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

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SUMMARY

The 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, 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 decarbonisation of electricity by 2040, enabled by considerable deployment of renewables (45-65% in 2030, to 60-70% in 2040, to 75-90% in 2050 in electricity generation) and carbon capture and storage (0.5-2 $GtCO_2$/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 phase out and reflect on the economic implications of investment, technical, and policy needs.

Keywords

Modelling, climate mitigation pathways, net-zero emissions, European climate policy, climate and energy transition

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[1] yet not with the pace required to collectively align with the Paris temperature goals[2,3]. Notably, long-term national pledges now predominantly include plans for achieving net-zero emissions (NZE) by or around mid-century[4]; by the end of 2022, over 120 countries had submitted a NZE target, altogether covering more than two thirds of global greenhouse gas (GHG) emissions[5].

Traditionally a frontrunner in international climate efforts[6], the European Union (EU) is on the verge of operationalising 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[7], by aiming to cut its emissions by 55% by the end of this decade, compared to 1990. The new target comes as a bold upgrade to the previous -40% target[8], which has been found attainable with the policies already in place but largely incompatible with the 2050 NZE target[9]. 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[10]. This means that any credible, actionable, 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[11-15], 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)[1], the Effort Sharing Regulation (ESR)[2], 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[16], Japan[17], USA[18-20], Canada[21], China[22]) or broader regions[23,24] (see Bistline[25] for an exhaustive overview) the EU's transition to carbon neutrality is not an underexplored theme amongst studies based on such models[26,27]. But, apart from analyses of individual EU countries[28-32], single-model studies[33,34], and global-level analyses without sufficient regional detail[5,35-37], 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

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[1] 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).

[2] 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.).

Plans (NECPs), the cumulative emissions impact of which sits at a modest 41% emissions reduction by the end of this decade[38], 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 decarbonisation 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 onwards 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 models (GEMINI-E3, ICES-XPS). On the other, we use four region-specific European models: of these, two are economy-wide, including an energy system model (EU-TIMES) and a macroeconometric 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 harmonised 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). Since 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_2 and LULUCF emissions' contributions to GHG emissions reduction targets (*low*, *medium*, *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 (a) 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%, (b) the EU-ETS burden sharing of 'Fit 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 18 December 2022, (c) no assumptions are made as to the EU's response to the Russia-Ukraine war, and (d) 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_2 emissions depending on assumptions regarding non-CO_2 and LULUCF emissions) to reach NZE by 2050. Emissions burden sharing between the EU-ETS and ESR sectors is a key question for EU policymakers. 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 to 1990. With the increased ambition of at least a 55% emissions reduction in 2030 compared to 1990[39], 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 to 2005 levels[40,41]. In the *NZE Benchmark* scenarios, by 2030 the modelled 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%][3] median emission reductions across models whereas the mitigation effort in the ESR is lower, at around -53% [-47 – -59%] relative to 2005; in 2050, mitigation in the EU-ETS further increases, reaching a median value of -118% [-104 – -158%], largely fuelled by bioenergy with carbon capture and storage (BECCS)—especially in GCAM—while mitigation in the ESR sector reaches a median value of -75% [-55 – -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_2 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_2 emission cuts in 2050 compared to 1990 levels among models, with non-CO_2 emissions being around 550 and 305 [303 – 310] $MtCO_2eq/y$ in GCAM and GEMINI-E3 respectively, in the range of the assumptions for all other models (290-560 $MtCO_2/y$).

Similarly, the role that the LULUCF sector could play in achieving NZE is also highly uncertain but tilting towards lower contributions. GCAM (with endogenous representation of LULUCF) shows a decline in the EU's carbon sink from 200 $MtCO_2eq/y$ in 2030 to 65 $MtCO_2eq/y$ 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_2 emissions (drawn directly from official European Commission data), and/or pessimism in the two models with endogenous representation (GCAM and GEMINI-E3).

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 twenty-seven EU Members States, four (Austria, Greece, Ireland, and Netherlands) do not reach their NZE commitments in any scenario, while three (Cyprus, Denmark, and Germany) appear to do so only in

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[3] We indicate the range of model results in brackets.

some scenarios; the twenty remaining countries achieve their commitment in most scenarios. Regarding member states not hitting their NZE targets, non-CO_2 emissions appear to constitute the largest chunk of any remaining emissions, mainly followed by transport CO_2 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 sectorally targeted measures—e.g., the Netherlands and Austria should prioritise reinforcing their mitigation efforts in their industry sector.

A sectoral deep dive

In economy-wide models, the decarbonisation of the European economy is driven by a rapid reduction of CO_2 emissions in the energy supply sector (Figure 2), which realises 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 decarbonisation of the power sector alongside an economy-wide reduction of fossil-fuel consumption are critical to reach NZE in 2050[44,45]. 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 that does not represent CCS and can thus only reach NZE with considerably higher policy costs.

