Science of the Total Environment 793 (2021) 148549

Contents lists available at ScienceDirect

Science of the Total Environment

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

Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison

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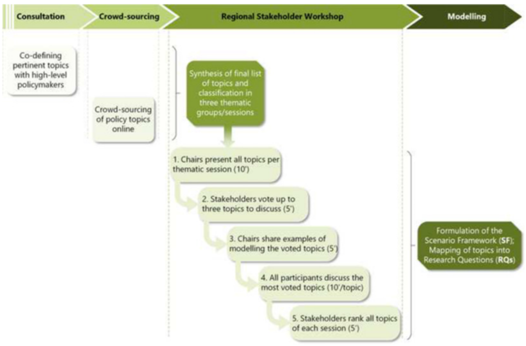
HIGHLIGHTS

- We define the scenario logic & scope of a model inter-comparison with stakeholders.
- We explore the EU's energy future, if its current policy is projected in the long run.
- The diverse modelling ensemble employed includes seven global and four regional models.
- Far from its new 2030 goal the EU is looking at a 1.0–2.35 $GtCO_2$ 2050 emissions range.
- We further assess CCS, hydrogen, transport electrification, energy security, and jobs.

GRAPHICAL ABSTRACT



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https://doi.org/10.1016/j.scitotenv.2021.148549

ARTICLE INFO

Article history:
Received 28 March 2021
Received in revised form 10 June 2021
Accepted 15 June 2021
Available online 21 June 2021

Editor: Kuishuang Feng

Keywords:
Europe
Energy system models
Model inter-comparison
Stakeholder engagement
Climate policy
Integrated assessment models

ABSTRACT

Recent calls to do climate policy research with, rather than for, stakeholders have been answered in non-modelling science. Notwithstanding progress in modelling literature, however, very little of the scenario space traces back to what stakeholders are ultimately concerned about. With a suite of eleven integrated assessment, energy system and sectoral models, we carry out a model inter-comparison for the EU, the scenario logic and research questions of which have been formulated based on stakeholders' concerns. The output of this process is a scenario framework exploring where the region is headed rather than how to achieve its goals, extrapolating its current policy efforts into the future. We find that Europe is currently on track to overperforming its pre-2020 40% target yet far from its newest ambition of 55% emissions cuts by 2030, as well as looking at a 1.0–2.35 $GtCO_2$ emissions range in 2050. Aside from the importance of transport electrification, deployment levels of carbon capture and storage are found intertwined with deeper emissions cuts and with hydrogen diffusion, with most hydrogen produced post-2040 being blue. Finally, the multi-model exercise has highlighted benefits from deeper decarbonisation in terms of energy security and jobs, and moderate to high renewables-dominated investment needs.

1. Introduction

Since the previous (5th) Assessment Report (AR5) on climate change mitigation of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2014), the policy landscape has markedly changed, notably orbiting on the Paris Agreement uniting and binding the globe into a common goal of limiting global warming to well-below-2 °C above pre-industrial levels (Peters et al., 2017). Critical products of policy negotiations and resulting pressures to the IPCC have since shifted the research agenda (Livingston and Rummukainen, 2020), as also reflected in the integrated assessment modelling literature, which has now been looking into more ambitious scenarios in line with the Paris long-term temperature goal (Rogelj et al., 2018; IPCC, 2018). Novel themes in climate and climate-economy modelling and analysis have recently included but are not limited to a growing and more thorough assessment of negative emissions technologies (Minx et al., 2017) and their limitations (Anderson and Peters, 2016), the role of energy demand (Grubler et al., 2018) and lifestyle shifts (Van Vuuren et al., 2018), the consideration of trade-offs with other Sustainable Development Goals (Nerini et al., 2019), an updated view of climate sensitivity (Sherwood et al., 2020), and a slow departure from unrealistic no-policy baselines (Hausfather and Peters, 2020; Grant et al., 2020). Notwithstanding this progress, the modelling world has fallen short of one promise: to include non-scientists at the heart of its process (Doukas and Nikas, 2021).

This shortfall has happened in spite of stakeholder-oriented policy-level initiatives brought about by UNFCCC processes like the Talanoa dialogue (Mundaca et al., 2019), numerous relevant calls in the literature for transdisciplinarity (e.g. Geels et al., 2016; Nikas et al., 2020a; Byrne et al., 2016) and knowledge co-creation (Mauser et al., 2013) following longstanding criticisms over stakeholders' role in climate science (Klenk et al., 2015) and representation in IPCC processes (Yamineva, 2017). Stakeholders have been involved in non-modelling aspects of climate science and policy (Galende-Sánchez and Sorman, 2021). In the modelling world, both the importance of stakeholders in scenario appraisal (van Vliet et al., 2020) and the divergence between expert expectations and modelled pathways (Van Sluisveld et al., 2018) are acknowledged. There have been certain public consultations in single-model studies at the national level, towards defining research questions (e.g., Nikas et al., 2020c), highlighting post-modelling uncertainty dimensions (e.g., Antosiewicz et al., 2020), or exploiting the merits of mixed-methods approaches (e.g., Forouli et al., 2019). Yet, not to the point of claiming society-wide representation or alignment between modelled outputs and stakeholder preferences (Xexakis et al., 2020). This is even less so in the resource-intensive global model inter-comparison projects that essentially form the bedrock of large scientific assessments like the IPCC's (Nikas et al., 2021). Apart from limited references to discussions with experts on assessing technological potential (Realmonte et al., 2019), collecting national climate policies (Roelfsema et al., 2020), or reviewing global-level results (Van Soest et al., 2017), there are no mentions of the word ‘stakeholder’ or ‘expert’ in any other of these global multi-model analyses published after the Paris Agreement.

Regardless of stakeholder demand for the questions driving them, the purpose of these multi-model exercises is to enhance the robustness and consistency of resulting insights, by exploiting the strengths of different models and examining how differing modelling theories, structures, and approaches respond to specific research questions (Doukas and Nikas, 2020). In fact, embracing this diversity, many such studies deliberately opt out of, or fail to engage in, harmonising model inputs (e.g., Edelenbosch et al., 2020 at the global level, or Oshiro et al., 2020 and Sugiyama et al., 2019 at the regional level). To increase the ability to interpret the results and understand the drivers of the produced ranges across models, many studies have instead attempted to partially harmonise assumptions, especially those related with socioeconomic parameters like economic and population growth (e.g., Gambhir et al., 2017 at the global level, or Paladugula et al., 2018 and Wang et al., 2020 at the regional level). Some studies documented efforts to further investigate harmonised technology or scenario input assumptions along with shared socioeconomic parameters (e.g., Vrontisi et al., 2018; Fujimori et al., 2019; Fofrich et al., 2020). Nevertheless, with few exceptions of comprehensive efforts (Bosetti et al., 2015; Realmonte et al., 2019), these exercises have only attempted harmonisation to limited extents. For example, Luderer et al. (2018) harmonised carbon prices without focusing on technoeconomic parameters; Butnar et al. (2020) compared assumptions on bioenergy with carbon capture and storage (BECCS), without harmonising them; and McCollum et al. (2018) compared energy efficiency investments across models, without harmonising respective technical and cost parameters. There have not been systematic efforts in the literature for harmonising emissions, policy, socioeconomic, technoeconomic, and other parameters, in support of model inter-comparison projects, to the extent of claiming that resulting ranges of outputs can be confidently traced only to the different ‘personalities’ of the employed models (Doukas et al., 2018).

Narrowing down the geographic focus to Europe, which recently updated its 2030 target to cutting emissions by 55%, several modelling studies have produced scenarios underpinning recent policy targets (Tsiropoulos et al., 2020). In the post-Paris literature, EU climate policy and low-carbon pathways have been assessed in limited single-model regional studies (Simoes et al., 2017; Capros et al., 2019) or integrative exercises soft-linking models (Vrontisi et al., 2020), as well as explicitly discussed in global inter-comparison studies (McCollum et al., 2018; Fragkos et al., 2021). However, the most recent multi-model endeavour focusing on the EU, analysing pathways in line with then decarbonisation targets in a 'backcasting' setting and harmonising certain socioeconomic projections (Capros et al., 2014b), dates before the updated policy ambition of the Paris Agreement and the highlighted need for stakeholder inclusiveness and representation.

This study carries out the first multi-model analysis focusing on Europe exploring implications of current policy projected into the future, in which both the scenario logic and the research questions have been informed by stakeholders, and significant socioeconomic and technoeconomic (as in technology costs) harmonisation efforts have been undertaken, acknowledging that pure inter-model diversity can mask too many different input assumption differences. It is driven by discussions held in a dedicated stakeholder workshop in Brussels, Belgium, in November 2019 (Doukas et al., 2020), and employs a comprehensive protocol for streamlining historical emissions, policy assumptions, socioeconomic parameters, and technology costs to updated datasets (Giarola et al., 2021a). The study also draws from a global-level implementation of the resulting scenario protocol, which explores where the world is headed given countries' current climate action and most recent pledges (Sognnaes et al., 2021). We expand the latter study's toolset to an ensemble that comprises seven global integrated assessment models (IAMs) and four European energy, macroeconometric and sectoral models, while narrowing down its focus to current European policy in order to address the stakeholders' research questions.

Section 2 documents the employed methods, including an overview of the Brussels stakeholder workshop process and outcomes, the co-design of the scenario protocol as well as focused research questions formulated based on the participating stakeholders' priorities, a presentation of the diverse modelling ensemble, and a transparent discussion of the input assumptions. Section 3 carries out the model inter-comparison exercise among all models, with the aim to discuss the resulting range of key parameters including energy CO_2 emissions (total and by sector), primary energy by fuel and final energy by sector, which constitute a cross-model common denominator. Section 4 presents the results of multi-model analyses of variables that are relevant to the main themes prioritised and discussed by stakeholders during the workshop, while Section 5 discusses the conclusions, caveats, and next steps of the study.

2. Methods and tools

2.1. Co-designing the scenario logic and research questions

As part of the PARIS REINFORCE research project, a regional workshop took place on November 21, 2019, in Brussels, Belgium. It was a pan-European initiative for the co-production of research underpinning new climate policy in Europe, drawing from the outcomes of five-month exhaustive consultation, in which high-level policymakers were introduced to the project and asked to provide policy areas that they would be most interested in research being carried out within. The consultation, along with an open crowd-sourcing process carried out via an online polling platform 24 h before the event, resulted in a list of 22 topics, which were broken down into 3 thematic groups. Stakeholders were invited based on their displayed participation or interest in previous European climate policy events, resulting in a sample of over 800 invitations. During the workshop, high-level staff of the EC directorates-general (DGs) for energy, climate and research, ministries and climate-related governmental bodies from EU Member States, international organisations, business representatives, and scientists participated. 57 individuals attended the workshop physically, although the event was also livestreamed to allow as large and diversified an audience as possible.

