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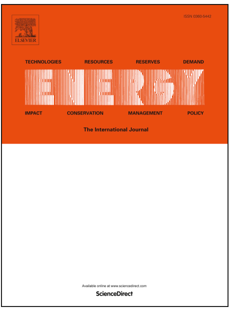

Narrative-driven alternative roads to achieve mid-century CO_2 net neutrality in Europe

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Robert Pietzcker	Writing - Original Draft, Review & Editing, Conceptualization, Methodology
Panagiotis Fragkos	Writing - Review & Editing, Conceptualization, Methodology
James Price	Writing - Review & Editing, Conceptualization, Methodology, Software
Will McDowall	Writing - Review & Editing, Conceptualization, Methodology, Investigation
Theofano Fotiou	Software, Formal analysis
Pelopidas Siskos	Software, Formal analysis
Gunnar Luderer	Supervision
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Narrative-driven alternative roads to achieve mid-century CO_2 net neutrality in Europe

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Abstract

The tightened climate mitigation targets of the EU green deal raise an important question: Which strategy should be used to achieve carbon emissions net neutrality? This study explores stakeholder-designed narratives of the future energy system development within the deep decarbonization context. European carbon net-neutrality goals are put under test in a model comparison exercise using state of the art Energy-Environment-Economy (E3) models: ETM-UCL, PRIMES and REMIND. Results show that while achieving the transition to carbon neutrality by mid-century is feasible under quite different future energy systems, some robust commonalities emerge. Electrification of end use sectors combined with large-scale expansion of renewable energy is a no-regret decision for all strategies; Carbon Dioxide Removal (CDR) plays an important role for achieving net-neutral targets under all scenarios, but is most relevant when demand-side changes are limited; hydrogen and synthetic fuels can be a relevant mitigation option for mid-century mitigation in hard-to-abate sectors; energy efficiency can reduce the supply system strain. Finally, high carbon prices (300-900€/tCO_2) are needed under all strategies in order to achieve carbon net neutrality in 2050.

Keywords: EU green deal, CO_2 net neutrality, decarbonization pathways, stakeholder driven scenarios, Energy-Environment-Economy models (E3), multi-model comparison

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1. Introduction

Europe aims to become the world's first climate-neutral continent[1,2]. The European Green Deal [1] and the submitted EU UNFCCC Mid-century Strategy [2] resolve upon achieving net-zero greenhouse gas emissions by 2050. However, the energy system transformation to carbon neutrality can be shaped in different ways. What are the implications and requirements of different transformation pathways?

Previous literature approached this question from a modelling perspective: evaluating the portfolio of technologies available and testing against the absence of crucial technological alternatives [3]–[5]. In this perspective, stakeholders' knowledge was mainly used as an ex-post validation step of the resulting simulated transformation pathways, rather than as an input into scenario design[3]. Recent years have seen increased development of narrative based studies, focusing in uncertain aspects of the energy system development, to inform European low-carbon transition alternatives ([6], [7]). Other studies have used energy system models together with pathways derived from transition theories ([8]).

This study takes a different approach to assess the transition to a net-zero Europe. We depart from stakeholders' knowledge as the foundation for the scenarios' conception and design phase. This approach belongs to a wider family of 'hybrid' and participatory scenario approaches that combine qualitative and participatory approaches with quantitative modelling ([9]–[11]). A stakeholder iterative process is used to formulate self-consistent narratives for possible future energy systems that could be driven by decarbonization policies and broader social, technological and economic trends. Techno-economic characteristics behind each stakeholder narrative description are consistently identified through a combination of insights derived from stakeholder expertise and quantitative techno-economic modelling. Three state of the art Energy-Environment-Economy (E3) models - ETM-UCL, PRIMES and REMIND-EU - are adapted and extended to represent with reasonable assumptions these future narratives in the form of alternative deep decarbonization pathways and are used in a multi-model scenario analysis framework to explore different strategies to achieve net zero emissions in the EU.

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[1] For this work we consider the climate ambition targets as shared by the 27 current EU Member States and United Kingdom (in short, EU-28 from now on). Accordingly, all energy and climate values shown are given for the EU-28 countries.

[2] CO_2 net neutrality in this work refers to achieving European net-zero carbon dioxide emissions by 2050. This can be done either by eliminating CO_2 emissions from the economy through mitigation measures and/or by offsetting residual emissions with carbon dioxide removal from the atmosphere.

[3] The term stakeholder refer to a person or group that has a direct interest or relation with the decarbonization process. It embodies actors from a variety of fields, including research, business, finance, industry associations, academia, national and EU policy makers.

The feasibility of each alternative narrative is put under test against ambitious European mitigation targets, in particular related to the goal of carbon neutrality by mid-century. Although the feasibility of limiting global warming to 1.5°C compared to the pre-industrial level was already investigated in the literature ([12], [13]), this paper provides new insights by conducting a model comparison exercise to analyse how the recently set and very stringent mid-century European mitigation targets can be achieved via different transformation strategies, each with consistent social, technological and economic trends. Sectoral and system-wide decarbonization transformation trajectories, their associated strategies and no-regret options[4] are identified and analysed in order to provide guidelines for implementing the decarbonization process in the EU.

