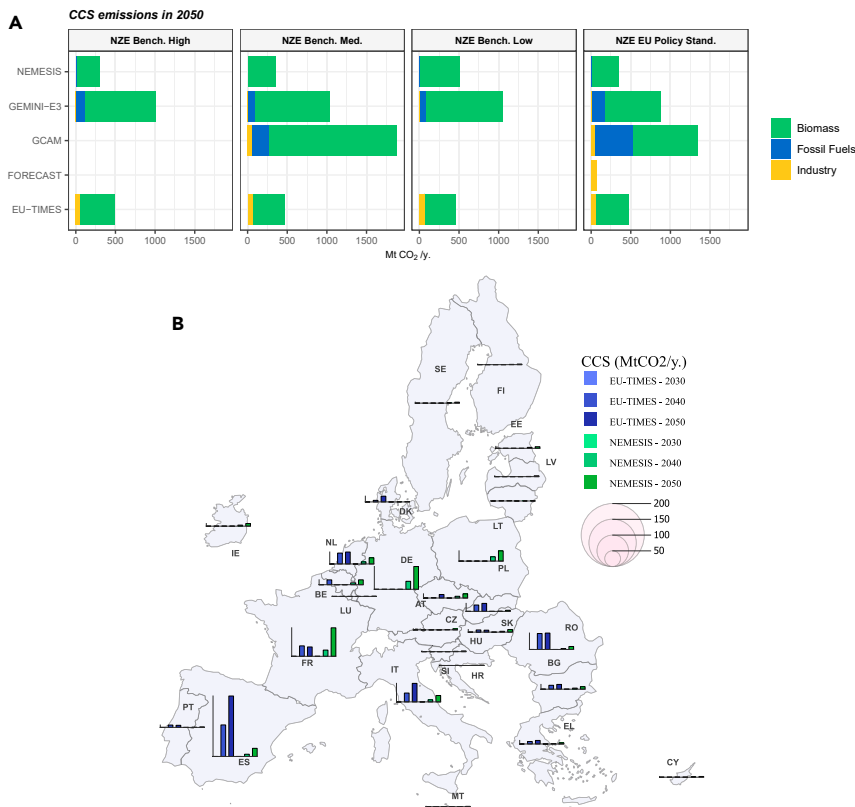
sectorally targeted measures—e.g., the Netherlands and Austria should prioritize reinforcing their mitigation efforts in their industry sector.

### A sectoral deep dive

In economy-wide models, the decarbonization of the European economy is driven by a rapid reduction of CO<sub>2</sub> emissions in the energy-supply sector (Figure 2), which realizes the strongest emissions reductions between 2020 and 2030, by 40% (22%–61%). Although the rate and degree of sectoral emissions cuts vary across models, all models show that full decarbonization of the power sector alongside an economy-wide reduction of fossil fuel consumption are critical to reach NZE in 2050.<sup>52,53</sup> All models show that the power generation and upstream energy sectors would undergo an early transformation and reach carbon neutrality between 2035 and 2045, facilitated by early deployment of negative emissions technologies and further diffusion of renewables—except for ICES-XPS, which does not represent CCS and can thus only reach NZE with considerably higher policy costs.

The scale of BECCS<sup>54</sup> deployment influences the mitigation burden on other sectors in NZE scenarios; for instance, large-scale deployment of BECCS to decarbonize the supply sector in GCAM in the scenarios reduces the mitigation burden on other sectors (Figure S2 shows carbon sequestration in 2050 by sector). All models show that the required rate of emissions reduction (w.r.t. 1990) in the transport sector in 2050 to align with the NZE goal, −62% [−7% to 94%], is lower than in other sectors.





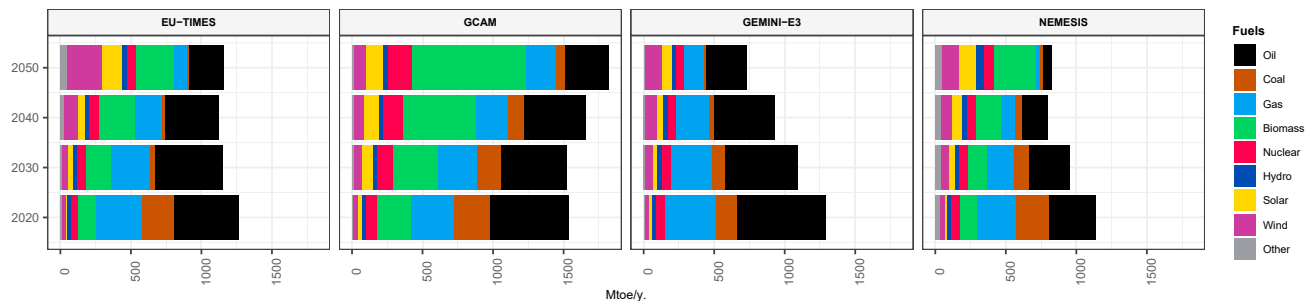
**Figure 3. Level of carbon capture and storage**

(A) In the EU across scenarios (CCS emissions in “industry” includes emissions from industrial processes and fuel combustion, and “biomass” and “fossil fuels” include emissions from biomass supply; FORECAST was only run for the NZE EU Policy Standard scenario; GCAM was not run for the high and low variants of the NZE Benchmark scenario) and (B) at the member state in the “NZE Benchmark—medium” scenario (MtCO<sub>2</sub>/year).

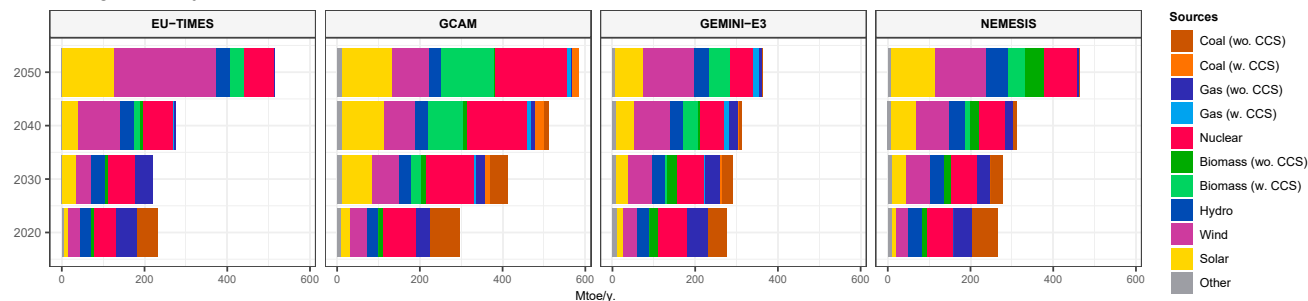
However, the sectoral model ALADIN, which incorporates detailed representation of the transportation sector, shows that an almost complete decarbonization of the sector is achievable, with sectoral emissions reaching  $-94\%$  (w.r.t 1990), far higher than the rest of the integrated models—this relatively bold reduction does not consider cross-sectoral dynamics such as deployment levels of negative emissions technologies in the power sector nor economy-wide cost optimization that economy-wide models pursue. To a lesser extent, this is observed in the building sector too, where the sector-detailed model FORECAST results show full decarbonization by 2050 in NZE scenarios, whereas the economy-wide models calculate a lower rate of decarbonization of  $-88\%$  [ $-65\%$  to  $-98\%$ ]. These findings (Figure 3A) are in line with reported insights on sectoral models featuring more mitigation levers allowing to achieve higher decarbonization in the literature.<sup>55</sup> In agriculture, forestry, and fisheries (AFOFI) and other sectors, models converge toward a CO<sub>2</sub> emissions reduction of approximately 88% (78–93%) in 2050.

Although BECCS offsets residual emissions from harder-to-abate sectors in NZE scenarios, this contribution markedly differs among member states in the EU-regional models (Figure 3B, as well as Figure S3 for residual emissions in 2050). EU-TIMES assumes the persistence of existing legal barriers to (BE)CCS deployment in the long run, contrary to NEMESIS that considers no legal constraint, in essence representing two different visions. For example, Poland and Germany could lack CCS deployment

**A Primary energy consumption in the NZE Benchmark Medium scenario**



**B Power generation by source in the NZE Benchmark Medium scenario**



**Figure 4. EU primary energy consumption and power generation in NZE Benchmark medium**  
(A) Primary energy consumption by fuel, (B) electricity generation by source.

entirely in 2050 should these barriers persist (EU-TIMES), but they could capture up to 32 [26–48] and 70 [61–99] MtCO<sub>2</sub>/year, respectively, in the NZE scenarios should these constraints be mitigated (NEMESIS). To counterbalance such limitations in some member states, EU-TIMES inevitably projects higher levels of (BE)CCS compared with NEMESIS—e.g., in Spain (almost 8-fold, 191 [165–192] MtCO<sub>2</sub>/year) and Romania (5-fold, 52 [52–62] MtCO<sub>2</sub>/year). Overall, in the NZE scenarios, model results suggest that the share of CO<sub>2</sub> removed by means of CCS would reach 13% [9%–42%] of the EU's CO<sub>2</sub> emissions from energy and processes in 1990, with maximum deployment achieved in GCAM (up to 1.9 GtCO<sub>2</sub>/year in 2050).