During the morning sessions, a detailed policy brief on what the climate-economy models can and cannot do was handed out, presented, and discussed with stakeholders, and the I^2AM PARIS platform (Nikas et al., 2021) was launched and thoroughly presented, allowing stakeholders to express their preferences over its final specifications, content, design, and directions. The afternoon consultation was broken down into three sessions, in respect to the 3 thematic groups of the 22 topics. During each session, a chairperson spent the first 10 min explaining each potential research area to the audience, then allowing participants to vote (via sli.do[1]) on and prioritise which questions they would be most interested in discussing. Given the range of proposed questions, this process was important to enable discussions to be held over the most important topics to the stakeholders. After topic selection, the floor was open for discussion between chairs and audience. Chairs spent 1–2 min introducing the discussion on each topic, and then stakeholders were able to raise any points or questions they had over the proposed research areas. Following the discussion, sli.do voting again allowed stakeholders to vote according to how relevant they see it for the project to follow up on and conduct research in each topic. The process is illustrated in Fig. 1.

During the first thematic session ('global threat, global pathways'), among the topics presented stakeholders chose to discuss behavioural change and potential failure of key technologies along with game-changing innovations; after a detailed discussion, the themes selected for the project to carry out research within included the three topics along with a realistic account of where the world is headed given collective current efforts and pledges. In the second session ('a Paris-consistent Europe'), despite the expected diversity in preferences among stakeholder groups, academics and non-academics alike highlighted questions revolving around electrification and hydrogen. In the final session ('sustainable climate action'), although scientists were mostly interested in the decline of carbon-intensive sectors and distributional impacts across Europe, non-academic stakeholders upvoted issues oriented on cross-sectoral impacts revolving around employment and investments.

Among the outcomes of the workshop, the prospect of understanding and realistically quantifying where the world and Europe are heading given current policy was not selected for discussion during the first thematic session, indicating that stakeholders understood the rationale and motivation behind it. Nonetheless, in the subsequent voting process, the topic was prioritised by the stakeholders as a research question for the modelling exercise to investigate, among others. This further highlighted a gap in the literature: pathways implied by current policies forward to 2050, explicitly considering the level of ambition encompassed in those policies and targets, are underrepresented in the modelling world—or non-existent for the European region, as discussed in Section 1. Most of the literature explores different mitigation trajectories consistent with a 2 °C- or 1.5 °C-interpretation of the Paris Agreement, in 'backcasting' approaches, in which models set out to describe what is needed from a technology and policy perspective, compared against unrealistic no-policy baselines (Grant et al., 2020) or relatively simplistic reference scenarios describing how emissions would develop in the future given the existing climate policies (e.g., McCollum et al., 2018; Roelfsema et al., 2020).

To design a scenario framework (SF) addressing this gap, we start from current EU policies, as documented until 2020 in Roelfsema et al. (2020), and update them accordingly with the policies currently in place. To interpret and measure mitigation effort, we use carbon price as a proxy of climate policy. We first calculate the carbon price in the EU that, absent any other policy, achieves the same levels of emissions as current policy by 2030. To extend mitigation effort post-2030, we extend this equivalent carbon price at the rate of GDP growth per capita after 2030, to represent a constant economic burden from carbon pricing (Strefler et al., 2021), as proxied by the ratio of carbon price to per capita income over time: for models with detailed energy system representations, current policies are simulated as constraints; for some macroeconomic models, they are instead applied as minimum subsidy levels to low-carbon technologies, boosting their uptake (for a detailed discussion of the scenario protocol see Sognnaes et al., 2021 and Appendix A). With this SF as a starting point, we map and group the prioritised topics in the resulting co-designed research questions (RQs), as described in Table 1.

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[1] https://www.sli.do/.

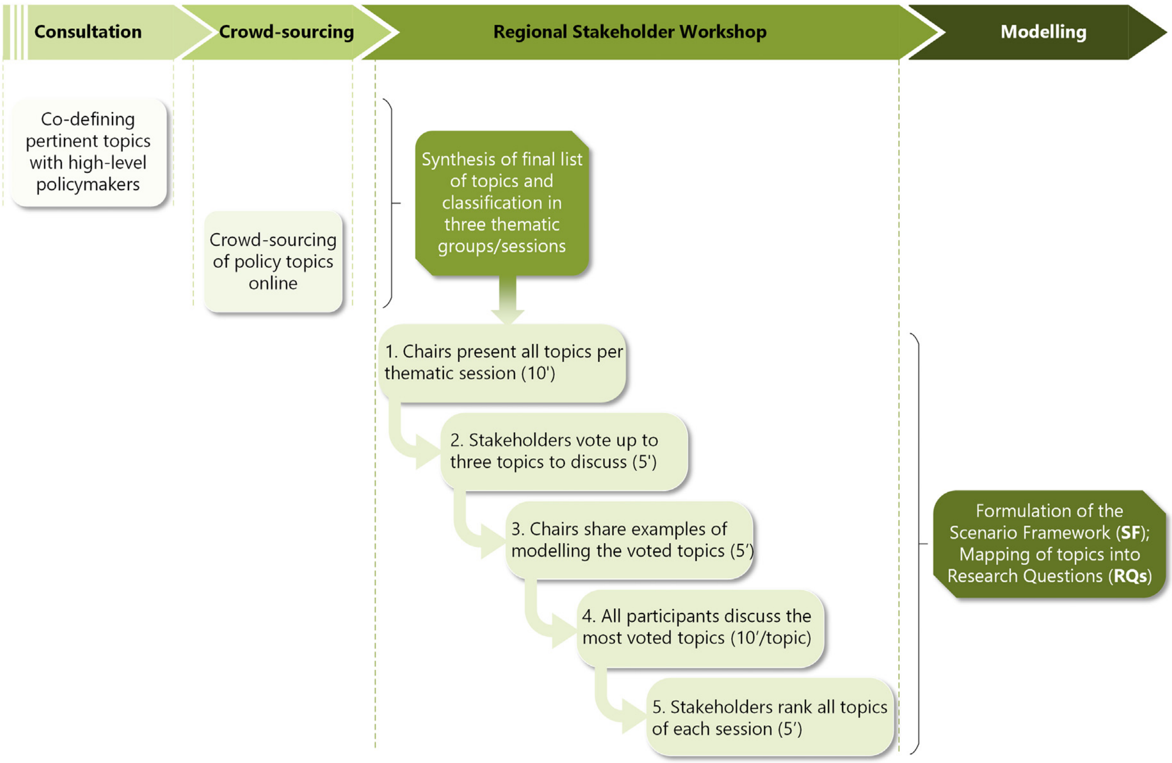

Fig. 1. Stakeholder engagement process and development of scenario framework and research questions.

2.2. Modelling ensemble

For the purposes of this study, we employ eleven models: seven global with explicit disaggregation of the European region, and four regional covering Europe in detail at the national level. We seek to enhance the robustness of results by exploiting the diversity of the modelling ensemble of this multi-model exercise: following the classification scheme of Nikas et al. (2019), the ensemble comprises two global general equilibrium IAMs (GEMINI-E3, ICES); two global partial equilibrium IAMs (GCAM, TIAM); one regional (EU-TIMES) and two global (MUSE, 42) energy system models; one regional (NEMESIS) and one global (E3ME) macroeconometric models; and two regional sectoral models, one for transport (ALADIN) and one for the residential and industry sectors (FORECAST). The models, along with their classification, coverage and description are presented in Appendix B; full documentation of the eleven models can be found in the I^2AM PARIS platform.[2]

Table 1
Mapping of stakeholder-selected topics with the scenario framework (SF) and research questions (RQs) of the study.

Workshop thematic sessions	Upvoted policy topics	Research questions
Session 1: 'Global threat, global pathways'	- Where is the world headed? (**SF**)	**RQ1**: Where is Europe headed in 2050: what do its middle-of-century emissions and energy mix look like, as a result of its current efforts? (Section 3)
	- Potential failure of key technologies - Game-changing innovations	**RQ2a**: What is the role of carbon capture and storage as a game changer? (Section 4.1.1) **RQ2b**: What is the role of import dependency in Europe? (Section 4.1.2)
	- Behavioural and lifestyle changes	*N/A; see Section 5, Nikas et al. (2020a)*
Session 2: 'A Paris-consistent Europe'	- The role of electrification and storage	**RQ3a**: What will the role of electrification be in the transport sector? (Section 4.2.1)
	- Hydrogen's future in industry, transport, & energy	**RQ3b**: What is the future of (grey, blue, and green) hydrogen in the EU, given its current policy? How does it fare against electrification? (Section 4.2.2)
Session 3: 'Sustainable climate action'	- Required investments and their implications - Implications for employment	**RQ4**: What are the costs and gains of current policy? What are the necessary investments to deliver on it? What are the employment implications of current EU policy? (Section 4.3)

2.3. Modelling inputs and assumptions

Towards enhancing the robustness of modelling outputs, to the extent of tracing resulting ranges to the structural and theoretical differences among this heterogeneous group of models, significant efforts were made to streamline and transparently document input variables across models. We use a comprehensive methodology for reducing model response undesired heterogeneity (i.e., heterogeneity that cannot be attributed to model diversity but different assumptions), described by Giarola et al. (2021a), focusing on Europe (EU-27, plus UK, EU hereinafter) (Table 2).[3]

It should be noted that the global models were run at the global level, employing similar harmonisation efforts and policy implementation for all regions of the world, as documented in Giarola et al. (2021a). In contrast to regional modelling runs that consider national specificity, regional technical (resource and storage) potential, and regional directives and effort sharing decisions, the global models consider inter-regional implications. These differences in scope and detail are considered in the following analysis. Furthermore, we do not

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[2] https://www.i2am-paris.eu/.

[3] A detailed harmonisation table can be found in the I^2AM PARIS workspace of this analysis at: https://www.i2am-paris.eu/pr_wwh/harmonisation_table.

Table 2
Modelling assumptions used in the study.

Type of input assumptions	Sources
Historical emissions	We align, or check for consistency, historical emissions across models with the Community Emissions Data System for CO_2, CH_4, and pollutants (Hoesly et al., 2018), the National Oceanic and Atmospheric Administration for fluorinated gases (World Meteorological Organization, 2018), and the PRIMAP dataset for N_2O (Gütschow et al., 2016), while for the four regional models (EU-TIMES, NEMESIS, FORECAST, ALADIN) we harmonise to, or check for consistency against, the annual EU GHG inventory (European Environmental Agency, 2019).
Socioeconomic parameters	We harmonise socioeconomic assumptions, using the EUROPOP database for population (European Commission, 2020c) and the 2018 Ageing Report for GDP per capita (European Commission, 2017).
Technoeconomic parameters	We share and/or check values for consistency in technoeconomic assumptions for representative technologies, based on the European National Energy and Climate Plans (NECP) reports (Mantzos et al., 2017) for power and buildings, on the TIAM database (Napp et al., 2019) and the National Renewable Energy Lab electrification futures study (Jadun et al., 2017) for transport, and on Voldsund et al. (2019) and Gardarsdottir et al. (2019) for CCS-integrated industrial technologies.
Other variables	Depending on the model structure and representation as inputs, we use different sources to harmonise other variables—for example, we harmonise sectoral value added for FORECAST, EU-TIMES, E3ME and ICES based on Eurostat (European Commission, 2020c), fossil fuel prices for FORECAST, EU-TIMES, NEMESIS, ICES, GEMINI-E3 and E3ME based on the 2019 World Energy Outlook “Current Policies” (International Energy Agency, 2019), exchange and interest rates for NEMESIS and E3ME based on the 2018 OECD Economic Outlook (OECD, 2018), etc.
Policies	We use a shared database of current policies in the EU, building on and expanding the CD-Links project database[a]. This database is available in the Supplementary Material. For other region's policies, as implemented in the global models, see Supplementary Material 6 in Giarola et al., 2021a).