The scale of BECCS[4] deployment influences the mitigation burden on other sectors in NZE scenarios; for instance, large-scale deployment of BECCS to decarbonise 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% – 94%], is lower than in other sectors. However, the sectoral model ALADIN, which incorporates detailed representation of the transportation sector, shows that an almost complete decarbonisation 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 optimisation 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 decarbonisation by 2050 in NZE scenarios, while the economy-wide models calculate a lower rate of decarbonisation of -88% [-65 – -98%]. These findings (***Figure 3***Figure 3a) are in line with reported insights on sectoral models featuring more mitigation levers allowing to achieve higher decarbonisation in the literature[46]. In agriculture, forestry, and fisheries (AFOFI) and other sectors, models converge towards a CO_2 emissions reduction of approximatively 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 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 entirely in 2050 should these barriers persist (EU-TIMES), but they could capture up to 32 [26 – 48] and 70 [61 – 99] $MtCO_2/y$ 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 to NEMESIS—e.g., in Spain (almost eightfold, 191 [165 - 192] $MtCO_2/y$) and Romania (fivefold, 52 [52 – 62] $MtCO_2/y$). Overall, in the NZE scenarios, model results

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[4] 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.

suggest that the share of CO_2 removed by means of CCS would reach 13% [9% – 42%] of the EU's CO_2 emissions from energy and processes in 1990, with maximum deployment achieved in GCAM (up to 1.9 $GtCO_2$/y 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 stabilisation 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_2 mitigation effort—sees both EU-TIMES and NEMESIS projecting higher total EU primary energy consumption in 2050 that in the other cases. This result indicates a higher direct or indirect mobilisation of electricity to further decarbonise 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, while 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 to 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 decarbonise 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), while 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 phase-out

The rapid decarbonisation of the EU power sector, enabled by large deployment of renewables (generating 50% [45 – 65%] in 2030 and 80% [64 – 89%] in 2050) and mobilisation 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_2 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 (a) socioeconomic drivers and (b) electrification of final demand sectors compared to the current policy baseline, as it is the main strategy of decarbonisation alongside cost-effective cleantech in electricity to reach NZE. All models attest to the crucial role of low-carbon electricity alongside 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 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 increase of final energy electrification rates in all EU countries is promoted by strong decarbonisation 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 onwards 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 towards NZE will imply large investment needs, according to our models (Figure 5a). EU-TIMES and NEMESIS estimate the additional average annual investment needs, compared to current policies (see Scenario Design in Experimental Procedures), to be 0.2% [-0.1 – 0.51%] of the EU-27 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: amongst 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 to 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[47].

In addition to investment needs, reaching NZE also entails economy-wide costs according to the two economic models reaching net zero, as compared to 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 – 11%] in ICES-XPS in the *NZE EU Policy Standard* scenario (see Table S3), since mitigation options are very limited (no CCS, hydrogen, or e-fuels). As a consequence, ICES-XPS reduces demand and economic activity to mitigate CO_2 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 decarbonisation 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 decarbonisation[48]. Indeed, this lack of technology representation harmonisation amongst our models helps elucidate the range of possibilities, on the one hand technological and on the other social and economic, which could constitute deep decarbonisation 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 towards 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[49]—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%[5] 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[50], the inter-model comparisons in this study highlight the need for large structural changes to accelerate EU-ETS sector decarbonisation. 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 decarbonisation with near-zero or negative CO_2 intensity in 2050 across the bloc, with most countries ranging from 0 to -150 gCO_2/kWh in 2050 and fossil fuel consumption declining by 50-90%.

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[5] 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.

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, favouring 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 recognised 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[51], underpinning the added value of detailed sectoral modelling[52].

Strong reliance on BECCS is a well-established criticism of modelled deep mitigation pathways[53-56], typically traded off against high policy costs, especially on the demand-side of the transition[57]. 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 $GtCO_2$[58] to as high as 300 $GtCO_2$[59]. Overall, our model ensemble reveals EU dependence on (BE)CCS ranging from as low as 0.3 $GtCO_2$/y in 2050; nonetheless, such low levels also question the realism of NZE pathways, with evidence in the literature suggesting even 0.2 $GtCO_2$/y may prove challenging for Europe, should distances between emissions sources and storage sites be considered[60]. 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)[12]—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 decarbonisation 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[26,27,34,61,62]. This, however, raises questions of feasibility considering a diversity of existing barriers to such levels of deployment[63,64], including potential environmental impacts[65], including on biodiversity[66,67] and land use[68], as well as socioeconomic implications of such rates of coal reduction[69]. Strong policies and government incentives are thus needed to overcome such hurdles. Furthermore, we also acknowledge that, from a certain penetration rate onwards, ranging from 55%[70] to 80%[71], 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 modelling 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[5].