**Transformation of energy and fossil fuel consumption**

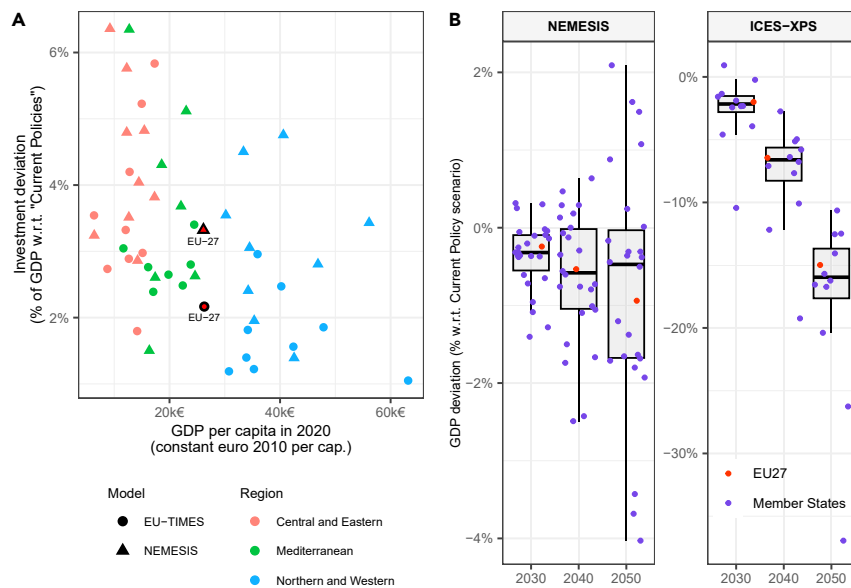
Between 2020 and 2040, almost all models used in this study indicate energy savings (measured as the difference in energy consumption between two periods), although to different extents. Variation can be attributed to model structure such as solution type, level of technology representation, and input substitutability. Models with detailed representation of the energy sector show reserved energy savings—e.g., in GCAM (no savings) and EU-TIMES (moderate savings, especially post-2030). Conversely, high energy savings are observed in top-down models, such as NEMESIS and GEMINI-E3, where additionally substitutability between production input and goods and services reduces the demand for energy. Between 2040 and 2050, when models mitigate emissions in the harder-to-abate sectors, EU-TIMES and NEMESIS project stabilization or increase of European primary energy consumption (Figure 4), due to high penetration of carbon-free electricity, less efficient in terms of primary energy. Looking across the different NZE Benchmark variants in the EU-regional models, we notice that the low case—i.e., when carbon neutrality requires stronger CO<sub>2</sub> mitigation effort—sees both EU-TIMES and NEMESIS projecting higher total EU primary energy consumption in 2050 than in the other cases. This result indicates a higher direct or indirect mobilization of electricity to further

decarbonize final energy consumption, as required in this NZE variant and because of lower efficiency of electricity consumption in terms of primary consumption than in the case of other fuels, thereby increasing primary energy consumption.

Fossil fuel consumption declines rapidly and significantly in all models (Figure 4) and all NZE scenarios. Coal is almost entirely phased out of the energy mix in EU-TIMES, GEMINI-E3, and NEMESIS—in GCAM, coal consumption declines but not as radically. The EU-regional models also indicate strong declines in gas consumption in NZE scenarios, whereas GEMINI-E3 and GCAM show lower gas cuts, due to larger fossil fuel CCS deployment—it should again be noted that developments related to the Russia-Ukraine conflict are not considered. In the NZE Benchmark medium scenario, oil consumption is also reduced—albeit to a lesser extent—across all models, with NEMESIS projecting close-to-phaseout by 2050. The way fossil fuel-based technologies are replaced by low-carbon options differs across models. For nuclear, we see bold growth in GCAM (+121% compared with 2020), moderate in EU-regional models (+37% in EU-TIMES; +25% in NEMESIS), and reverse in GEMINI-E3 (−20%) by 2050. Expectedly, renewable energy grows consistently across models to decarbonize the EU energy system, albeit at different shares and deployment rates of sources. In all models, biomass consumption increases significantly, especially in GCAM that relies strongly on BECCS to reach the NZE target, as well as in EU-TIMES (where biomass shares double by 2040), and in NEMESIS post-2040. Wind is also deployed extensively in all models. The largest deployment can be seen in EU-TIMES (250 Mtoe in 2050), whereas NEMESIS and GEMINI-E3 project wind power almost quadrupling by 2050; GCAM sees slow deployment of wind in primary energy consumption (from 64 Mtoe in 2020 to 89 Mtoe in 2050). Solar deployment also sees massive increases by a factor ranging from 5 (GEMINI-E3) to 11 (EU-TIMES) times from 2020 to 2050. In all models, the use of hydro does not grow as rapidly as all other renewables.

### Power-sector transformation and coal phaseout

The rapid decarbonization of the EU power sector, enabled by large deployment of renewables (generating 50% [45–65%] in 2030 and 80% [64–89%] in 2050) and mobilization of (BE)CCS, lead to increased electricity consumption in all final sectors and across NZE scenarios—Figure S4 shows the share of each technology in the power sector in 2050, by country, scenario, and model. In GEMINI-E3, the CO<sub>2</sub> price increase induces a substitution of fossil energy by non-energy inputs (efficiency gains) and also a substitution of fossil energy by electricity, e.g., in the transport sector, but this increase in electricity consumption is rather limited and efficiency gains dominate. In GCAM, NEMESIS, and EU-TIMES, electricity demand increases due to (1) socioeconomic drivers and (2) electrification of final demand sectors compared with the current policy baseline because it is the main strategy of decarbonization alongside cost-effective cleantech in electricity to reach NZE. All models attest to the crucial role of low-carbon electricity alongside the electrification of the end-use sector. In GCAM, this relationship is almost linear, with almost two-thirds of total secondary energy coming from electricity in 2050. Similar rates are reached and further accelerated post-2040 in EU-TIMES. In NEMESIS, electricity use accelerates between 2040 and 2050 but makes up about half of secondary energy in 2050. Finally, in GEMINI-E3, electrification is smoother (around one-third of the mix in 2050). Electrification of final energy consumption is projected to grow in all member states in an NZE-aligned pathway (see Figure S5), albeit not as homogeneously nor as consistently between the two EU-regional models—from 29% in Belgium up to 57% in Ireland in EU-TIMES, and from 34% in Denmark to 68% in Belgium in NEMESIS. Despite considerable differences (as evident for Belgium), both models agree that



**Figure 5. Economic impacts of the NZE scenario on member states investments' needs in the NZE Benchmark—medium scenario and on GDP in the NZE EU Policy Standard scenario**

(A) Additional investments in 2050 and (B) GDP deviation in 2050 in comparison to current policies. Only EU-TIMES and NEMESIS deliver investments and NEMESIS and ICES-XPS GDP deviations at member-state level. ICES-XPS does not include CCS, hydrogen, and e-fuels as mitigation options, thereby raising the GDP impacts. Table S1 offers the classification of each member state in the three regions.

acceleration of the electrification rate of final energy use to reach NZE is faster for countries with low electrification rates today—e.g., countries such as Hungary or Poland contrary to countries such as Sweden or Finland.

Such an increase of final energy electrification rates in all EU countries is promoted by strong decarbonization of their power sector and, critically, coal phaseout. Again, both models with detailed disaggregation display difference in the rate of coal consumption among member states. The energy-system model EU-TIMES sees coal phaseout in power generation as an immediate mitigation option across the bloc, from 2030 onward in almost all countries, except in Poland, Germany, and Finland, with an outstanding share around 2%–5%. With more rigid representation of the power sector, the macroeconomic model NEMESIS projects slower coal decline: nonetheless, by 2030, eight countries are projected to achieve almost complete coal phaseout (<2%), and by 2045, only Poland's and Bulgaria's coal shares remain above 2% (see Figure S6).