[a] https://www.climatepolicydatabase.org/.

compare our resulting trajectories against a counterfactual baseline, as the aim of this exercise is exactly to produce a representative and realistic baseline that reflects current policy efforts and their projection forward. As such, we report our findings in absolute terms rather than in terms of impacts relative to a baseline. Exceptions include comparison against historical data (e.g., 1990 as a reference point for emissions), shares of fuel mixes in a given year, or employment implications against model-specific no-policy baselines that serve as a limited effort to address respective stakeholders' concerns.

3. An inter-comparison study of EU emissions and energy system in 2050

In response to the stakeholders' interest in a targeted and detailed account of ‘where Europe is headed’ given its current policy efforts, the co-designed scenario framework allows projecting EU climate change mitigation-related indicators assuming these efforts are extrapolated into the future based on growth per capita, but not further reinforced. For this purpose, we begin with an analysis of a set of key cross-model common indicators for the EU region: total CO_2 emissions from energy (i.e., fossil fuel combustion), CO_2 emissions from energy by sector, primary energy by fuel and final energy by sector.

3.1. CO_2 emissions from energy

Except for the two sector-specific models, ALADIN and FORECAST, all other models deliver outlooks of total EU CO_2 emissions from energy (Fig. 2a). From 1990 to 2015, annual CO_2 emissions in the EU have decreased from 4.12 to 3.26 Gt, an average decline of 0.9% per year. Since 2005, the more stringent climate regulation via the EU Emission Trading System (EU ETS) (European Parliament and Council, 2003) has resulted in an accelerated decline (2% per year). Between 2020 and 2030, models project on average a slight reinforcement of the CO_2 emissions reduction rate and an absolute reduction compared to 1990 ranging from −33% to −45%. Assuming a range of non-CO_2 emissions between 0.5 and 0.67 $MtCO_{2eq.}$ in 2030 (European Commission, 2019, 2020d), the corresponding CO_2 emissions from energy should be between 2.9 and 2.7 Gt to reach the now-outdated EU target of −40% of GHG emissions reduction in 2030 compared with 1990 (European Council, 2014). Expectedly, all nine models show the EU will reach the former −40% milestone; but, more importantly, almost all models display overperformance, given the current policies in place. With these estimates for non-CO_2 emissions (excluding land-use), GHG emissions reduction in 2030 will range between −39% and −51%, compared to 1990 levels, which is insufficient to comply with the new EU Green Deal objective of a 55% GHG reduction target (European Commission, 2020d). These results on energy CO_2 emissions are in line with existing scenarios in the literature (European Commission, 2016; Mantzos et al., 2019) that range between 2.8 and 2.9 Gt. After 2030, the average annual rate of CO_2 emissions decline is lower, except for GCAM and MUSE, for which the decarbonisation rate is stronger.

The key takeaway here is that median EU CO_2 emissions in 2050 are about 2.1 Gt, with a broad range of about 1.0–2.35 Gt, representing a CO_2 emissions drop of −43% to −76% compared to 1990. This inter-comparison showcases that, of the models capable of projecting until 2050 (i.e., excluding 42), the three global partial equilibrium models (TIAM, MUSE and GCAM) are more optimistic in the longer run (0.97–1.66 $GtCO_2$), compared to the global CGE models and the regional EU models (2.11–2.35 $GtCO_2$). This is mainly due to a higher flexibility in terms of available mitigation options in these models, considering the availability of advanced decarbonisation technologies[4] as well as the larger technical potential of key technologies (e.g., biomass, solar, and wind). By contrast, EU regional models contain more granular assessments about technical potentials of specific technologies (e.g., CO_2 storage, biomass, solar, and wind), market barriers, and specific national policies (e.g., national restrictions to CCS applications), thereby offering a critical ‘reality check’ on global models.

By sector, the reduction of energy CO_2 emissions (Fig. 2b) shows similar patterns across models and time, despite significant variability. Energy supply is the largest contributor of emissions cuts between 2020 and 2050 in almost all models, with GCAM even showcasing negative emissions in 2050. The median CO_2 emissions from EU energy supply declines by 47% between 2020 and 2050. Median decarbonisation rates in industry (42%), buildings (30%) and transport (32%), between 2020 and 2050, are relatively similar but differ significantly across models. It is noteworthy that the two sector-specific models, FORECAST (buildings and industry) and ALADIN (transport) show significant emissions cuts in their sectors, compared to other models. For example, CO_2 emissions from the built environment decline by 45% in FORECAST but remain relatively stable in GEMINI-E3. Similarly, mid-century transport decarbonisation reaches 80% in comparison with 2020 levels in ALADIN but remains moderate (below 35%) in many other models. Finally, industrial CO_2 emissions display the largest variability, a large reduction of above 40% in FORECAST, GCAM, NEMESIS and TIAM, even reaching zero emissions in MUSE, and again moderate decarbonisation in GEMINI-E3.

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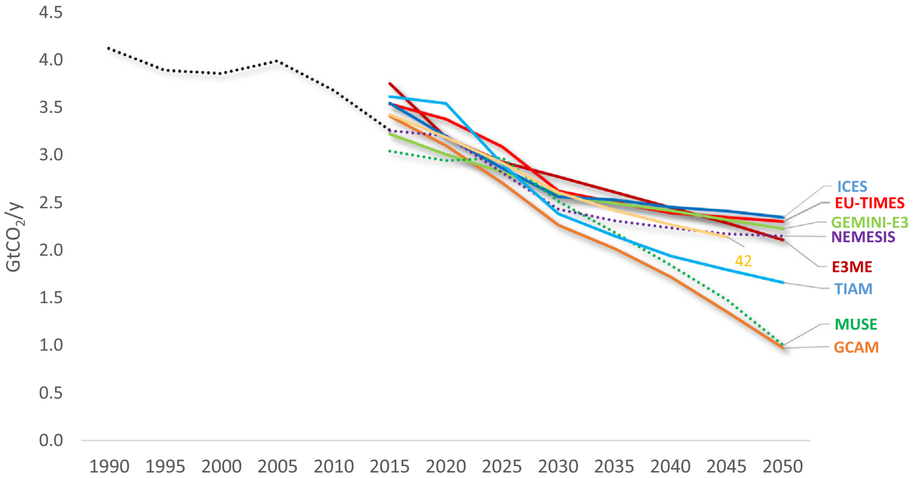
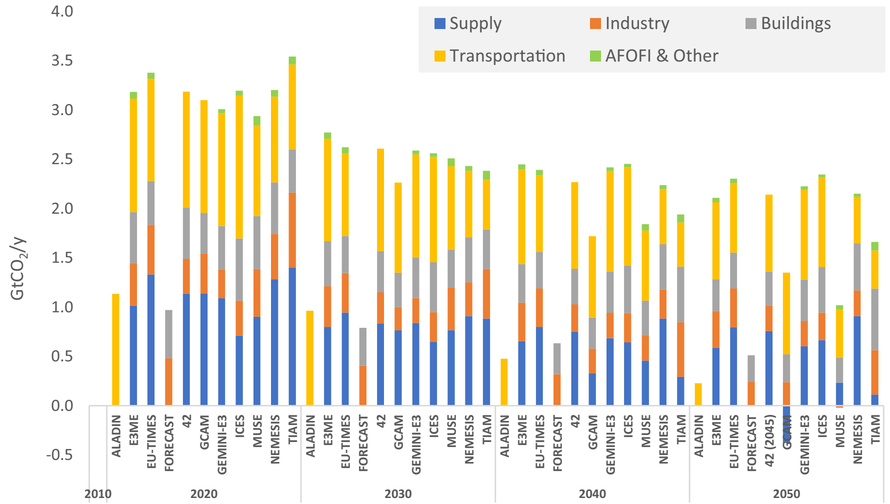
[4] CCS in power generation and industry, hydrogen, direct air capture, etc., see also Sections 4.1.1 & 4.2.2.



(a) Trajectory of total energy CO₂ emissions



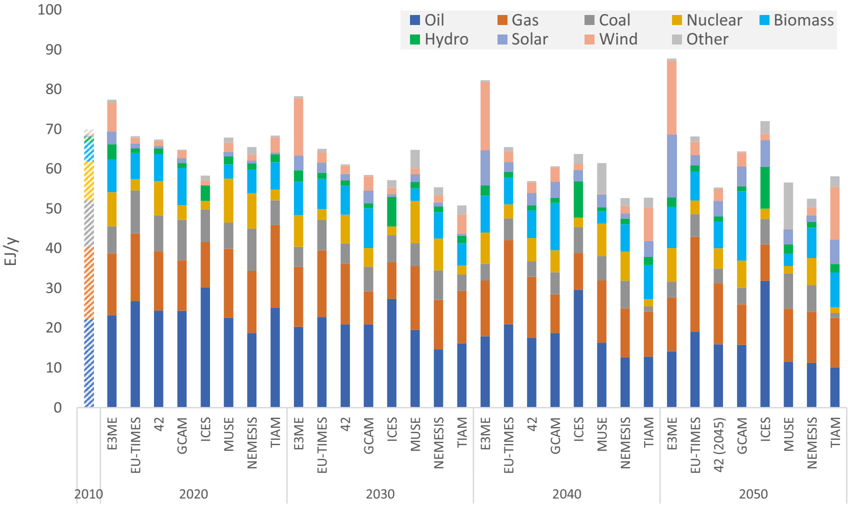
(b) Energy CO₂ emissions by sector in 2020, 2030, 2040 and 2050

Fig. 2. CO$_2$ emissions from energy in the EU across models, (a) total values until 2050—black dotted line: historical data from European Environmental Agency (2020); (b) by sector in 2010 (historical values), 2020, 2030, 2040, and 2050. "AFOFI & Other" includes emissions from fossil fuels combustion in the agriculture, fisheries and forestry, as well as other emissions not allocated, fuel fugitive emissions are accounted in 'supply'. Despite harmonisation, allocation by sector can slightly differ according to models due to different sector granularity. For the 42 model, 2045 values are displayed instead of 2050.