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_2 emissions storage among Member States[72,73]. Similarly, the geopolitics of carbon storage may soon become important considering, e.g., the storage potentials in Nordic European countries[74]. 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[75,76]. It also calls for policies that ensure a fair and just economic burden among EU countries[77,78], since the investment burden is expected to be stronger for less developed Member States, confirming the scarce evidence in the literature[79]. 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_{2022}, in line with estimates from the European Commission and the literature[34,80,81].

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[25], such as fossil fuel reductions and CCS use against decarbonisation as well as per capita electricity and final energy against electrification, with findings from the IPCC's 6th 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 large economies with equally ambitious targets, including the US and Canada.

To summarise key policy takeaways, this study's modelled 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 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_2 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[82]. 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 prioritising 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 a cost-efficient approach to achieving NZE by 2050, since 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[83], the region must further mitigate emissions in all end-use sectors through higher electrification and alternative technologies and fuels, thereby promoting heavy investments in not yet mature technologies. 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 amongst 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, while EU power supply should achieve near-to-complete decarbonisation 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, as well as bioenergy) in power generation at unprecedented rates[5] 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 towards 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 $0.75GtCO_2$ in 2050.

Despite the robustness of these insights, it should be noted that model inter-comparisons do not come without disagreement among models, as 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, as our results hint at different levels of disagreement in terms of technological choices and sectoral mitigation cost-effectiveness towards 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 fuelled 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 modelling studies assessing the long-term implications of these developments[84,85], only one benchmarked the effects against EU current policies, NDC, and net-zero pledges[86], 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 harmonisation 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).

Materials availability

This study did not generate new unique reagents.

Data and code availability

The datasets generated during, and analysed in, the current 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 modelling 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[10] but, as with other multi-model studies exploring 1.5°C and net-zero pathways[5], 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 modelling teams. Nevertheless, this broad ensemble employed here represents a wide diversity of modelling philosophies and frameworks, including partial equilibrium (GCAM, EU-TIMES), computable general equilibrium (GEMINI-E3, ICES-XPS), and macroeconometric (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 summarises 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[87], 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[88].

EU-TIMES is an enhanced version of the open source JRC-EU-TIMES model[89]. It is a multi-region European version of TIMES and represents the EU Member States and neighbouring countries. The model is designed for analysing the role of energy technologies and innovation needs for meeting European energy and climate policy targets[9]. It can consider policies affecting the entire energy system, sectors, as well as (sets of) various technologies/commodities[90].

FORECAST is a bottom-up simulation model for analysing the long-term development of energy demand and emissions for the industry, residential and tertiary sectors at national level, considering a broad range of mitigation options to reduce CO_2 emissions, combined with a high level of technological detail[91]. The FORECAST-Industry model considers energy efficiency, switching to new low-carbon processes, renewables and low-carbon energy carriers, carbon capture and storage (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[92], exploring the interactions between energy, agriculture and land use, economy and climate[93]; it operates on a "recursive dynamic" cost-optimisation 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[94]. GCAM portrays Europe combining two main region aggregates: EU-15 (including the UK) and EU-12 (excluding Croatia).

GEMINI-E3 is a multi-country, multi-sector, recursive computable general equilibrium (CGE) model[95] 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[96,97]. 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[98]; for the purposes of this study, the XPS version is used[99] with a more detailed representation of government behaviour 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+[100,101]. 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[102]. NEMESIS includes a detailed energy-environment module that allows the model to deal with climate mitigation policies, at EU and EU-national level[103,104].

Scenario Design

As *reference scenario*, we use—as well as harmonise the entire model ensemble to–the pre-defined set of socioeconomic and technoeconomic parameters developed in Giarola et al.[105] and implemented in Nikas et al.[9], with updated projections for GDP and fossil fuels prices described in Cassetti et al.[104]. Fossil fuels prices projections come from International Energy Agency[106], 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 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)[9]. 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 to 1990 and NZE in 2050) as emissions caps, and the models calculate the model-optimal (or least-cost) pathway towards 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_2 and LULUCF emissions to the GHG mix (*low*, *medium*, *high*); the more the non-CO_2 and LULUCF emission reductions contribute to the total GHG emissions targets, the lower the CO_2 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[7] 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_2 emissions. With these assumptions, the EU-ETS emissions reduction leads to -61% compared to 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_2 emissions projections are at the EU level and mainly stem from European Commission projections. For the non-CO_2 emissions by Members State, we use the Commission's reference scenario[107]: starting from total EU27 non-CO_2 emissions (Tables 3-4), we use the share of each Member State in the EU-27 non-CO_2 emissions in 2030, 2040, 2050 from European Commission[108] to calculate the non-CO_2 emissions by Member State in our scenarios. For LULUCF emissions by Member State, there is no such projection to our knowledge; we therefore apply the average share of each member state in the EU-27 LULUCF emissions from 2000 to 2020[42] to the EU27-level assumptions used in our scenarios (Tables 3-4).