### Investment needs and economic implications

The transformation of European economies toward NZE will imply large investment needs, according to our models (Figure 5A). EU-TIMES and NEMESIS estimate the additional average annual investment needs, compared with current policies (see scenario design in experimental procedures), to be 0.2% (–0.1% to 0.51%) of the EU-27 gross domestic product (GDP) in 2030, 1% (0.4%–1.5%) in 2040, and 2.2% (1.5%–4.4%) in 2050. Both models show that the investment efforts to support EU mitigation ratcheting are relatively stronger for less economically advanced economies within the bloc: among member states with the lowest GDP per capita in 2020 in the EU, central and eastern European countries generally require higher investments (relative to their GDP) compared with northern and western member

states—and even to Mediterranean countries (see classification in [Table S1](#)). This hints at the need to establish solidarity policies among European countries to support the required investments, such as the Just Transition Mechanism.<sup>56</sup>

In addition to investment needs, reaching NZE also entails economy-wide costs according to the two economic models reaching net zero, compared with a current policies scenario and measured as GDP deviations ([Figure 5B](#)), with GDP losses at the EU level of 0.4% in 2030, 0.9% in 2040, and 2.3% in 2050 in GEMINI-E3 and 0.1%, 0.6%, and 1% in NEMESIS in the NZE Benchmark medium scenario (see also [Table S2](#)). From a national perspective, the expected GDP impact varies between countries as much as it does between models, mainly driven by the availability of advanced technologies. The cost of mitigation in terms of GDP loss reaches 15% (GDP change: −37% to 11%) in ICES-XPS in the NZE EU Policy Standard scenario (see [Table S3](#)) because mitigation options are very limited (no CCS, hydrogen, or e-fuels). As a consequence, ICES-XPS reduces demand and economic activity to mitigate CO<sub>2</sub> emissions, thereby significantly impacting GDP in the entire bloc and showcasing that failure to deploy at-scale game-changing technologies (i.e., carbon capture and hydrogen) could render deep decarbonization in Europe much more challenging to manage at reasonable economic cost. An alternative policy-relevant interpretation of this result is that a deliberate, or planned, action on the demand side, reducing energy demand, could alleviate the reliance on low-carbon technologies, currently at pre-commercial stages of development, to achieve deep decarbonization.<sup>57</sup> Indeed, this lack of technology representation harmonization among our models helps elucidate the range of possibilities, on the one hand technological and on the other social and economic, which could constitute deep decarbonization strategies for Europe. In NEMESIS, such abatement with large demand reductions does not occur as more mitigation options are available; however, the transformations to comply with GHG mitigation ambition and the resource availability enabling these investments drive different inflation pressures among member states (see [Table S3](#)), leading to some GDP losses for some countries (such as Poland, Estonia, or Portugal) despite the positive impact of the investments leading to GDP gains in others (e.g., Belgium, Slovakia, or Latvia). As well as the equity implications of the GDP impacts across member states, an equally important equity implication will emerge from the intra-state distribution of gains and losses, which will be highly dependent on policy design, including related policy adjustments such as around tax redistributions. We do not consider such detailed factors in this analysis.

## DISCUSSION

A detailed multi-model analysis of EU pathways toward climate neutrality, with critical insights at the member-state level, has been missing in the literature. Here, we contribute to bridging this gap by using seven models with different granularity, theory, and structure to assess mitigation pathways that are aligned with the EU's 2050 net-zero target and shed light on the requirements along the way.

Several robust findings emerge from our model inter-comparisons of the entailed transformation. We find that the “cost-optimal” burden sharing between the EU-ETS (−56% to −71%)—in line with previous study ranges<sup>58</sup>—and the ESR (−35% to −45%) to achieve a 55% emissions reduction in 2030 is well aligned with the original “Fit for 55” proposal of −61%<sup>59</sup> and −40% (w.r.t. 2005), respectively. On the way to NZE by 2050, our model ensemble projects near-NZE (~97% [80%–108%] emissions reductions relative to 2005) in the EU-ETS sector and around 53%

[47%–59%]) emissions cuts in the ESR sector in 2040. Apart from the importance of considering all available technologies, which appears correlated with lower mitigation costs and agrees with recent scientific insights,<sup>60</sup> the inter-model comparisons in this study highlight the need for large structural changes to accelerate EU-ETS sector decarbonization. In particular, all models agree on the crucial role of power generation and the upstream energy sector in accelerating the transformation via greater deployment of renewables and CCS technologies, allowing emissions cuts in demand-side sectors through electrification of final energy use. The important role of electricity in NZE scenarios is also evident in [Figure S7](#), showing higher electrification of final energy use (40%–50%) in 2050 on EU average (from 23% in 2020)—which, however, does not necessarily lead to increased final energy consumption per capita according to three of the four models (EU-TIMES, GEMINI-E3, and NEMESIS)—as well as rapid power-sector decarbonization with near-zero or negative CO<sub>2</sub> intensity in 2050 across the bloc, with most countries ranging from 0 to –150 gCO<sub>2</sub>/kWh in 2050 and fossil fuel consumption declining by 50%–90%.

The demand side, and notably the transport sector, appears harder-to-abate owing to inclusion in the models of relatively limited and costly technological options. Such sectors could be compensated for by negative emissions—especially BECCS in power generation, as well as natural sinks, favoring some member states in reaching NZE targets earlier and begging the question of how to equitably fund LULUCF emissions. Alternatively, and to avoid reliance on NETs, it must be recognized that such sectors could benefit deeply from the rapid development and deployment of a range of earlier-stage demand-side technologies and measures, not fully represented in large-scale IAMs,<sup>61</sup> underpinning the added value of detailed sectoral modeling.<sup>62</sup>

Strong reliance on BECCS is a well-established criticism of modeled deep mitigation pathways,<sup>63–66</sup> typically traded off against high policy costs, especially on the demand side of the transition.<sup>67</sup> Our results do not escape this overreliance: indicatively, GCAM already reaches in 2050 the lower bound potentials of EU storage capacity discussed in the literature, which range from as low as 20–60 GtCO<sub>2</sub><sup>68</sup> to as high as 300 GtCO<sub>2</sub>.<sup>69</sup> Overall, our model ensemble reveals EU dependence on (BE)CCS ranging from as low as 0.3 GtCO<sub>2</sub>/year in 2050; nonetheless, such low levels also question the realism of NZE pathways, with evidence in the literature suggesting even 0.2 GtCO<sub>2</sub>/year may prove challenging for Europe, should distances between emissions sources and storage sites be considered.<sup>70</sup> Furthermore, biomass consumption in all models in 2030 (130–338 Mtoe) and 2050 (270–310 Mtoe) are close to medium and high estimates of the EU biomass potential (130–480 Mtoe in both 2030 and 2050)<sup>12</sup>—except for GCAM, with its high reliance on BECCS, outperforming this range for 2050 (800 Mtoe) and thus hinting at substantial future biomass import requirements.

To comply with complete, rapid decarbonization of the power sector, solar and wind should be massively deployed, alongside complete phaseout of unabated coal power out by 2040 or earlier, confirming previous findings.<sup>28,29,36,71,72</sup> This, however, raises questions of feasibility considering a diversity of existing barriers to such levels of deployment,<sup>73,74</sup> including potential environmental impacts,<sup>75</sup> including on biodiversity<sup>76,77</sup> and land use,<sup>78</sup> as well as socioeconomic implications of such rates of coal reduction.<sup>79</sup> Strong policies and government incentives are thus needed to overcome such hurdles. Furthermore, we also acknowledge that, from a certain penetration rate onward, ranging from 55%<sup>80</sup> to 80%,<sup>81</sup> the increase of variable renewable energy in the power sector may push upward electricity costs, and such

rates are indeed approached by our models post-2040. Acknowledging the often misalignment between modeling tools, such as the ones used here, and real-world developments, these hurdles are only part of the broader feasibility challenges that the EU may face on its way to delivering on its net-zero ambitions.<sup>5</sup>

Our results also point to the need of implementing an EU-wide strategy for the deployment of carbon storage technologies, considering local specificities, such as physical constraints and acceptability, and ensuring fairness in EU markets for CO<sub>2</sub> emissions storage among member states.<sup>82,83</sup> Similarly, the geopolitics of carbon storage may soon become important considerations, e.g., the storage potentials in Nordic European countries.<sup>84</sup> Avoiding unfair and potentially unbearable economic impacts of achieving NZE in the EU calls for a policy framework that supports research, development, and demonstration investments in not yet commercially mature low-carbon technologies.<sup>85,86</sup> It also calls for policies that ensure a fair and just economic burden among EU countries<sup>87,88</sup> because the investment burden is expected to be stronger for less developed member states, confirming the scarce evidence in the literature.<sup>89</sup> At the EU level, additional investment needs reach 0.8% (0.5%–1.5%) of EU GDP annually, over the period 2020–2050—i.e., around 150 (74–268) billion EUR<sub>2022</sub>, in line with estimates from the European Commission and the literature.<sup>36,44,90</sup>

Finally, we observe that our results are placed overall well within the range of the broader NZE scenario literature for the EU—[Figure S8](#) that compares our study's findings around key indicators,<sup>27</sup> such as fossil fuel reductions and CCS use against decarbonization, as well as per capita electricity and final energy against electrification, with findings from the IPCC's 6<sup>th</sup> Assessment Report scenario database, both for the EU and for other economies with announced NZE targets. In the same figure, we observe, for instance, that reliance on CCS is low in scenarios where electricity dominates final energy, showing how electrification of end-use sectors can be a resilient strategy if CCS technologies do not scale up adequately in the coming decades. We also observe that final energy per capita is overall lower in the EU than in large economies with equally ambitious targets, including the US and Canada.