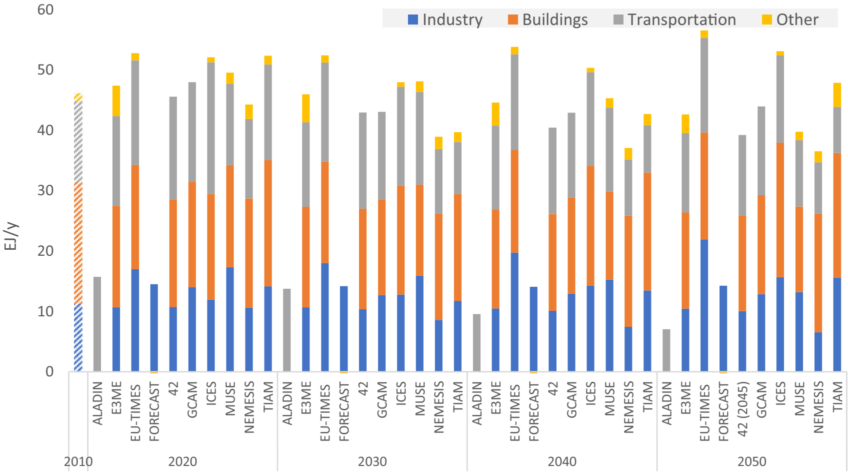
3.2. Primary and final energy

From an energy perspective, eight models detail EU primary energy by fuel (Fig. 3a). The 2020–2050 evolution of total primary energy consumption differs among models. Global macroeconomic models show an increase (13%–24%); EU-TIMES and GCAM project relative stability whereas 42, MUSE, NEMESIS, and TIAM show a decline instead. The median value of all models for EU primary energy in 2020 is 67.7 EJ/y—i.e., a moderate reduction compared to 2010 (70 EJ/y). It then continues to decline until 2030 (59.9 EJ/y), before slightly growing to remain relatively stable onwards (61.3 EJ/y in 2050). These numbers are in line with existing projections of primary consumption (European Commission, 2016; Mantzos et al., 2019) that are around 60 in 2030 and 54–58 EJ/y in 2050. Despite this variance on the projections of future EU energy efficiency, all models foresee decarbonisation of the EU energy system, with a median CO$_2$ emissions intensity declining from 48.3 kgCO$_2$/GJ in 2020 to 30.5 kgCO$_2$/GJ in 2050. This drop ranges across models, from −16% to −68%, with technology-rich models showing steeper decarbonisation compared to macroeconomic (CGE and macroeconometric) models. Only TIAM from the entire ensemble reaches the EU 2030 energy efficiency target of at least 32.5% cuts (translated into 53.3 EJ/y in primary energy consumption), followed by NEMESIS coming relatively close to the target. This highlights that, for most models, the 2030 EU efficiency target requires further efforts and, to some extent, is more constraining than the respective GHG emissions reduction target (Aune and Golombek, 2021).

Projections of primary energy consumption by fuel show similar behaviour as far as the evolution of the shares of fossil fuels and renewable energy sources (RES) in the EU primary energy mix is concerned. The former declines in all models, from 59 to 86% in 2020 to 36–71% in 2050. As the EU is a net importer of fossil fuels (especially so for oil and gas), these results hint at higher energy security in the future, despite the modelled policy strength falling significantly short of meeting the EU's net-zero emissions 2050 goal. Among the models, this decline of fossil fuel consumption takes different forms. This stands also among energy models: in EU-TIMES, part of the decline of oil and coal consumption is balanced by an increase in gas consumption, of which about 9% is used in carbon capture and storage (CCS) plants by 2050; in 42, on the other hand, gas consumption remains relatively stable between 2020 and 2045 whereas coal and oil consumption displays strong reductions; while MUSE projects a significant reduction of oil and gas but shows an increase in coal. In TIAM, coal consumption displays bolder cuts by 2050 (−81%). The share of RES (biomass, hydro, solar and wind energy) grows moderately in all models, with an EU median



(a) Primary energy consumption by fuel



(b) EU final energy consumption by sector

Fig. 3. The EU energy system in 2010 (historical values calculated by authors based on Eurostat, 2021), 2020, 2030, 2040 and 2050: (a) primary energy consumption by fuel ('other' may include municipal/industrial solid waste, etc.); and (b) final energy consumption by sector. Despite harmonisation, allocation by fuel/sector can slightly differ according to models due to different fuel/sector granularity. For the 42 model, 2045 values are displayed instead of 2050.

of 15% in 2020 growing to 27% in 2050. Looking at median values, solar and wind consumption show significant growth in the same period—400% and 84%, respectively. Median values for hydro power consumption remain relatively constant, although projections among models vary: E3ME projects a decline, whereas others (EU-TIMES, MUSE, and particularly ICES) project a significative increase. Biomass consumption grows moderately in four models (E3ME, EU-TIMES, NEMESIS, and TIAM), and significantly in GCAM (almost doubling), but remains constant in 42 and drops in MUSE. Finally, models show a relatively stable nuclear share in the EU fuel mix with negligible changes overall. This technology and fuel share analysis highlights how, even with closely harmonised technoeconomic assumptions, there remains considerable inter-model diversity of results. While a full understanding of these differences is outside the scope of this study, it demonstrates that not just technoeconomic details, but others such as substitutability between technologies, technology availability and sectoral granularity all need fuller inter-comparison. In the meantime, the model diversity serves as a useful tool in exploring a significant share of the future possibility space.

From 2020 to 2030, the eight models overall project a reduction of total final energy consumption (by 1–24%) (Fig. 3b). Nevertheless, by 2050, total final energy varies significantly in terms of model behaviour, as well as within classes (except for macroeconometric models that consistently project reduction). It either declines boldly (E3ME, 42, MUSE and NEMESIS; as well as ALADIN for transport only) or showcases initial drops followed by rebounds, which are either late and moderate (EU-TIMES and GCAM) or early and significant (ICES and TIAM). In 2020, models' median values have grown since 2010, from 46.2 to 48 EJ/y. Thereafter, the median value of EU final energy consumption declines up to 2030 (44.5 EJ/y), before stabilising until 2050. Breaking it down by sector, the median final energy consumption of EU industry is slightly lower in 2050 than in 2020. EU-TIMES, ICES and TIAM project increasing final energy in industry, while MUSE and NEMESIS expect a reduction. In the building sector, only ICES and NEMESIS project a growing final energy consumption in 2050: the median value is 17.5 EJ/y in 2020 (down 13% from 2010), then slightly declines in 2030 and remains relatively stable thereafter. For transportation, all models show a reduction in energy consumption by 2050, down by almost a half in ALADIN and TIAM; a third in NEMESIS and ICES; a quarter in 42; and less so in E3ME, EU-TIMES, GCAM and MUSE.

Despite important heterogeneity among models, this analysis of cross-model common denominator indicators shows many similar behaviours for the EU region. The modelling ensemble overall shows significant CO_2 emissions reductions in 2030, overperforming the EU's pre-2020 -40% GHG emissions reduction target but insufficient to meet the new EU Green Deal target (−55%). The energy supply sector is consistently the top contributor to decarbonisation by 2050. Furthermore, the share of fossil fuels in the EU energy mix is robustly—yet with different implications for other technologies across models—projected to significantly drop by 2050, in contrast to renewables and in particular solar and wind energy growing, quintupling and doubling by 2050 respectively.

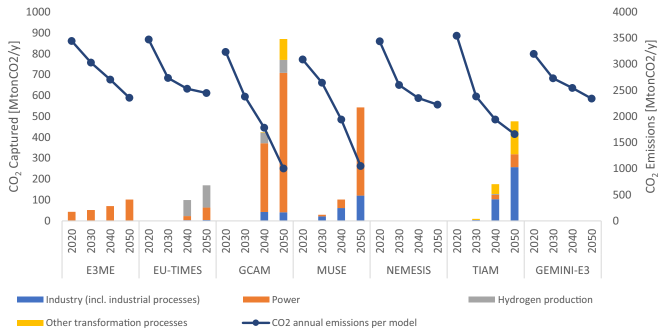
4. A multi-model approach to addressing stakeholders' questions

In this section, we delve into each of the research questions co-designed with stakeholders (Table 1), after grouping their concerns and topics of interest, in multi-model settings, depending on the capabilities of the employed models.

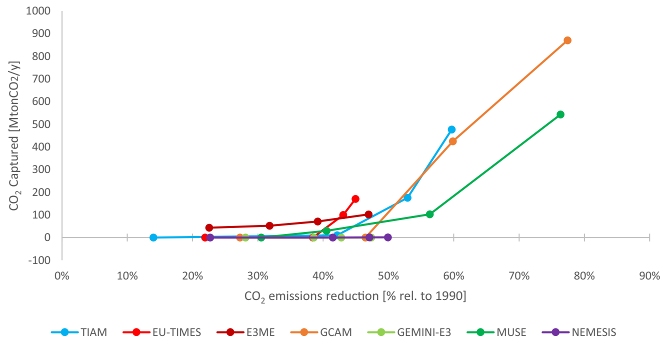
4.1. Potential failure of key technologies

4.1.1. The role of CCS as a game changer

CCS is considered a possible option for abating CO_2 emissions, particularly from power generation as well as other hard-to-decarbonise sectors, like heavy industries and energy transformation. However, barriers still exist and hinder large-scale development of these technologies, which are not yet at market deployment stage due to various technical and non-technical reasons (Budinis et al., 2018). The role of this possible game-changing technology is explored in seven of the employed models: E3ME, EU-TIMES, GCAM, GEMINI-E3, MUSE, NEMESIS, and TIAM. Apart from GEMINI-E3 and NEMESIS (partly reflecting limited decarbonisation resulting from current policy efforts, and for GEMINI-E3 also less detailed representation of the technology in power generation), even in this scenario representing a moderate increase in climate policy strength in line with economic growth, all models foresee an active role of the technology, mainly post-2040, although to different extents (Fig. 4a). E3ME and EU-TIMES show a lower rate of CCS penetration in electricity generation, reaching a capture rate of 102 and 170 $MtCO_2$/y in 2050, respectively, while the global, technology-rich models TIAM, GCAM and MUSE deliver high capture rates, on average 630 $MtCO_2$/y by 2050. As discussed in Section 3, these three models show deeper emissions cuts, and this is largely attributed to their technological richness, the relatively larger potential of low-carbon technologies, model capabilities, and as shown here the flexibility for CCS to penetrate the electricity mix and be deployed in other sectors (mainly industry). Except for EU-TIMES, according to which bioenergy with CCS (BECCS) penetrates only from 2050 (contributing to 12% of captured CO_2), in global models (TIAM, GCAM, and E3ME) BECCS penetrate at earlier stages. On average, contribution of BECCS in these models represents approximately 50% of captured CO_2 in 2030 and 56% in 2050.



(a) CCS-captured CO_2 by sector vs. CO_2 emitted



(b) CCS-captured CO_2 - CO_2 reduction levels ratio

Fig. 4. CO_2 captured by CCS (a) by sector (left-hand axis) vs. total CO_2 emitted (right-hand axis), and (b) against CO_2 reduction levels (since 1990, based on European Environmental Agency, 2019).