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_2 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_2 emissions. Finally, featuring limited representation of mitigation technologies and only representing energy CO_2 emissions, ICES-XPS only delivers results for the *high* variant of the *NZE Benchmark* scenario. Consequently, we limit ICES-XPS model results to economic aspects of the analysis. See Table 6 for an overview of which scenarios were implemented in each model.

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AUTHORS 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.Al-D. (FORECAST-Industry), Ş.A. (FORECAST-Buildings), D.v.d.V. (GCAM), M.V. and S.P. (GEMINI-E3), L.C., E.D. (ICES), B.B., A.F., P. Le-M. and P.Z. (NEMESIS), Validation: B.B, A.N., S.M., P.Le-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.

DECLARATIONS OF INTERESTS

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

The other authors declare no competing interests.

INCLUSION AND DIVERSITY STATEMENT

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

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MAIN FIGURE TITLES AND LEGENDS

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_2 *and LULUCF emissions used by the models not covering them—see Experimental Procedures for additional information. Historical values come from EEA*[42,43]*. Sectoral models are not presented here, as they do not cover the entire economy; ICES-XPS is not presented either, because it includes only* CO_2 *emissions from energy. Exogenous assumptions are detailed in Table 3.*

Figure 2. EU sector reduction of CO_2 ***emissions from energy and industrial processes (w.r.t. 1990).*** *The ICES-XPS model does not cover* CO_2 *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 & 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).*

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 "Fossils Fuels" include emissions from energy supply; FORECAST was only run 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 (*$MtCO_2/y.$*).*

Figure 4. EU primary energy consumption and power generation in NZE Benchmark Medium. *(a) Primary energy consumption by fuel, (b) electricity generation by source.*

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, (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.*

MAIN TABLES, TABLE TITLES, AND LEGENDS

Table 1: Main features (type, team, version, EU geographical representation, and sectoral granularity) of each model if 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	Macro-econometric
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, 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_2 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 Households expenditures	As economic activities and Households expenditures	As economic activities and Households expenditures
	Buildings	No	No	Very detailed	Detailed	As economic activities and Households expenditures	As economic activities and Households expenditures	As economic activities and Households 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%

Table 3: Detailed emissions caps for the EU27 in the NZE Benchmark scenarios (in GtCO2eq.).

	Historical data		**Assumed contribution of non-CO_2 and LULUCF emissions to GHG mitigation**					
	1990	**2005**	**2030**			**2050**		
			Climate Target Plan (-55% w.r.t 1990)			**Net Zero Emissions**		
			Low	**Medium**	**High**	**Low**	**Medium**	**High**
CO_2 (w/o LULUCF & w/ in't transport)	4.05	4.00	1.81	1.90	1.99	-0.27	0.01	0.22
CO_2 (w/o LULUCF & w/ intra-EEA aviation[*])	3.91	3.79	--	--	--			
Non-CO_2 (w/o LULUCF & 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 & w/ in't transport)	4.82	4.48	2.17	2.17	2.17	0.00	0.00	0.00
Total (w/o LULUCF & w/ intra-EEA aviation[*])	4.89	4.58						

Source: historical values[42]; LULUCF emissions authors' calculation based on: 2030-low: current LULUCF regulation[109] 2030-medium: average of low and high, 2030-high: new objectives from 'Fit for 55'[110], 2050-low: scenario "Baseline"[81], 2050-medium: idem 2030-high and 2050-high: scenario "Life1.5LB"[81]; Non-CO_2 emissions authors' calculation based on: 2030-low: scenario "Mix-50"[108], 2030-medium: average of low and high, 2030-high: "All bank"[108], 2050-low: EU reference scenario 2020[107], 2050-medium: scenario "Combo"[81] and 2050-high: scenario "Life1.5LB"[81]

[*]: *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[42,43].*

Additional Note: Original data have been corrected for the UK where relevant.

Table 4: Detailed GHG emissions caps in EU27 for the NZE EU Policy standard scenario

GtCO$_2$eq./y.	**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$_2$ emissions (wo. LULUCF and w. in't transport)	0.98	0.79	0.69	0.54	0.30
Total (w. LULUCF & w. in't transport)	4.82	4.48	3.63	2.17	0.00

Source: historical values[42,43]; LULUCF and non-CO$_2$ emission: same as "medium" case in the NZE-benchmark scenario

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

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.

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