To summarize key policy takeaways, this study's modeled results support the latest "Fit for 55" objectives in terms of EU-ETS and ESR targets in 2030. However, to keep the goal of NZE within grasp, the model ensemble reasonably robustly indicates that the EU should start aiming for net zero in the EU-ETS sectors and over 50% emissions reductions in the ESR sectors by 2040. An important consideration lies in the need to diversify the power-sector technological investment portfolio today, especially since our analysis suggests a net-zero European economy would require negative CO<sub>2</sub> emissions intensity in electricity by 2050. This, in turn, implies achieving a net-zero electricity system by as early as 2040, as also recommended in the first flagship report of the European Scientific Advisory Board on Climate Change.<sup>91</sup> In that direction, the EU should foster an enabling RES investment environment while phasing out coal-fired electricity well before 2040, which requires early investments in grid infrastructure, as well as prioritizing critical supporting actions related to spatial planning frameworks, environmental provisions, and just transition funds for coal regions. Developing and deploying BECCS in the energy-supply sector appears to be a cost-efficient approach to achieving NZE by 2050 because this is the only option to help deliver carbon-negative electricity in our models (and, indeed, in many other energy models). This implies the bloc should therefore accelerate the debate on, and prepare to invest in creating, CCS infrastructure, as well as accordingly plan a sustainable biomass production/import strategy by the end of this decade. This

should be done alongside early and detailed assessment of carbon storage potentials across the EU. Should BECCS deployment prove more challenging or remain uncertain,<sup>92</sup> the region must further mitigate emissions in all end-use sectors through higher electrification and alternative technologies and fuels, thereby promoting heavy investments in technologies that are not mature yet. Similar reservations are relevant for carbon dioxide remove technologies in general. The heavy focus on BECCS in this study can be attributed to other such technologies being typically underrepresented in climate- and energy-economy models, including the ones employed here.

Drawing from what are among the most robust model insights (i.e., insights gained with high agreement across the employed model ensemble—see [Figure S9](#)), we recommend that, for the EU to achieve NZE by 2050, electricity should make up a third of the bloc's final energy already by 2030. Investments in and the largest chunks of deployment of (BE)CCS should happen before 2040, which is earlier and at a faster rate than the foreseen decline of nuclear in the region, whereas EU power supply should achieve near-to-complete decarbonization by the end of the next decade. Our model analysis also hints at choices that the EU can make in a coordinated manner (see [Figure S10](#)). For example, the bloc could either invest heavily in further diffusing renewables (solar, wind, and bioenergy) in power generation at unprecedented rates<sup>5</sup> by 2040 (55%–70%) and 2050 (65%–80%) or retain high levels of nuclear (~30%) all the way to net zero—unless it pursues an efficient mix of the two options. At the same time, our analysis indicates that (BE)CCS are potentially very important toward NZE—notably, strong investments in and penetration of BECCS by 2030 (10%), 2040 (17%–18%), and 2050 (20%) could provide leeway for European transportation to keep emitting up to 0.75GtCO<sub>2</sub> in 2050.

Despite the robustness of these insights, it should be noted that model inter-comparisons do not come without disagreement among models because their diversity in economic theory, structure, technology representation, and granularity is the main reason why these exercises are carried out in the first place. We acknowledge that our exercise is no exception because our results hint at different levels of disagreement in terms of technological choices and sectoral mitigation cost-effectiveness toward net zero (e.g., [Figure S9](#)). [Table S4](#) describes how each model decides which technologies to deploy in each time step, both in theory (elasticities of substitution, diffusion curves, logit choice, or cost optimality) and in practice, notably in terms of uptake of CCS, nuclear, and renewables in this study. [Table S5](#) then performs a deep dive into the divergences observed among or across models and offers an explanation for each model straying from the median values of sectoral emissions, electrification, and key technologies' shares in power generation. Still on the limitations front, as no assumptions were made about the EU's policy response to the energy-supply crisis following and further fueled by the Russia-Ukraine conflict, we acknowledge that considering the latest energy landscape and prescribing possible strategies to replace the lost Russian gas in the bloc could have impacted our results. Among the few modeling studies assessing the long-term implications of these developments,<sup>93,94</sup> only one benchmarked the effects against EU current policies, NDC, and net-zero pledges,<sup>95</sup> showing no emissions impacts, as these are driven by climate ambition rather than energy-supply disruptions and strategies. Nonetheless, our study's projected energy mix and sectoral configurations to 2050 may have diverged, if such implications were considered, primarily in this decade, as our results suggest that all fossil fuels, including gas, are already in decline post-2030. As with most multi-model studies, another caveat lies in the constraints associated with model capabilities: despite efforts for input harmonization



across models, not all technologies nor emissions are equally represented in the models (e.g., ICES-XPS does not include hydrogen or CCS and could only deliver the high variant of our NZE Benchmark scenario—see [scenario implementation in each model](#) in [experimental procedures](#)).

## EXPERIMENTAL PROCEDURES

### Resource availability

#### *Lead contact*

Further information and requests for resources and materials should be directed to and will be fulfilled by the lead contact, Alexandros Nikas ([anikas@epu.ntua.gr](mailto:anikas@epu.ntua.gr)).

#### *Materials availability*

This study did not generate new unique reagents.

#### *Data and code availability*

The datasets generated during, and analyzed in, this study are available from a public repository (<https://doi.org/10.5281/zenodo.10044337>). Source data are provided with this paper.

The code availability for the individual models used in this paper varies and contact should be made to individual modeling groups. The GCAM model is available for download from <https://github.com/JGCRI/gcam-core>.

### Model ensemble

Single-model studies, even if undertaken with broad sensitivity analysis, are likely to only span a small part of the future possibility space. Multi-model studies, on the other hand, have the ability to explore more of the possibility space<sup>10</sup> but, as with other multi-model studies exploring 1.5°C and net-zero pathways,<sup>5</sup> these tend to be an “ensemble of opportunity.” This means they are not a systematic choice of models, designed to represent all key dimensions driving different possible future pathways. Rather, they are a representation of a variety of models available through different participating modeling teams. Nevertheless, this broad ensemble employed here represents a wide diversity of modeling philosophies and frameworks, including partial equilibrium (GCAM, EU-TIMES), CGE (GEMINI-E3, ICES-XPS), and macroeconomic (NEMESIS). Moreover, this ensemble of five whole-system models is complemented with two models representing the transport (ALADIN) and buildings and industry (FORECAST) sectors, thereby representing a very broad span of models to explore in depth the possible transformations across the whole energy system and individual sectors.

Below, we list and detail the seven models used in this research; [Table 1](#) further summarizes their main features.

ALADIN is an agent-based simulation model for assessing market diffusion of alternative drives (passenger and heavy-duty) vehicles in Germany and Europe until 2050,<sup>96</sup> based on driving data of thousands of individual vehicles treated as agents, with changes in prices, user preferences, and model availability leading to road transport market evolution.<sup>97</sup>

EU-TIMES is an enhanced version of the open source JRC-EU-TIMES model.<sup>98</sup> It is a multi-region European version of TIMES and represents the EU member states and neighboring countries. The model is designed for analyzing the role of energy technologies and innovation needs for meeting European energy and climate policy

targets.<sup>9</sup> It can consider policies affecting the entire energy system, sectors, as well as (sets of) various technologies/commodities.<sup>99</sup>

FORECAST is a bottom-up simulation model for analyzing the long-term development of energy demand and emissions for the industry, residential and tertiary sectors at the national level, considering a broad range of mitigation options to reduce CO<sub>2</sub> emissions, combined with a high level of technological detail.<sup>100</sup> The FORECAST-Industry model considers energy efficiency, switching to new low-carbon processes, renewables and low-carbon energy carriers, CCS, as well as circular economy and recycling, material efficiency, and substitution along the value chain.

GCAM is a global IAM representing human and earth system dynamics,<sup>101</sup> exploring the interactions between energy, agriculture and land use, economy, and climate.<sup>102</sup> It operates on a “recursive-dynamic” cost-optimization basis, solving for the least-cost energy system in a given period before moving to the next time period and performing the same exercise. We use GCAM v5.3 in this analysis.<sup>103</sup> GCAM portrays Europe as combining two main region aggregates: EU-15 (including the UK) and EU-12 (excluding Croatia).

GEMINI-E3 is a multi-country, multi-sector, recursive CGE model,<sup>104</sup> simulating all relevant domestic and international markets, which are assumed to be perfectly competitive—except for foreign trade, in which goods of the same sector produced by different countries are considered economically different and not perfectly competitive.<sup>105,106</sup> The global GEMINI-E3 version is used covering the EU-27+UK as an aggregate.

ICES-XPS is a recursive-dynamic multi-regional CGE model developed to assess economy-wide impacts of climate change policies.<sup>107</sup> For the purposes of this study, the XPS version is used<sup>108</sup> with a more detailed representation of government behavior and private households. It assumes market equilibrium simultaneously in each market and region and requires calibration to data on national and international socio-accounting information, as well as a series of elasticities of substitution. The ICES-XPS model covers Europe combining detailed representation of specific member states (Czech Republic, Finland, France, Germany, etc.) and aggregate regions (RoEU).