Comparing results in absolute terms hints that the way in which the different models foresee emissions reductions when extrapolating the current policy framework using the carbon price equivalent also influence the absolute deployment of CCS plants: expectedly, higher CCS deployment allows bolder decarbonisation of the system. Combining CO_2 capture rates with CO_2 emissions cuts compared to 1990 (Fig. 4b) also allows to compare CCS adoption rates with climate policy ambition, illustrating at what point of currently mobilised decarbonisation this technology is required to further progress, thereby possibly hinting limitations of mitigation in Europe without its at-scale deployment. Regardless of the number of CCS plants available, in E3ME, the technology comes into play already from low decarbonisation levels, with a growing yet limited contribution, contrary to all other models: EU-TIMES suggests a later, steep increase but with a high penetration rate onwards considering the limited decarbonisation foreseen in the model; in the global, technology-rich models (GCAM, TIAM and MUSE), CCS is a critical factor and game-changing enabler of the deep decarbonisation foreseen, but it becomes so only upon hitting high decarbonisation levels (40–60%). Results from these models are in line with scenarios underpinning recent policy targets (Tsiropoulos et al., 2020), despite the latter looking into more ambitious action (80% cuts to net zero in 2050).

Our results justify stakeholders' concerns over the potential failure of CCS as a game changer in the EU energy system. We see that, without setting in motion actions to deliver on the EU's increased climate ambitions, as reflected in its December 2020 NDC and broader mid-century vision for climate neutrality, CCS deployment is critical to achieving deep emissions cuts and eventually nearing climate targets (Bui et al., 2018; Korkmaz et al., 2020). The technology's at-scale deployment has long been considered critical, yet dependent on broader policy efforts (Dalla Longa et al., 2020), enabling factors in infrastructure and capital/fuel markets (Odenberger and Johnsson, 2010), and the interplay with the evolution of other low-carbon technologies (Simoes et al., 2017). There exist other critical social/socioeconomic factors weighing in the success of an impactful CCS strategy in the EU, some of which cannot be integrated in typical integrated assessment modelling frameworks: social acceptance of such plants at the local level, for example, is deemed critical for the technology's successful deployment in Europe (d'Amore et al., 2020). Our results should be interpreted alongside the adopted scenario framework; different policy efforts may completely change the role of CCS even in the longer run (e.g., Vrontisi et al., 2020).

4.1.2. Security of supply across the EU: the role of import dependency

Besides decarbonisation dimensions, energy security is also an area of interest for stakeholders on moving towards a sustainable energy transition. Here, we look at energy security and import dependency for a European energy system that changes in line with current policy efforts projected in the longer term. Currently the EU is a net importer of fossil fuels and expected to rely much more on gas and less on coal and oil in the future (European Commission, 2020a). Some Member States have acknowledged the importance of improving energy

Table 3
EU system import dependency (%imports/PEC).

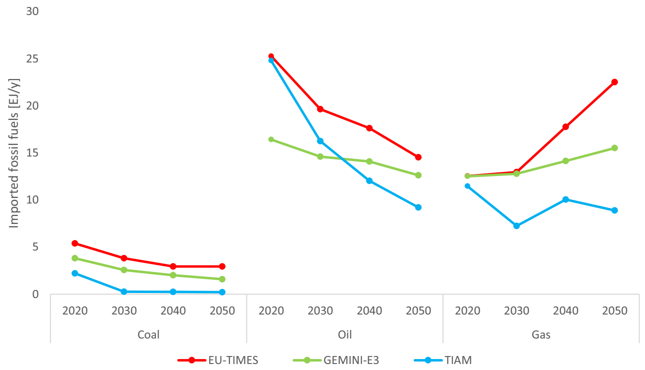
	EU-TIMES	GEMINI-E3	TIAM
2020	−62.5%	−58.6%	−56.2%
2030	−58%	−59%	−47%
2040	−60%	−59%	−42%
2050	−61.9%	−59.2%	−31.5%

efficiency—thus reduction of gross inland consumption—and increase of domestic renewables to reduce reliance on fossil fuel imports. However, it is also important to have specific policies to guarantee security of supply, by diversifying fossil supply routes, and avoiding a simple switch from the import of fossil fuel to another (e.g., Nikas et al., 2020b; Antosiewicz et al., 2020).

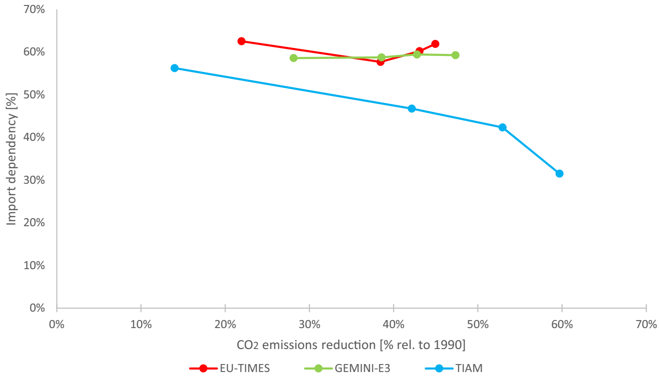
Some energy security-related insights can be analysed comparing results from global models GEMINI-E3 and TIAM, and the regional EU-TIMES model. Total import dependency (estimated as the ratio of imported energy sources to total primary energy) is projected steady until the middle of the century in EU-TIMES (62%) and GEMINI-E3 (59%), while in TIAM it decreases to slightly above 30% (Table 3).

The decarbonisation achieved in 2050, under current policy scenarios, is accompanied by a stable projected primary energy in EU-TIMES compared to 2020. Despite growing energy service demands in the next decades, energy efficiency is expected to contribute to decoupling GDP (increasing by ~50%) from energy consumption. This effect is even more pronounced in the TIAM and GEMINI-E3 models, where primary energy is projected to decrease by ~15% compared to 2020 values. Furthermore, in all models, use of fossil fuels decreases, though to different extents. Comparing different resources, all models agree that oil and coal imports will decrease between 2020 and 2050, while natural gas outlooks differ across models and levels of ambition. Gas imports increase with an average rate of 0.7–2%/y (EU-TIMES and GEMINI-E3 respectively), while in TIAM it tends to reduce in the long run (−0.8%/y) but retains some important role in the transition (Fig. 5a). In contrast to declining fossil fuel dependence, biomass use increases moderately in EU-TIMES (0.34%/y) and TIAM (0.6%/y)— it is unavailable in GEMINI-E3. Biomass imports are available in EU-TIMES, yet negligible (~2.4% of biomass primary energy in 2050).

Comparing total import dependency with the decarbonisation achieved allows assessing how energy source imports may be affected by mitigation efforts. Fig. 5b shows that, in the global partial equilibrium models, import dependency decreases in time, in line with decarbonisation efforts, thereby attesting to future low-carbon energy systems relying less and less on imports, substituted primarily by energy savings and domestic energy resources. It is noteworthy that costs of fossil fuels in other regions are calculated endogenously in global models, but exogenously in the regional model.



(a) Fossil fuel imports



(b) Imported fuels and CO_2 reduction levels

Fig. 5. Fossil fuel imports under current policy efforts: (a) imported fuels until 2050; and (b) import dependency in relation to CO_2 emissions reduction levels (since 1990, based on European Environmental Agency, 2019).

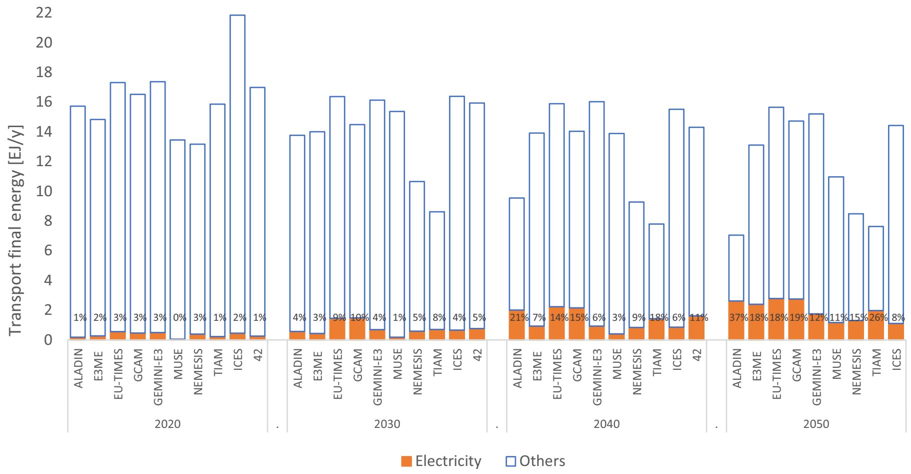
4.2. Electrification and hydrogen

4.2.1. The role of electrification in transportation

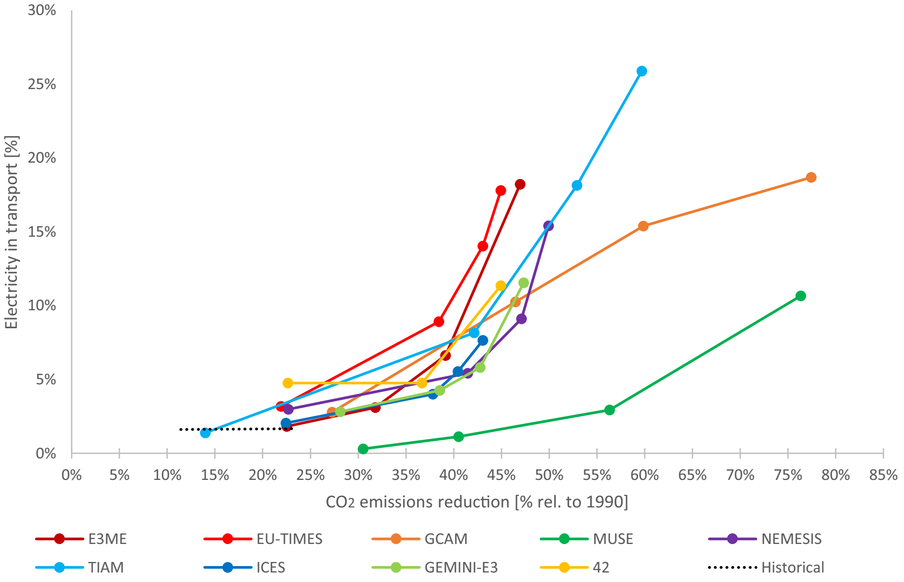
Globally, the transport sector is in a critical transition (Koasidis et al., 2020a). Despite efficiency improvements, electrification and greater use of biofuels, global transport emissions have been increasing, making up a quarter of direct CO_2 emissions from fuel combustion, with road transport remaining the largest source (International Energy Agency, 2020b). In the EU, although transport emissions have stabilised after steady growth until 2007 (European Environmental Agency, 2019), they still make up 29.6% of total direct CO_2 emissions from fuel combustion. Electric vehicles (EVs) are considered a valuable option to reduce direct emissions and energy intensity of road mode, and their deployment is steeply growing (International Energy Agency, 2020a). Here, drawing from stakeholders' concerns, we explore the extent to which electrification plays a role in the future EU total transport sector, comparing scenario results from the entire modelling ensemble, except FORECAST. All ten models foresee a growth of electricity penetration in transport (Fig. 6a). In 2030, the share of electricity in transport total final energy ranges in 1–10%, rising to 7–37% in 2050. In absolute terms, electricity consumption is foreseen to grow in the sector with an annual rate of 3–12%/y between 2020 and 2050. Fig. 6b further underpins a relation between transport electrification and energy system decarbonisation. The EU-TIMES, E3ME, NEMESIS, 42, GEMINI-E3, TIAM and ICES models showcase a steeper increase of electrification with decarbonisation, while GCAM and MUSE show a slightly lower slope. Moreover, ALADIN (excluded from the figure, being a sectoral model) suggests that electricity dominates the sector when sectoral CO_2 emissions drop by at least 39% compared to 1990.

4.2.2. The future of hydrogen in the EU, given its current policy efforts

Most hydrogen is currently used in oil refining and chemical production, produced with fossil fuel processes, namely grey/brown hydrogen. In a low-carbon future, hydrogen is generally expected to grow, becoming a leading energy vector to sustain decarbonisation of hard-to-electrify demand sectors, like heavy-duty transportation, navigation, aviation, and energy-intensive industries (Koasidis et al., 2020b), or used for energy storage (European Commission, 2020b) sustaining the uptake of large RES shares in the power sector. The deployment of sustainable hydrogen using fossil fuels with CCS or renewable electricity, namely blue or green hydrogen respectively, is strictly related to innovations in technologies like CCS, energy storage, electrolysers, fuels cells, etc.



(a) Electricity in EU transport final energy consumption



(b) Transport electrification vs. CO_2 emissions cuts

Fig. 6. EU transport sector electrification: (a) in final energy consumption in 2020, 2030, 2040 and 2050; and (b) in relation to CO_2 emissions reduction levels (since 1990, based on European Environmental Agency, 2019).

Here, we use modelling results to address this research question coming from stakeholders and investigate what role, in a context of current policy efforts being projected in the future, is foreseen for hydrogen, its production pathways and performance against electricity. The hydrogen chain is included in five models[5]: GCAM, TIAM, and EU-TIMES, in which an explicit representation of both supply (hydrogen production and transformation) and demand side is available; and the ALADIN and FORECAST sectoral models, where only demand sectors are represented. Concerning hydrogen supply, EU-TIMES, GCAM and TIAM (Fig. 7a) foresee increasing amounts of hydrogen production from 2030 onwards, yet still marginal compared to electricity: in 2050, hydrogen production is on average 94% lower than electricity. However, results hint a transition in hydrogen production: while most hydrogen is expected to be grey in 2030, by 2050 the models show conversion to blue hydrogen, underpinning the increase of natural gas in the energy system, and to a lesser extent to green. These findings indicate that current policies are not enough to drive a complete change from grey towards green hydrogen in EU by 2050, also highlighting the role of natural gas as more than a transition fuel in two of these models (see Section 4.1.2).

Focusing on demand, in the industry sector (Fig. 7b), the share of hydrogen grows moderately in the models, delivering on average 1% of total sector consumption in 2030 and 3.5% in 2050, remaining negligible against electricity. In transport, only TIAM shows important hydrogen deployment, delivering 7% of total consumption in 2030 and 17% in 2050. In all other models, hydrogen remains a niche technology achieving in 2050 an average of 0.7% of consumption. Despite differences among modelling results, in a scenario projecting current policy efforts into the future, electricity is foreseen to significantly outperform hydrogen, which will have limited applications mainly in industry. Comparing the penetration of electricity and hydrogen with delivered decarbonisation (Fig. 7c) shows that hydrogen comes into play with higher level of decarbonisation compared to electricity: higher than 38% (relative to 1990 levels) in EU-TIMES, 42% for TIAM and 47% for GCAM. The two sectoral models confirm this finding: ALADIN quantifies a 39% emissions reduction in transport before seeing any hydrogen emerging, and FORECAST foresees hydrogen penetrating in industry when a minimum level of 30% emissions cuts is achieved.

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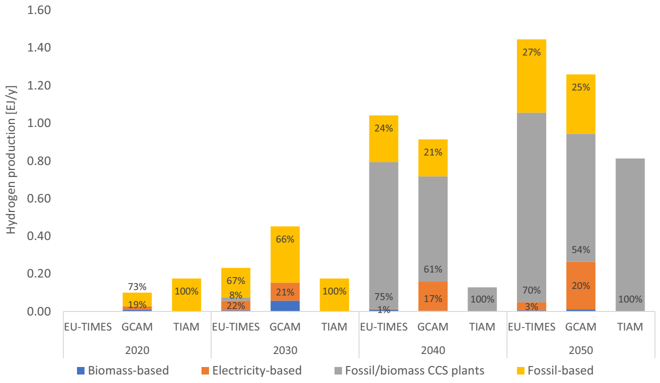
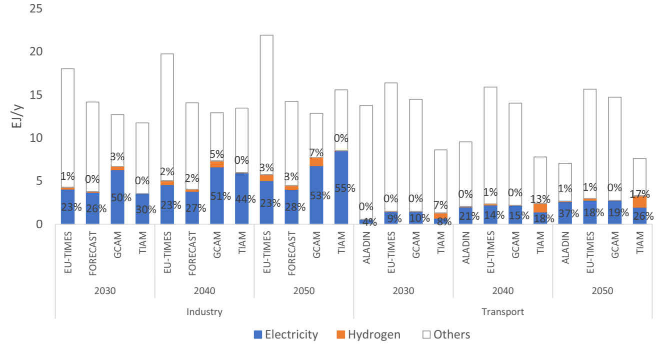
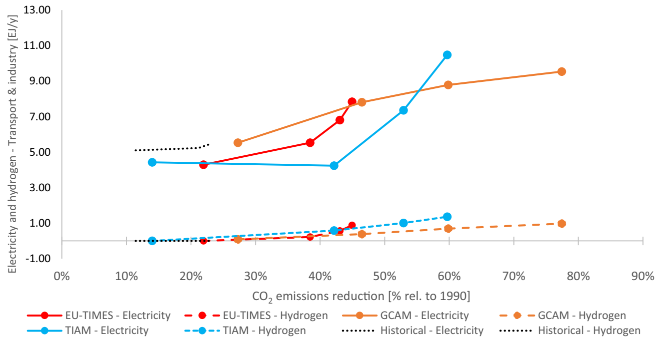
[5] MUSE also covers the hydrogen chain, but it eventually did not play role in the results to report it.



(a) Hydrogen production by fuel



(b) Electricity & hydrogen final demand



(c) Electricity & hydrogen use vs. CO_2 emissions cuts

Fig. 7. Projected hydrogen production in the EU (a) by fuel in final demand; as well as compared to electricity (b) in final transport and industry demand and (c) in relation to CO_2 emissions reduction levels (since 1990, based on European Environmental Agency, 2019).

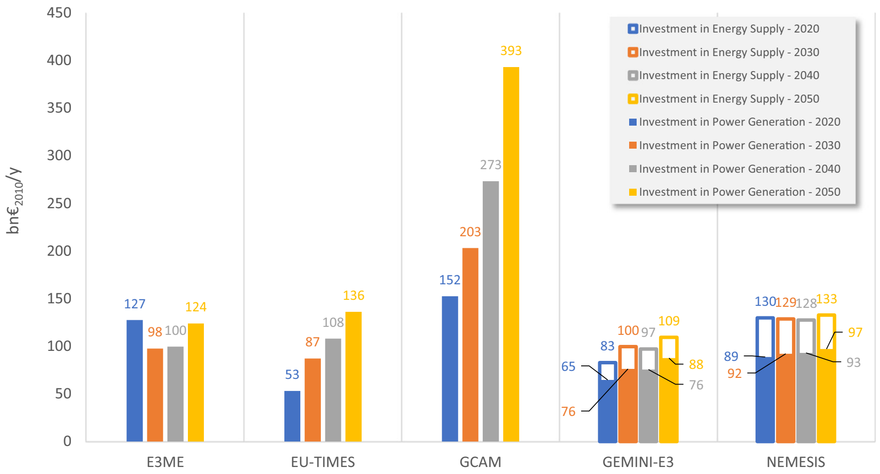
4.3. Costs, gains, investments, and employment

Common practice in the literature suggests that the socioeconomic impact of climate action in a region be analysed by comparing against a counterfactual or ‘reference’ scenario (for Europe, e.g., Vielle, 2020; Vrontisi et al., 2020). The scenario framework adopted in this study, however, in response to criticisms in the literature over the absence of meaningful such trajectories (Hausfather and Peters, 2020; Grant et al., 2020), aims to develop—and focuses explicitly on—such a reference baseline scenario. This means that no counterfactual scenario has been designed, employed, and compared against for the purposes of this modelling exercise. Nevertheless, a limited effort is made in this section to touch upon this concern raised by the stakeholders, based on the macroeconomic models of the employed ensemble: these can deliver information on the policy costs of the scenarios modelled, referring to their own no-policy counterfactual trajectories, which are therefore not harmonised across the models. Among these, the two global CGE models (GEMINI-E3 and ICES) show negative GDP impacts of current policy efforts, relative to their no policy counterfactuals, when these are extrapolated into the future. The two macroeconometric models, on the other hand, display different behaviour: NEMESIS shows negligible GDP impacts, while E3ME projects positive impacts on GDP, which however do not consider potential reductions of climate change damages. Among the many theoretical differences between the two modelling approaches (Robinson, 2006), this gap can be attributed to the way capital markets are modelled (Pollitt and Mercure, 2018): in general equilibrium models, interest rates balance the resources used for investments and the savings, implying an important ‘crowding-out’ or eviction effect of mitigation-related investments against other investments; in macroeconometric models, on the other hand, this eviction effect is moderate because there is monetary creation. Furthermore, between the two macroeconometric models used here, NEMESIS is an EU model while E3ME is a global model, meaning that the latter considers current policy efforts across the globe and therefore inter-regional impacts—i.e., the implications of non-EU climate action on the EU economy.

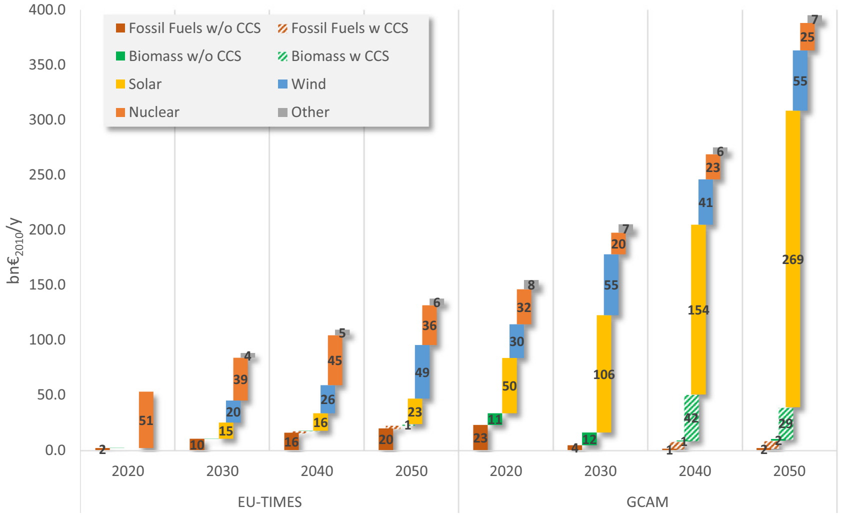
Similarly, in terms of employment, in the absence of a harmonised counterfactual scenario across models, we can only discuss certain insights of the current EU policies' impact on employment relative to a no-policy counterfactual, of which only the macroeconometric models allow a qualitative analysis, given their disaggregation level in the labour market (Nikas et al., 2019). The two models show relatively similar results, with positive impact of a long-term projection of current policy efforts on total employment. Both showcase positive employment impacts on manufacturing and negative on the energy sector, but E3ME projects negligible implications for energy-intensive industries, contrary to the negative impacts in NEMESIS. The global E3ME model also forecasts new jobs created in the services sector but employment losses in agriculture, with NEMESIS showing negligible and positive impacts, respectively. Again, these impacts are stated relative to a no-policy counterfactual, which itself does not consider any negative jobs implications from climate change damages.