NEMESIS is a sectoral, detailed macroeconomic model specifically designed for the EU+.<sup>109,110</sup> It is a system of economic models for every European country (including the United Kingdom), devoted to study issues that link economic development, competitiveness, employment, and public accounts to economic policies and, notably, all structural policies involving long-term effects.<sup>111</sup> NEMESIS includes a detailed energy-environment module that allows the model to deal with climate mitigation policies at the EU and EU-national level.<sup>112,113</sup>

### Scenario design

As reference scenario, we use—as well as harmonize the entire model ensemble to—the pre-defined set of socioeconomic and technoeconomic parameters developed in Giarola et al.<sup>114</sup> and implemented in Nikas et al.,<sup>9</sup> with updated projections for GDP and fossil fuels prices described in Cassetti et al.<sup>113</sup> Fossil fuel prices projections come from the International Energy Agency,<sup>115</sup> without considering long-lasting implications of the Russia-Ukraine conflict for European energy markets. This scenario implements EU current climate change mitigation policies, up to 2030 and as close as possible to legal text, as of June 2021—i.e., considering the EU's

**Table 4. Detailed GHG emissions caps in EU27 for the NZE EU Policy Standard scenario**

GtCO <sub>2</sub> equiv/year	1990	2005	2019	2030	2050
EU-ETS	–	2.07	1.44	0.81	–0.24
EU-ETS (incl. NO + IS + LI)	–	2.09	1.47	0.82	–
ESR (w. in't transports)	–	2.73	2.44	1.64	0.55
LULUCF	–0.21	–0.31	–0.25	–0.27	–0.31
Non-CO <sub>2</sub> emissions (wo. LULUCF and w. in't transport)	0.98	0.79	0.69	0.54	0.30
Total (w. LULUCF and w. in't transport)	4.82	4.48	3.63	2.17	0.00

Source: historical values<sup>41,47</sup>; LULUCF and non-CO<sub>2</sub> emission: same as “medium” case in the NZE Benchmark scenario.

NB: original data have been corrected from the UK when relevant.

2030 climate-energy framework with a GHG emissions reduction target of at least 40%. Post-2030 mitigation effort is extrapolated based on the emissions intensity rate, as presented in Nikas et al. (App. A).<sup>9</sup> This reference scenario, titled “current policies” scenario, is only used as a counterfactual baseline against which the economic burden to achieve NZE is assessed.

On top of the reference scenario, the NZE Benchmark scenario implements the current most ambitious GHG emissions reduction targets proposed by the EU (i.e., 55% in 2030 compared with 1990 and NZE in 2050) as emissions caps, and the models calculate the model-optimal (or least-cost) pathway toward these targets without the implementation of a specific climate policy (e.g., EU-ETS) in 2020–2025. The models covering all GHG emissions include the caps detailed in Table 2. For models with limited emissions coverage, we assume three possible levels of contribution from non-CO<sub>2</sub> and LULUCF emissions to the GHG mix (low, medium, and high). The more the non-CO<sub>2</sub> and LULUCF emission reductions contribute to the total GHG emissions targets, the lower the CO<sub>2</sub> emissions cap is (see Table 3). By default, we assume no changes in the rest of the world, meaning that regions outside the EU continue to implement their policies currently in place.

The NZE EU Policy Standard scenario, in addition, implements the EU-level policy instruments as proposed in the “Fit for 55” policy package<sup>7</sup> regarding burden sharing between the EU-ETS and ESR sectors. To do so, in all models, the GHG emissions cap at EU level in the ESR sectors in 2030 is set at –40% in comparison to 2005 (without considering national targets) and –80% in 2050 (i.e., –20 pp per decade), and the GHG emissions caps in the EU-ETS sectors are then calculated to reach the total EU GHG emissions reduction targets (see Table 2). Here, we assume the medium case of emissions projections from Table 3, for models that do not cover LULUCF and/or non-CO<sub>2</sub> emissions. With these assumptions, the EU-ETS emissions reduction leads to –61% compared with 2005 in 2030 and negative emissions in 2050 (see Table 4). Again, we assume no changes in the rest of the world, meaning that regions outside the EU continue to implement their policies currently in place. It should be noted that the sector-specific models (ALADIN for transport and FORECAST for industry and buildings) only implement this scenario—see [scenario implementation in each model](#) in [experimental procedures](#).

Scenario assumptions for LULUCF and non-CO<sub>2</sub> emissions projections are at the EU level and mainly stem from European Commission projections. For the non-CO<sub>2</sub> emissions by member state, we use the Commission’s reference scenario<sup>46</sup>: starting from total EU27 non-CO<sub>2</sub> emissions (Tables 3 and 4), we use the share of each member state in the EU-27 non-CO<sub>2</sub> emissions in 2030, 2040, and 2050 from the European Commission<sup>45</sup> to calculate the non-CO<sub>2</sub> emissions by member state in our

**Table 5. Recycling scheme of carbon revenues**

GEMINI-E3	Carbon revenues are recycled via a lump-sum transfer to households after ensuring the balancing of the government account. There is no international transfer.
ICES-XPS	Carbon revenues enter the government budget and are redistributed to households and government proportionally. There is no international transfer.
NEMESIS	Carbon revenues are recycled to private actors (firms and households) proportionally to the direct cost that the implementation of carbon prices induces for them. An energy-intensive industry will then receive more than a less intensive one. There is no international transfer.

scenarios. For LULUCF emissions by member state, there is no such projection to our knowledge; therefore, we apply the average share of each member state in the EU-27 LULUCF emissions from 2000 to 2020<sup>41</sup> to the EU27-level assumptions used in our scenarios (Tables 3 and 4).

### Recycling scheme of carbon revenues

Here, we outline the recycling scheme of carbon revenues in the three macroeconomic models of the analysis (GEMINI-E3, ICES, and NEMESIS) in the NZE scenarios (Table 5).

### Scenario implementation in each model

In sector-specific models (ALADIN and FORECAST), we only implement the NZE EU Policy Standard scenario because the difference between scenarios is irrelevant for these models. In GCAM, we only implement one variant (assumed to be the medium case) of the NZE Benchmark scenario, as the model represents both LULUCF and non-CO<sub>2</sub> emissions. In GEMINI-E3, we simulate all three cases of the NZE Benchmark scenario but only with regard to the assumptions on LULUCF emissions, as the model represents non-CO<sub>2</sub> emissions. Finally, featuring limited representation of mitigation technologies and only representing energy CO<sub>2</sub> emissions, ICES-XPS only delivers results for the high variant of the NZE Benchmark scenario. Consequently, we limit the ICES-XPS model results to economic aspects of the analysis. See Table 6 for an overview of which scenarios were implemented in each model.

### SUPPLEMENTAL INFORMATION

Supplemental information can be found online at <https://doi.org/10.1016/j.joule.2023.11.002>.

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**Table 6. Model implementation per model**

	NZE Benchmark—low	NZE Benchmark—medium	NZE Benchmark—high	NZE EU Policy Standard
ALADIN	–	–	–	X
FORECAST	–	–	–	X
GCAM	–	X	–	X
ICES-XPS	–	–	X	X
GEMINI-E3	X	X	X	X
EU-TIMES	X	X	X	X
NEMESIS	X	X	X	X

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## AUTHOR CONTRIBUTIONS

Conceptualization, B.B., A.N., S.M., A.G., and K.K.; methodology, B.B., A.N., S.M., A.E., A.C., and M.V.; software, F.N. (ALADIN), A.E., A.C., and M.G. (EU-TIMES), K.A.-D. (FORECAST-industry), Ş.A. (FORECAST-buildings), D.-J.v.d.V. (GCAM), M.V. and S.P. (GEMINI-E3), L.C. and E.D. (ICES), B.B., A.F., P.L.-M., and P.Z. (NEMESIS); validation: B.B., A.N., S.M., P.L.-M., and P.Z.; formal analysis, B.B., A.N., and S.M.; data curation, B.B.; writing – original draft, B.B., A.N., A.G., K.K., and S.M.; writing – review & editing, all authors with notable contributions from B.B., A.N., A.G., S.M., and K.K.; visualization, B.B. and S.M.; supervision: A.N.; project administration, A.N. and H.D.; funding acquisition, A.N. and H.D.

## DECLARATION OF INTERESTS

A.G. is an employee of the Accelerator for Systemic Risk Assessment (ASRA), hosted within the UN Foundation.

## INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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## REFERENCES

- Climate Action Tracker (2022). CAT climate target update tracker - climate targets - status of the NDC update process. <https://climateactiontracker.org/climate-target-update-tracker/>.
- Sognnaes, I., Gambhir, A., van de Ven, D.J., Nikas, A., Anger-Kraavi, A., Bui, H., Campagnolo, L., Delpiazzo, E., Doukas, H., Giarola, S., et al. (2021). A multi-model analysis of long-term emissions and warming implications of current mitigation efforts. *Nat. Clim. Change* 11, 1055–1062.
- Grant, N. (2022). The Paris Agreement's ratcheting mechanism needs strengthening 4-fold to keep 1.5°C alive. *Joule* 6, 703–708.
- Höhne, N., Gidden, M.J., den Elzen, M., Hans, F., Fyson, C., Geiges, A., Jeffery, M.L., Gonzales-Zuñiga, S., Mooldijk, S., Hare, W., et al. (2021). Wave of net zero emission targets opens window to meeting the Paris Agreement. *Nat. Clim. Change* 11, 820–822.
- Van de Ven, D.-J., Mittal, S., Gambhir, A., Doukas, H., Giarola, S., Hawkes, A., Koasidis, K., Koberle, A., Lamboll, R., McJeon, H., et al. (2023). A multi-model analysis of post-Glasgow climate action and feasibility gap. *Nat. Clim. Change* 13, 570–578.
- Oberthür, S., and Dupont, C. (2021). The European Union's international climate leadership: towards a grand climate strategy? *J. Eur. Public Policy* 28, 1095–1114.
- European Commission (2021). 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality. COM(2021) 550 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021DC0550>.
- European Council (2014). The 2030 climate and energy policy framework. Conclusions - 23/24 October 2014. <https://www.consilium.europa.eu/en/policies/climate-change/2030-climate-and-energy-framework/>.
- Nikas, A., Elia, A., Boitier, B., Koasidis, K., Doukas, H., Cassetti, G., Anger-Kraavi, A., Bui, H., Campagnolo, L., De Miglio, R., et al. (2021). Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison. *Sci. Total Environ.* 793, 148549.
- Nikas, A., Gambhir, A., Trutnevte, E., Koasidis, K., Lund, H., Thellufsen, J.Z., Mayer, D., Zachmann, G., Miguel, L.J., Ferreras-Alonso, N., et al. (2021). Perspective of comprehensive and comprehensible multi-model energy and climate science in Europe. *Energy* 215, 119153.
- Moutinho, V., Moreira, A.C., and Silva, P.M. (2015). The driving forces of change in energy-related CO<sub>2</sub> emissions in Eastern, Western, Northern and Southern Europe: the LMDI approach to decomposition analysis. *Renew. Sustain. Energy. Rev.* 50, 1485–1499.
- Ruiz, P., Nijs, W., Tarydas, D., Sgobbi, A., Zucker, A., Pilli, R., Jonsson, R., Camia, A., Thiel, C., Hoyer-Klick, C., et al. (2019). ENSPRESO-an open, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials. *Energy Strategy Rev.* 26, 100379.
- Eyl-Mazzega, M.A., and Mathieu, C. (2020). The European Union and the energy transition. In *The Geopolitics of the Global Energy Transition. Lecture Notes in Energy*, 73, M. Hafner and S. Tagliapietra, eds (Springer), pp. 27–46.
- Paraschiv, S., and Paraschiv, L.S. (2020). Trends of carbon dioxide (CO<sub>2</sub>) emissions from fossil fuels combustion (coal, gas and oil) in the EU member states from 1960 to 2018. *Energy Rep.* 6, 237–242.
- Duijndam, S., and van Beukering, P. (2021). Understanding public concern about climate change in Europe, 2008–2017: the influence of economic factors and right-wing populism. *Clim. Policy* 21, 353–367.
- The EU's cap-and-trade system that governs the heavy-emitting supply-side activities from power stations, energy-intensive heavy industry (e.g., oil refineries, steelworks, and

- producers of iron, aluminium, cement, paper, and glass) and civil aviation of all 27 member states (plus Iceland, Norway, and Liechtenstein).
17. The EU's regulation that corresponds to demand-side sectors (domestic transport excluding aviation, buildings, agriculture, small industry, and waste) and is supported by several regulatory policies (e.g., for renewable energy, energy efficiency, emissions performance standards, etc.).
  18. Vats, G., and Mathur, R. (2022). A net-zero emissions energy system in India by 2050: an exploration. *J. Clean. Prod.* 352, 131417.
  19. Oshiro, K., Masui, T., and Kainuma, M. (2018). Transformation of Japan's energy system to attain net-zero emission by 2050. *Carbon Manag.* 9, 493–501.
  20. Horowitz, R., Binsted, M., Browning, M., Fawcett, A., Henly, C., Hultman, N., McFarland, J., and McJeon, H. (2022). The energy system transformation needed to achieve the U.S. long-term strategy. *Joule* 6, 1357–1362.
  21. Williams, J.H., Jones, R.A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., and Torn, M.S. (2021). Carbon-neutral pathways for the United States. *AGU Adv.* 2. e2020AV000284.
  22. Browning, M., McFarland, J., Bistline, J., Boyd, G., Muratori, M., Binsted, M., Harris, C., Mai, T., Blanford, G., Edmonds, J., et al. (2023). Net-zero CO<sub>2</sub> by 2050 scenarios for the United States in the Energy Modeling Forum 37 study. *Energy Clim. Chang.* 4, 1–13.
  23. Dion, J., Kanduth, A., Moorhouse, J., and Beugin, D. (2021). Canada's net zero future: finding our way in the global transition (Canadian Institute for Climate Choices). [https://climatechoices.ca/wp-content/uploads/2021/02/Canadas-Net-Zero-Future\\_FINAL-2.pdf](https://climatechoices.ca/wp-content/uploads/2021/02/Canadas-Net-Zero-Future_FINAL-2.pdf).
  24. Duan, H., Zhou, S., Jiang, K., Bertram, C., Harmsen, M., Kriegl, E., van Vuuren, D.P., Wang, S., Fujimori, S., Tavoni, M., et al. (2021). Assessing China's efforts to pursue the 1.5°C warming limit. *Science* 372, 378–385.
  25. Handayani, K., Anugrah, P., Goembira, F., Overland, I., Suryadi, B., and Swandaru, A. (2022). Moving beyond the NDCs: ASEAN pathways to a net-zero emissions power sector in 2050. *Appl. Energy* 311, 118580.
  26. Bataille, C., Waisman, H., Briand, Y., Svensson, J., Vogt-Schilb, A., Jaramillo, M., Delgado, R., Arguello, R., Clarke, L., Wild, T., et al. (2020). Net-zero deep decarbonization pathways in Latin America: challenges and opportunities. *Energy Strategy Rev.* 30, 100510.
  27. Bistline, J.E.T. (2021). Roadmaps to net-zero emissions systems: emerging insights and modeling challenges. *Joule* 5, 2551–2563.
  28. Tsiropoulos, I., Nijs, W., Tarvydas, D., and Ruiz Castillo, P. (2020). Towards net-zero emissions in the EU energy system by 2050: insights from scenarios in line with the 2030 and 2050 ambitions of the European Green Deal, EUR 29981 EN (Publications Office of the European Union). <https://publications.jrc.ec.europa.eu/repository/handle/JRC118592>.
  29. Hainsch, K., Löffler, K., Burandt, T., Auer, H., Crespo del Granado, P.C., Pisciella, P., and Zwickl-Bernhard, S. (2022). Energy transition scenarios: what policies, societal attitudes, and technology developments will realize the EU Green Deal? *Energy* 239, 122067.
  30. Wiese, F., Thema, J., and Cordroch, L. (2022). Strategies for climate neutrality. Lessons from a meta-analysis of German energy scenarios. *Renewable and Sustainable Energy Transition* 2, 100015.
  31. Gaeta, M., Nsangwe Businge, C., and Gelmini, A. (2021). Achieving net zero emissions in Italy by 2050: challenges and opportunities. *Energies* 15, 46.
  32. Scheepers, M., Palacios, S.G., Jegu, E., Nogueira, L.P., Rutten, L., van Stralen, J., Smekens, K., West, K., and van der Zwaan, B. (2022). Towards a climate-neutral energy system in the Netherlands. *Renew. Sustain. Energy Rev.* 158, 112097.
  33. Glynn, J., Gargiulo, M., Chiodi, A., Deane, P., Rogan, F., and Ó Gallachóir, B. (2019). Zero carbon energy system pathways for Ireland consistent with the Paris Agreement. *Clim. Policy* 19, 30–42.
  34. Millot, A., Krook-Riekkola, A., and Maizi, N. (2020). Guiding the future energy transition to net-zero emissions: lessons from exploring the differences between France and Sweden. *Energy Policy* 139, 111358.
  35. Nijs, W., Ruiz Castillo, P., Tarvydas, D., Tsiropoulos, I., and Zucker, A. (2018). Deployment scenarios for low carbon energy technologies, JRC112915. <https://publications.jrc.ec.europa.eu/repository/handle/JRC112915>.
  36. Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., De Vita, A., Sakellaris, K., and Sakellaris, K. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy* 134, 110960.
  37. Van Soest, H.L., den Elzen, M.G.J., and van Vuuren, D.P. (2021). Net-zero emission targets for major emitting countries consistent with the Paris Agreement. *Nat. Commun.* 12, 2140.
  38. Schreyer, F., Luderer, G., Rodrigues, R., Pietzcker, R.C., Baumstark, L., Sugiyama, M., Brecha, R.J., Ueckerdt, F., and Ueckerdt, F. (2020). Common but differentiated leadership: strategies and challenges for carbon neutrality by 2050 across industrialized economies. *Environ. Res. Lett.* 15, 114016.
  39. Huppmann, D., Rogelj, J., Kriegler, E., Krey, V., and Riahi, K. (2018). A new scenario resource for integrated 1.5°C research. *Nat. Clim. Change* 8, 1027–1030.
  40. European Commission (2020). An EU-wide assessment of National Energy and Climate Plans – driving forward the green transition and promoting economic recovery through integrated energy and climate planning. COM(2020) 564 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A564%3AFIN>.
  41. European, Environmental Agency (2022). Annual European Union greenhouse gas inventory 1990–2020 and inventory report 2022 submission to the UNFCCC Secretariat. <https://www.eea.europa.eu/publications/annual-european-union-greenhouse-gas-1>.
  42. European Commission (2018). Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending regulation (EU) no 525/2013 and decision no 529/2013/EU. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32018R0841>.
  43. European Commission (2021). Proposal for a regulation of the European Parliament and of the Council amending Regulations (EU) 2018/841 as regards the scope, simplifying the compliance rules, setting out the targets of the Member States for 2030 and committing to the collective achievement of climate neutrality by 2035 in the land use, forestry and agriculture sector, and (EU) 2018/1999 as regards improvement in monitoring, reporting, tracking of progress and review. COM(2021) 554 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0554>.
  44. European Commission (2018). A clean planet for all: a European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy, In-depth analysis in support of the commission communication. COM(2018) 773. [https://knowledge4policy.ec.europa.eu/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision\\_en](https://knowledge4policy.ec.europa.eu/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en).
  45. European Commission (2020). Stepping up Europe's 2030 climate ambition - investing in a climate-neutral future for the benefit of our people - impact assessment. SWD(2020) 176 final Part 1/2 and 2/2. [https://knowledge4policy.ec.europa.eu/publication/communication-com2020562-stepping-up-europe%E2%80%99s-2030-climate-ambition-investing-climate\\_en](https://knowledge4policy.ec.europa.eu/publication/communication-com2020562-stepping-up-europe%E2%80%99s-2030-climate-ambition-investing-climate_en).
  46. European Commission (2021). EU reference scenario 2020 - energy, transport and GHG emissions - trends to 2050. [https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020\\_en](https://energy.ec.europa.eu/data-and-analysis/energy-modelling/eu-reference-scenario-2020_en).
  47. European; Environmental Agency (2021). System. European Union Emissions Trading System (EU ETS) data from EUTL. <https://www.eea.europa.eu/data-and-maps/data/european-union-emissions-trading-schema-16>.
  48. European Commission (2019). 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. COM(2019) 640 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN>.
  49. European Commission (2021). Proposal for a directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757. COM(2021), 551