Apart from this qualitative analysis, we extract some quantitative indicators across models providing insights into the economic impacts of current EU climate policies, namely in terms of energy investments (Fig. 8a). Only two models calculate annual investments in the broader energy supply sector, showcasing either a relative stability over time (NEMESIS) or a moderate increase (GEMINI-E3). Three more models complement them in terms of investments in power generation (E3ME, EU-TIMES, and GCAM). Here, again, we can see differences in terms of evolution or absolute values, depending on the model perspective. Despite differences in the levels of investments overall, top-down macroeconomic models show moderate changes between 2020 and 2050: a slight increase in NEMESIS, from 89 to 97 bn€$_{2010}$/y, and a sharper one in GEMINI-E3, from 65 to 88 bn€$_{2010}$/y; and a near-term decline in the next decade in E3ME, from 127 to 98 bn€$_{2010}$/y, before a rebound to 124 bn€$_{2010}$/y in 2050. On the other hand, the technology-richer models project an acceleration of European investments in the power sector from 2020 to 2050: both EU-TIMES and GCAM showcase a 2.5-fold increase, with the former calculating an investment of ~136 bn€$_{2010}$/y in 2050 and the latter an impressive 400 bn €$_{2010}$/y for the same year, reflecting the stronger decarbonisation of the energy sector (see Section 3). Except for GCAM, these values are relatively coherent with Zhou et al. (2019) and slightly higher than Capros et al. (2018).

The two technologically detailed models also capture the investment requirements by power generation technology (Fig. 8b). In accordance with fuel evolution (see Section 3), RES-related investments dominate the mix, followed by nuclear. Solar power generation in GCAM represents one-third of overall investments in electricity in 2020 and two-thirds in 2050 (from 50 to 270 bn€$_{2010}$/y). In EU-TIMES, wind investments reach 50 bn€$_{2010}$/y in 2050, corresponding to one-



(a) Investments in energy supply and power generation



(b) Investment in electricity by power generation technology

Fig. 8. Investments (a) in energy supply and power generation by model, (b) disaggregated by technology in EU-TIMES and GCAM.

third of the investment mix. Nuclear investments are also high in both models, with up to 36 bn€$_{2010}$/y in 2050. Finally, investments in CCS-integrated power are relatively moderate in EU-TIMES (4 bn€$_{2010}$/y in 2050) but significant in GCAM (48 and 36 bn€$_{2010}$/y in 2040 and 2050, respectively), hinting the importance of CCS deployment in the decarbonisation of the electricity sector (see Section 4.1.1).

5. Conclusions

In the literature, the climate policy scenario space is crowded and yet very little of that space traces back to what stakeholders are ultimately concerned about. This study drew from this gap and documented a stakeholder-driven model inter-comparison exercise, both the scenario logic behind and the research questions of which were informed by stakeholders' concerns. The resulting framework indicated another knowledge gap: most multi-model studies tend to explore ‘backcasting’ mitigation pathways and to assess them against under-elaborated or unrealistic no-policy or business-as-usual baselines. Our exercise, therefore, sought to bridge this gap by outputting a realistic reference of where the EU is headed, assuming policy ambition stagnation by extrapolating its current efforts into the long term. Where relevant, we tried to compare our results with findings in the literature. To the extent possible, we explained the ranges of results tracing them back to specific model characteristics/levels of detail.

Among key findings in response to stakeholders' questions, we found that the EU is currently on track to overperforming its previous target of 40% emissions cuts, although clearly requires further efforts for its 2030 energy efficiency target, and is still far from its newest ambition of 55% emissions cuts by 2030. It is also looking at a 1.0–2.35 $GtCO_2$ emissions range in 2050, which can be broken down to 2.1–2.35 $GtCO_2$ produced by EU-regional and global macroeconomic models, and 1.0–1.65 $GtCO_2$ coming from global bottom-up models, mainly tracing back to modelling theories, detail of representation of regional potentials, and confidence in key technologies. For example, we consistently found that the level of CCS deployment appears intertwined with deeper emissions cuts, in the current policy context; within individual models, the same can be said about transport electrification, which seems important for maximising emissions reduction by 2050. CCS also seems to play a pivotal role in hydrogen diffusion (with most hydrogen produced post-2040 being blue, coming from CCS-integrated sources), which is nonetheless significantly outperformed by electrification.

The novelty of the employed approach, in which stakeholders' concerns and questions informed the scenario framework and scope of the exercise, is reflected in that it allowed numerous modelling teams to extract information that is relevant to what troubles decision makers and other climate stakeholders and that is not typically highlighted in scientific articles aimed at supporting or underpinning energy and climate policy. It therefore helped assess and better understand topics that are of concern to the engaged stakeholders, such as the role of key technologies, economic growth, employment, etc., instead of anchoring to details of emissions and energy mixes that are typically highlighted in traditional modelling exercises. Even in terms of questions that have been explored in recent literature, our stakeholder-driven setting allowed us to make progress towards openness of and inclusiveness in the scientific process. It is broadly acknowledged that further work is needed in the climate-economy modelling literature to emphasise principles of open (Pfenninger et al., 2018; Morrison, 2018) as well as comprehensive and comprehensible science (Nikas et al., 2021), towards legitimising and building trust in the modelling tools and their results. At the same time, the employed approach also allowed to define and adopt a scenario logic that is heavily underrepresented in the literature: while studies exploring ambition and mitigation efforts in backcasting settings tend to focus more on the resulting mitigation trajectories than on their ‘reference’ scenarios against which these are assessed, this research instead delved into and analysed in more detail such a reference baseline per se. In essence, the employed scenario logic attempted to serve the stakeholders' need for more realistic reference scenarios describing the current situation, which will allow to better appreciate what must be done.

And this scenario logic would not have been designed without stakeholders expressing their limited understanding of what ‘we are currently looking at’ before grasping ‘what we need to do’ against that.

There are, however, important caveats concerning this research. It must be stressed that the resulting ‘representative baseline’ scenario produced in this study only reflects the currently implemented policies. For the EU regional models as well as the EU region in the global models, this encompasses an up-to-date representation of the policies comprising the “2030 climate and energy framework”, including sector-specific policies. As reflected in the Supplementary Material, this includes the ETS, the Effort Sharing Regulation (ESR), the Road Vehicle Emission Performance Standards for Cars and Vans, the LULUCF Regulation, the Energy Efficiency Directive (EED) and the Renewable Energy Directive (RED II). But it does not orient on its previous (−40%) or new (−55%) 2030 pledges. In other words, the motivation driving this research has been to capture where the EU is headed given its overall policies currently in place, not what its current ambition is (as reflected in its NDC) nor where it wants to eventually go (i.e., a 1.5 °C-compliant pathway), and this is how our results should be interpreted. This also means that, although this is not a backcasting exercise, it comes as little surprise that our model inter-comparison confirms that a continuation of currently implemented policies to 2030 is found to meet the previous pledge of −40% emissions cuts by the end of the decade. Nevertheless, it also showcases that, aside from overperforming this target, meeting the newly agreed, more ambitious target of −55% emissions cuts by 2030 will require a drastic upgrade of the measures, in which this overarching goal must be broken down; it also makes a comprehensive effort to define the emissions gap that must be bridged.

Moreover, from a methodological point of view, the study seeks to establish a novel multi-model analysis framework, in which research has been designed with, rather than carried out for, stakeholders. Although our research process has included thorough and meaningful information of, consultation with, and engagement of stakeholders, there are more challenging steps to claiming a shift from participation to co-production of knowledge and policy (Galende-Sánchez and Sorman, 2021). For example, this entails standardising a co-creative scenario process, in which the scenario framework can be directly co-produced with stakeholders rather than developed based on a posteriori interpretation of their concerns in a closed scientific process, as well as looping results back to the individuals engaged to assess the extent, to which the protocol and results provided are novel, useful, aligned with their expectations, and practical in terms of transforming into action. This represents a call for research efforts towards a truly co-creative scientific process, one that engages with stakeholders in the beginning of the research design but interacts with different bodies of knowledge and non-scientific actors throughout, towards achieving transdisciplinarity (Nikas et al., 2020a).

Then, from an empirical point of view, there is always room to improve efforts for harmonising inputs and reducing model response heterogeneity that traces back to input variance. More importantly, our novel framework did not manage to explore all prioritised topics and to address all communicated concerns. For example, although there have been research perspectives of incorporating hard-to-model questions on behavioural and lifestyle change (Trutnevyte et al., 2019), in line with a stakeholder-driven and inclusive approach (Nikas et al., 2020a), these were clearly not addressed in the proposed modelling framework. Furthermore, some aspects like extreme decarbonisation and increased ambition did not fit into a scenario exploring where we are headed given current policy efforts projected into the future and aiming to design a realistic reference scenario for future studies. Other topics, like possible failure of CCS, could only partially be addressed in this scenario: although our study showed that failure of key technologies could bring us to a more static representation of the energy-economy system, as described by macroeconomic models, running the models with technological constraints to sufficiently and explicitly respond to this question remained outside the main scope of assessing implications of current policy projection. Similar limitations concern stakeholders' questions on the decline of carbon-intensive sectors or the need for a comprehensive assessment of distributional and employment impacts. These limitations act as an urgent call for research based on better suited toolsets and frameworks, as well as other modes of engagement with non-scientific actors.

CRediT authorship contribution statement

A.N. and H.D. coordinated the stakeholder-inclusive protocol, with contributions from all authors; B.M., A.N., and G.Z. coordinated the organization of the workshop. B.B., G.C., A.C., A.E., K.K., and A.N. conceptualised the research. B.B., I.S., and G.P.P. coordinated the protocol for scenarios, which were designed by all authors, with notable contributions from L.C., H.D., A.E., A.G., S.G., A.Kob., S.M., A.N., S.P., D.-J.v.d.V., J.R., and M.V.; B.B., A.G., S.G., S.M., A.N., and D.-J.v.d.V. coordinated the harmonisation protocol; all authors were involved in the model analysis, with notable contributions from D.-J.v.d.V., J.M. (GCAM), A.G., A.Kob., N.G., S.M. (TIAM), S.G., A.Hawk. (MUSE), A.Kol. (42), S.P., M.V. (GEMINI-E3), L.C., E.D. (ICES), A.A.-K., H.B. (E3ME), B.B., A.F., P. Le M., P.Z. (NEMESIS), G.C., A.C., R.D.M., A.E., M.G. (EU-TIMES), A.Her. (FORECAST), F.N., and P.P. (ALADIN). B.B. and A.E. compiled the results. B.B., A.C., A.E., K.K., and A.N. discussed the results as well as created the figures, with feedback from all other authors. A.N. coordinated the writing of the paper; all authors provided feedback and contributed to writing the paper, with notable contributions from B.B., A.C., A.E., and K.K.