- final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0551>.
50. European Commission (2021). Proposal for a regulation of the European Parliament and of the Council amending regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement. COM(2021) 555 final. <https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52021PC0555>.
51. We indicate the range of model results in brackets.
52. Davis, S.J., Lewis, N.S., Shaner, M., Aggarwal, S., Arent, D., Azevedo, I.L., Benson, S.M., Bradley, T., Brouwer, J., Chiang, Y.M., et al. (2018). Net-zero emissions energy systems. *Science* 360, eaas9793.
53. Bistline, J.E.T., and Blanford, G.J. (2021). The role of the power sector in net-zero energy systems. *Energy Clim. Change* 2, 100045.
54. Our models only rely on BECCS as negative emissions technology because alternative technological options, such as direct air capture (DAC), biochar, and others, are not consistently represented across models. GCAM, in addition, allows carbon removal by terrestrial carbon sinks.
55. Wachsmuth, J., and Duscha, V. (2019). Achievability of the Paris targets in the EU—the role of demand-side-driven mitigation in different types of scenarios. *Energy Effic.* 12, 403–421.
56. European Union (2021). Regulation (EU) 2021/1229 of the European Parliament and of the Council of 14 July 2021 on the public sector loan facility under the Just Transition Mechanism. <http://data.europa.eu/eli/reg/2021/1229/oj>.
57. Creutzig, F., Roy, J., Lamb, W.F., Azevedo, I.M.L., Bruine de Bruin, W., Dalkmann, H., Edelenbosch, O.Y., Geels, F.W., Grubler, A., Hepburn, C., et al. (2018). Towards demand-side solutions for mitigating climate change. *Nat. Clim. Change* 8, 260–263.
58. Pietzcker, R.C., Osorio, S., and Rodrigues, R. (2021). Tightening EU ETS targets in line with the European Green Deal: impacts on the decarbonization of the EU power sector. *Appl. Energy* 293, 116914.
59. Although our analysis draws from the original ‘Fit for 55’ –61% proposal for the EU-ETS, rather than the provisionally agreed upon target of –62% on 18 December 2022, this has no impact on our NZE Benchmark Scenarios, in which our models were allowed to select the cost optimal pathway to NZE in 2050 and according to which the proposed and now provisionally agreed EU-ETS and ESR burden sharing was validated.
60. Gambhir, A. (2023). This really does change everything: attaining 1.5°C needs all available mitigation levers. *Environ. Res. Lett.* 18, 22001.
61. Perdana, S., Xexakis, G., Koasidis, K., Vielle, M., Nikas, A., Doukas, H., Gambhir, A., Anger-Kraavi, A., May, E., McWilliams, B., et al. (2023). Expert perceptions of game-changing innovations towards net zero. *Energy Strategy Rev.* 45, 101022.
62. Gambhir, A., Ganguly, G., and Mittal, S. (2022). Climate change mitigation scenario databases should incorporate more non-IAM pathways. *Joule* 6, 2663–2667.
63. Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., et al. (2014). Betting on negative emissions. *Nat. Clim. Change* 4, 850–853.
64. Anderson, K., and Peters, G. (2016). The trouble with negative emissions. *Science* 354, 182–183.
65. Butnar, I., Li, P.H., Strachan, N., Portugal Pereira, J., Gambhir, A., and Smith, P. (2020). A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise. *Environ. Res. Lett.* 15, 84008.
66. Fajardy, M., Köberle, A., Mac Dowell, N., and Fantuzzi, A. (2019). BECCS deployment: a reality check. Grantham Institute briefing paper28. <https://mronline.org/wp-content/uploads/2021/04/BECCS-deployment-a-reality-check.pdf>.
67. Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D.L., Rao, N.D., Riahi, K., Rogelj, J., De Stercke, S., et al. (2018). A low energy demand scenario for meeting the 1.5°C target and sustainable development goals without negative emission technologies. *Nat. Energy* 3, 515–527.
68. Fuss, S., Lamb, W.F., Callaghan, M.W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., et al. (2018). Negative emissions—part 2: costs, potentials and side effects. *Environ. Res. Lett.* 13, 63002.
69. International Association of Oil and Gas Producers (2019). The potential for CCS and CCU in Europe, report to the thirty second meeting of the European Gas Regulatory Forum 5–6 June 2019. <https://iogpeurope.org/resource/the-potential-for-ccs-and-ccu-in-europe-report-to-the-thirty-second-meeting-of-the-european-gas-regulatory-forum-5-6-june-2019/>.
70. Rosa, L., Sanchez, D.L., and Mazzotti, M. (2021). Assessment of carbon dioxide removal potential via BECCS in a carbon-neutral Europe. *Energy Environ. Sci.* 14, 3086–3097.
71. Victoria, M., Zhu, K., Brown, T., Andresen, G.B., and Greiner, M. (2020). Early decarbonisation of the European energy system pays off. *Nat. Commun.* 11, 6223.
72. Victoria, M., Zeyen, E., and Brown, T. (2022). Speed of technological transformations required in Europe to achieve different climate goals. *Joule* 6, 1066–1086.
73. Ellis, and Ferraro. (2016). The social acceptance of wind energy; EUR 28182.
74. Doukas, H., Arsenopoulos, A., Lazoglou, M., Nikas, A., and Flamos, A. (2022). Wind repowering: unveiling a hidden asset. *Renew. Sustain. Energy Rev.* 162, 112457.
75. Capellán-Pérez, I., De Castro, C., and Arto, I. (2017). Assessing vulnerabilities and limits in the transition to renewable energies: land requirements under 100% solar energy scenarios. *Renew. Sustain. Energy Rev.* 77, 760–782.
76. Hernandez, R.R., Easter, S.B., Murphy-Mariscal, M.L., Maestre, F.T., Tavassoli, M., Allen, E.B., Barrows, C.W., Belnap, J., Ochoa-Hueso, R., Ravi, S., et al. (2014). Environmental impacts of utility-scale solar energy. *Renew. Sustain. Energy Rev.* 29, 766–779.
77. Dhar, A., Naeth, M.A., Jennings, P.D., and Gamal El-Din, M.G. (2020). Perspectives on environmental impacts and a land reclamation strategy for solar and wind energy systems. *Sci. Total Environ.* 718, 134602.
78. Van de Ven, D.J., Capellan-Peréz, I., Arto, I., Cazcarro, I., de Castro, C., Patel, P., and Gonzalez-Eguino, M. (2021). The potential land requirements and related land use change emissions of solar energy. *Sci. Rep.* 11, 2907.
79. Gambhir, A. (2023). Powering past coal is not enough. *Nat. Clim. Change* 13, 117–118.
80. Heptonstall, P.J., and Gross, R.J.K. (2021). A systematic review of the costs and impacts of integrating variable renewables into power grids. *Nat. Energy* 6, 72–83.
81. Reichenberg, L., Hedenus, F., Odenberger, M., and Johnsson, F. (2018). The marginal system LCOE of variable renewables – evaluating high penetration levels of wind and solar in Europe. *Energy* 152, 914–924.
82. Nehler, T., and Fridahl, M. (2022). Regulatory preconditions for the deployment of bioenergy with carbon capture and storage in Europe. *Front. Clim.* 4, 874152.
83. Mac Dowell, N., Reiner, D.M., and Haszeldine, R.S. (2022). Comparing approaches for carbon dioxide removal. *Joule* 6, 2233–2239.
84. Anthonsen, K.L., Aagaard, P., Bergmo, P.E.S., Erlström, M., Fareide, J.I., Gislason, S.R., Mortensen, G.M., and Snæbjörnsdóttir, S.Ó. (2013). CO<sub>2</sub> storage potential in the Nordic region. *Energy Procedia* 37, 5080–5092.
85. Polzin, F., and Sanders, M. (2020). How to finance the transition to low-carbon energy in Europe? *Energy Policy* 147, 111863.
86. Blanchard, O., Gollier, C., and Tirole, J. (2022). The portfolio of economic policies needed to fight climate change, Peterson Institute for International Economics, WWP no 22-18. <https://www.jstor.org/stable/resrep47224>.
87. Patrizio, P., Pratama, Y.W., and Mac Dowell, N.M. (2020). Socially equitable energy system transitions. *Joule* 4, 1700–1713.
88. Kyriazi, A., and Miró, J. (2022). Towards a socially fair green transition in the EU? An analysis of the just transition fund using the multiple streams framework. *Comp. Eur. Politics*, 1–21.
89. Zhou, W., McCollum, D.L., Fricko, O., Gidden, M., Huppmann, D., Krey, V., and Riahi, K. (2019). A comparison of low carbon investment needs between China and Europe in stringent climate policy scenarios. *Environ. Res. Lett.* 14, 54017.

90. McCollum, D.L., Zhou, W., Bertram, C., de Boer, H.-S., Bosetti, V., Busch, S., Després, J., Drouet, L., Emmerling, J., Fay, M., et al. (2018). Energy investment needs for fulfilling the Paris Agreement and Achieving the Sustainable Development Goals. *Nat. Energy* 3, 589–599.
91. European Scientific Advisory Board on Climate Change (2023). Scientific advice for the determination of an EU-wide 2040 climate target and a greenhouse gas budget for 2030–2050. <https://climate-advisory-board.europa.eu/reports-and-publications/scientific-advice-for-the-determination-of-an-eu-wide-2040/scientific-advice-for-the-determination-of-an-eu-wide-2040-climate-target-and-a-greenhouse-gas-budget-for-2030-2050.pdf>.
92. Lane, J., Greig, C., and Garnett, A. (2021). Uncertain storage prospects create a conundrum for carbon capture and storage ambitions. *Nat. Clim. Change* 11, 925–936.
93. Mannhardt, J., Gabrielli, P., and Sansavini, G. (2023). Collaborative and selfish mitigation strategies to tackle energy scarcity: the case of the European gas crisis. *Iscience* 26, 106750.
94. Chepeliev, M., Hertel, T., and van der Mensbrugge, D. (2022). Cutting Russia's fossil fuel exports: short-term economic pain for long-term environmental gain. *World Economy* 45, 3314–3343.
95. Perdana, S., Vielle, M., and Schenkery, M. (2022). European economic impacts of cutting energy imports from Russia: a computable general equilibrium analysis. *Energy Strategy Rev.* 44, 101006.
96. Plötz, P., Gnann, T., and Wietschel, M. (2014). Modelling market diffusion of electric vehicles with real world driving data—Part I: model structure and validation. *Ecol. Econ.* 107, 411–421.
97. Plötz, P., Gnann, T., Jochem, P., Yilmaz, H.Ü., and Kaschub, T. (2019). Impact of electric trucks powered by overhead lines on the European electricity system and CO<sub>2</sub> emissions. *Energy Policy* 130, 32–40.
98. Simoes, S., Nijs, W., Ruiz, P., Sgobbi, A., Radu, D., Bolat, P., Thiel, C., and Peteves, S. (2013). The JRC-EU-TIMES model. Assessing the long-term role of the SET plan energy technologies. <https://publications.jrc.ec.europa.eu/repository/handle/JRC85804>.
99. Sgobbi, A., Nijs, W., De Miglio, R., Chiodi, A., Gargiulo, M., and Thiel, C. (2016). How far away is hydrogen? Its role in the medium and long-term decarbonisation of the European energy system. *Int. J. Hydrog. Energy* 41, 19–35.
100. Fleiter, T., Rehfeldt, M., Herbst, A., Elsland, R., Klingler, A.L., Manz, P., and Eidelloth, S. (2018). A methodology for bottom-up modelling of energy transitions in the industry sector: the FORECAST model. *Energy Strategy Rev.* 22, 237–254.
101. Edmonds, J.A., Wise, M.A., and MacCracken, C.N. (1994). Advanced energy technologies and climate change: an analysis using the global change assessment model (GCAM). No. PNL-9798 (Pacific Northwest National Lab., PNNL). <https://www.osti.gov/biblio/1127203>.
102. Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R.Y., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., et al. (2019). GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. *Geosci. Model Dev.* 12, 677–698.
103. Kyle, P., Hejazi, M., Kim, S., Patel, P., Graham, N., and Liu, Y. (2021). Assessing the future of global energy-for-water. *Environ. Res. Lett.* 16, 24031.
104. Bernard, A., and Vielle, M. (2008). Gemini-E3, a general equilibrium model of international-national interactions between economy, energy and the environment. *Comput. Manag. Sci.* 5, 173–206.
105. Vielle, M. (2020). Navigating various flexibility mechanisms under European burden-sharing. *Environ. Econ. Policy Stud.* 22, 267–313.
106. Perdana, S., and Vielle, M. (2022). Making the EU Carbon Border Adjustment Mechanism acceptable and climate friendly for least developed countries. *Energy Policy* 170, 113245.
107. Eboli, F., Parrado, R., and Roson, R. (2010). Climate-change feedback on economic growth: explorations with a dynamic general equilibrium model. *Environ. Dev. Econ.* 15, 515–533.
108. Parrado, R., Bosello, F., Delpiazzo, E., Hinkel, J., Lincke, D., and Brown, S. (2020). Fiscal effects and the potential implications on economic growth of sea-level rise impacts and coastal zone protection. *Clim. Change* 160, 283–302.
109. Brécard, D., Fougeyrollas, A., Le Mouél, P., Lemiale, L., and Zagamé, P. (2006). Macroeconomic consequences of European research policy: prospects of the Nemesis model in the year 2030. *Res. Policy* 35, 910–924.
110. Capros, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., Busch, S., Resch, G., Blesl, M., and Bollen, J. (2014). Description of models and scenarios used to assess European decarbonisation pathways. *Energy Strategy Rev.* 2, 220–230.
111. Capros, P., Paroussos, L., Fragkos, P., Tsani, S., Boitier, B., Wagner, F., Busch, S., Resch, G., Blesl, M., and Bollen, J. (2014). European decarbonisation pathways under alternative technological and policy choices: a multi-model analysis. *Energy Strategy Rev.* 2, 231–245.
112. Ravet, J., Boitier, B., Grancagnolo, M., Le Mouél, P., Stirbat, L., and Zagamé, P. (2019). The shape of things to come: ex-ante assessment of the economic impact of Horizon Europe. *fteval J. Res. Technol. Policy Eval.* 47, 96–105.
113. Cassetti, G., Boitier, B., Elia, A., Le Mouél, P., Gargiulo, M., Zagamé, P., Nikas, A., Koasidis, K., Doukas, H., and Chiodi, A. (2023). The interplay among COVID-19 economic recovery, behavioural changes, and the European Green Deal: an energy-economic modelling perspective. *Energy (Oxf)* 263, 125798.
114. Giarola, S., Mittal, S., Vielle, M., Perdana, S., Campagnolo, L., Delpiazzo, E., Bui, H., Kraavi, A.A., Kolpakov, A., Sognaes, I., et al. (2021). Challenges in the harmonisation of global integrated assessment models: A comprehensive methodology to reduce model response heterogeneity. *Sci. Total Environ.* 783, 146861.
115. International Energy Agency (2020). World energy outlook 2020 (IEA). <https://www.iea.org/reports/world-energy-outlook-2020>.