Declaration of competing interest

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

Acknowledgements

This work was supported by the H2020 European Commission (EC) Project “PARIS REINFORCE” under Grant Agreement No. 820846. N.G.

was supported by the Natural Environment Research Council (NERC) (grant no. NE/L002515/1) and the Department for Business, Energy and Industrial Strategy (BEIS). The sole responsibility for the paper content lies with the authors; the paper does not necessarily reflect the opinions of the EC or BEIS.

Appendix A. Scenario protocol

The scenario used in this study is designed to reflect current levels of mitigation efforts in the EU, referred to as current policies. To extend the mitigation efforts implied by current policies to 2030 (the period for which current policies' impact can reasonably be projected) beyond 2030, we use the carbon prices that, on their own (absent other current policies), achieve the same levels of emissions as current policies in 2030. We call these carbon prices “equivalent carbon prices” (ECPs).

We extend the ECPs in the EU, growing at the rate of GDP per capita from 2030 onwards, to represent a “constant” economic burden from carbon pricing, as proxied by the ratio of carbon price to per capita income over time. After 2030, current policies are assumed to remain in place as “constant” or “minimum” bounds on effort.

The implementation of current policies after 2030 as “constant” or “minimum” levels depends on the model:

- For models that have detailed representations of energy systems (bottom-up), current policies are simulated as constraints. For example, where current policies represent the achievement of a minimum share of renewables in power generation, or minimum vehicle efficiency standards, then these policies are kept constant (i.e., a constant minimum share of renewables, or constant minimum vehicle efficiency) beyond 2030. Note that the renewables shares, or vehicle efficiency levels, are not kept constant, but rather at a constant minimum bound—this allows the models to simulate over-achievement against these policy targets, if e.g. the cost-competitiveness of renewables or more efficient vehicles drives them to do so.
- For macroeconomic models (top-down), policies are more commonly applied as minimum subsidy levels to specific low-carbon technologies, to encourage their take-up. In such cases, these subsidies are held constant in the period beyond 2030, to simulate a continuation of policy support for these technologies.

In particular, for all models (except for *42*, see below) we carry out the following steps:

1) We implement current EU policies to 2030, and record emissions in 2030.
2) We re-run the models without current policies, using EU economy-wide carbon prices to reach the levels of emissions in 2030 recorded in Step (1). Depending on the model, the emissions in 2030 can be implemented as caps, allowing the model to find the corresponding carbon prices endogenously. The ECPs in 2030 are the carbon prices that reproduce the emissions caused by current policies to 2030 in the EU—i.e., the emissions recorded in the Step (1).
3) We run the model from 2030 until 2050, with the ECPs growing with GDP per capita in the EU. The starting point should be the end point of the scenario run in Step (2). We then record emissions trajectories to 2050.
4) We re-run the model from the beginning, with
    a. Current policies to 2030, kept as constant or minimum levels after 2030.
    b. The emissions trajectories in Step (3), as emissions caps. Depending on the model, the carbon prices needed above current policies to achieve the required emissions reductions may be computed endogenously by the model.

The *42* model does not calculate carbon prices. In this respect, only for this model:

1) We keep the rate of change in emissions intensity of GDP constant after 2030.
2) We implement current policies to 2030, record the resulting emissions in the EU in the modelled period, and compute the annualised rate of change of emissions intensity (emissions per GDP) to 2030.
3) Starting with emissions in 2030 recorded in Step (1), we compute emissions pathways to 2050 by applying the annualised rate of change of emissions intensity computed in Step (1) beyond 2030. This step does not involve running the model.
4) We re-run the model from the beginning, with
    a. Current policies to 2030, kept as constant or minimum levels after 2030.
    b. The emissions trajectories in Step (2), as caps.

The evolution of carbon prices across models—except for the two sectoral models, FORECAST and ALADIN; and 42, which does not support a carbon price—is presented in Fig. A1.

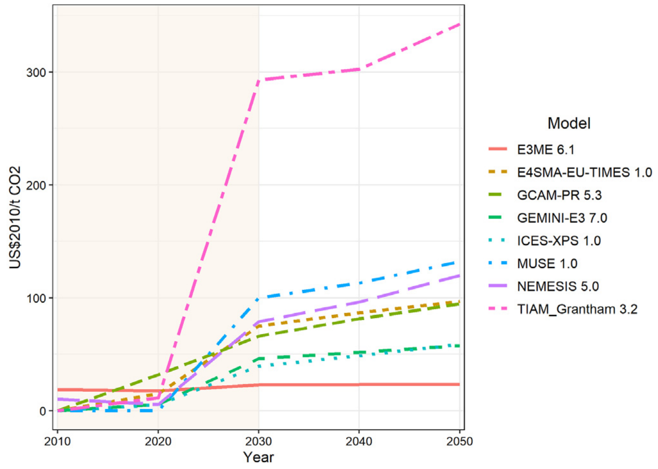


Fig. A1. Carbon price trajectories across models.

It should be noted that, while the carbon price is “model-specific” in the sense that it varies significantly by model (some models requiring a much higher carbon price than others to reach the same target, as also evident in Fig. A1), it has a consistent definition and interpretation across models. A different approach, such as equalising the economic burden instead of the carbon price, on the other hand, would be defined in much more heterogeneous ways across our models, depending on the model type. While this does not make it impossible in principle to use, e.g., a “constant economic burden” approach, the use of different measures of economic burden in each model would render this a much more complicated and hence difficult-to-interpret approach. Such an approach would not reflect consistency across models, if the measures of economic burden vary too much. The starting point of our projecting approach is consistent (across models) measures of “effort” caused by current policies, which are then projected forward. This is also the main reason behind carbon price (and emissions intensity) being a widely used and well understood variable in integrated assessment modelling research.

Appendix B. Modelling ensemble (type, coverage, description, EU disaggregation)

Type	Model (version)	Coverage	Description and EU disaggregation
General equilibrium	GEMINI-E3	World	*GEMINI-E3* (Bernard and Vielle, 2008) is a multi-country, multi-sector, recursive computable general equilibrium (CGE) model 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 (Vielle, 2020; Babonneau et al., 2020). The global GEMINI-E3 version is used covering the EU-28 as an aggregate.
	ICES (XPS 1.0)	World	*ICES* is a recursive-dynamic multi-regional CGE model developed to assess economy-wide impacts of climate change policies (Eboli et al., 2010); for the purposes of this study, the XPS version is used (Parrado et al., 2020) with a more detailed representation of government behaviour and private households. Like GEMINI-E3, it assumes market equilibrium simultaneously in each market or region and requires calibration to data on national and international socio-accounting information as well as a series of elasticities of substitution. The ICES model covers Europe combining detailed representation of specific Member States (Czech Republic, Finland, France, Germany, etc.) and aggregate regions (RoEU).
Partial equilibrium	GCAM (v5.3)	World	*GCAM* is a global IAM representing human and Earth system dynamics (Edmonds et al., 1994), exploring the interactions between energy, agriculture and land use, economy and climate (Calvin et al., 2019); 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 (Kyle et al., 2021). GCAM portrays Europe combining two main region aggregates: EU-15 and EU-12.
	TIAM (Grantham)	World	*TIAM* is a multi-region, global version of TIMES that combines an energy system representation of fifteen regions, among which Europe is portrayed as a single aggregated region, with options to mitigate non-CO_2 greenhouse gases as well as non-energy CO_2 mitigation options, such as afforestation, in each of these regions. As such, it can be used to explore a variety of questions on how to mitigate climate change through energy system transformations, as well as reductions in non-energy CO_2 emissions and non-CO_2 emissions. The model operates on a "perfect foresight" welfare cost-optimisation basis: all consequences of technology deployments, fuel extraction and energy price changes over the entire time horizon are considered when minimising the cost of the energy system. The TIAM-Grantham version is used (Napp et al., 2017).
Energy system	EU-TIMES	Europe	*EU-TIMES* is an enhanced version of the open source JRC-EU-TIMES model (Simoes et al., 2013), a European version of TIMES, designed for analysing the role of energy technologies and innovation needs for meeting European energy and climate policy targets, representing EU Member States and neighboring countries, where each country is modelled as one region. It can consider policies affecting the entire energy system, sectors, group of or individual technologies/commodities (Sgobbi et al., 2016; Blanco et al., 2018).
	MUSE	World	*MUSE* is an agent-based, partial equilibrium modelling environment for the assessment of how national or multi-regional energy systems may change over time (Giarola et al., 2021b; Kerdan et al., 2019), from production of primary resources, through conversion, and finally end-use consumption to meet economy-wide service demands, explicitly characterising the decision-making process of firms and consumers in the energy system and capturing various features of market imperfection. The MUSE model covers Europe combining detailed representation of specific Member States (Denmark, Finland) and aggregate regions (EU7, EU18).
	42	World	*42* is a simulation model providing the detailed energy balances for 50 countries and regions, whereby energy consumption is modelled as a combination of gross, structural, and technological factors, considering the energy intensities trajectories of various sectors and using their historical trends to estimate realistic transition pathways (Shirov et al., 2016). 42 does not support a carbon price; instead, it used the rate of change in emissions intensity of GDP up to 2030, then kept it constant post-2030, as in Fawcett et al. (2015) and Vandyck et al. (2016).
Macroeconometric	NEMESIS	Europe	The *NEMESIS* model (Brécard et al., 2006; Capros et al., 2014a) is a sectoral, detailed macroeconometric system of models for every European country, for studying issues linking economic development, competitiveness, employment, and public accounts to economic and structural policies involving long-term effects (Capros et al., 2014b; Ravet et al., 2019).
	E3ME (v6.1)	World	*E3ME* is a highly disaggregated macroeconometric model that is detailed in energy technologies like CGE models but does not assume optimal agent behaviour nor market clearance to reach short-term equilibrium (Barker, 1998); it uses historical data and econometrically estimated parameters relations to dynamically simulate the behaviour of the economy. In this study, we use E3ME v6.1 (Hafner et al., 2020; Bachner et al., 2020). The E3ME model covers Europe at the regional level as well as at the national level (Member States plus candidate countries).
Sectoral	ALADIN	Europe	*ALADIN* (Plötz et al., 2014) is an agent-based simulation model for assessing market diffusion of alternative fuel (passenger and heavy-duty) vehicles in Germany and Europe until 2050, 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 (Plötz et al., 2019).
	FORECAST	Europe	*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 (Fleiter et al., 2018).

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148549.

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