In order to achieve these objectives, the next section describes the methods used in this work (section 2), including the stakeholder designed narratives, the scenarios definition, climate policy targets and energy system models used. In the results section (section 3) we discuss the feasibility of decarbonization pathways based on the stakeholder driven narratives, robust strategies shared by the different decarbonization strategies, and narrative specific insights useful to orient current policy design. Finally, summary and policy-relevant conclusions are presented in section 4.

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2. Methods

2.1. From stakeholder narratives to model assumptions

A stakeholder iterative co-design process developed alternative narratives that describe possible future energy system pathways that achieve deep decarbonization targets. This process included several stages. Firstly, a survey was sent to 50 selected stakeholders and decision makers from a variety of fields, including research, business (including finance), industry associations, academia, national and EU policy makers. Participants were selected based on their expertise in long-term EU energy and climate issues, and aimed to capture a variety of technological, institutional and geographic perspectives.

A subsequent workshop, involving 22 expert participants drawn from research organisations (n=14), governments (n=4) and various business sectors (n=4), focused on the core elements used to construct the narratives: the big picture trends that might shape European decarbonisation pathways, the technologies and systems that are most relevant, and the energy and climate policies required. Stakeholders provided their views on the perceived importance and likelihood of various scenario elements (i.e. statements about possible

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[4] This paper considers consistent results across all models and different future decarbonization strategies as no-regret strategies for the decarbonization process implementation.

future states of the European energy system), and discussed the potential interactions or inconsistencies between scenario elements.

This workshop output provided the ‘building blocks’ to construct the first set of narratives, which were further discussed by the modelling teams. The narratives were then used to inform parameter value choices for the models. An initial iteration of modelling results was then produced, and the draft narratives and associated techno-economic modelled scenarios were then used as input to a following stakeholder workshop focused on policymakers, and aimed in testing and refining the narratives. Finally, the decarbonization narratives were defined. A fuller account of each stage of the narrative development process can be found in a series of project reports ([14]–[16]).

This paper presents results of three narratives developed during this process. The first narrative depicts a world driven by the emergence of new players in the energy system bridging the divide between utilities and customers, fundamentally changing both supply and demand. This narrative is called *New Players and Systems* (*New Players*). The second is an *Incumbents’ Renewal* world (*Incumbents*), where today’s big utilities adapt to remain relevant, promoting a supply side driven low-carbon transformation, with limited infrastructure and consumer side change. The third possible outcome is a world in which energy and resource efficiency is a goal in itself, and stronger awareness for health and non-material well-being changes lifestyles: the *Efficiency and Sufficiency* narrative (*Efficiency*).

Defining conceptually the narratives was just one of the necessary steps to simulate the alternative low carbon pathways. Modellers and stakeholders engaged in an iterative design and validation process transforming each stakeholder narrative concept into techno-economic expectations, and then translating both into consistent modelling assumptions to be able to realistically quantify the consequences of the alternative decarbonization pathways.

The modelling assumptions representing the stakeholder-developed narratives encompass several dimensions of a low carbon economy transition, such as: openness to change consumer end-use habits and lifestyles; technological change; growth of renewables and various forms of storage and the difficulty of system integration; power-to-gas and power-to-liquids alternative development and related infrastructure requirements; bioenergy potential; alternative economic restructuring (e.g. circular economy); incumbent technologies alternatives and strategies; and CO_2 capture and storage or reuse. A detailed list of each narrative techno-economic feature and its respective modelling assumptions can be found in Table 2 (Annex A).

As a design decision, the models assumptions and the parametrization of the decarbonization narratives was left, to a certain degree, at the discretion of each modelling team, but based on the qualitative narratives

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co-developed with stakeholders. This led to results that span a substantial range of input modelling assumptions, thus yielding a much stronger test for the robustness of the identified results and trends across the different models and scenarios. We consider this differentiation on modelling assumptions as a sensitivity test to the conclusions drawn in this study ([3], [17])[5].

A summary of the core attributes of each narrative scenario can be found in Table 1. More details can be found in Table 2 (Annex A).

Table 1. Narratives description.

Narrative	Brief Description
New Players *and Systems*	Focus on end-use/scalable technologies enabling electrification of energy services (electric vehicles, heat pumps) and large-scale expansion of variable renewable energy combined with storage.
Incumbents' *Renewal*	Focus on supply side change; large scale technologies (CCS and Nuclear); clean synfuels allow end users to keep their liquid/gas-based appliances and the current energy infrastructure.
Efficiency *and Sufficiency*	Focus on demand savings and change of usage patterns. New lifestyle changes and efficiency measures and related investment, including in building retrofits, circular economy, etc.

In summary, the main techno-economic assumptions in the *New Players and Systems* scenario portray a world in which electricity produced from renewable technologies becomes the core of the energy supply sector, while customers embrace new electricity-based end-use technologies like battery-electric vehicles and heat pumps, thus enabling wide-spread electrification of energy services and industrial processes in order to achieve the ambitious mitigation goals.

The co-benefits between a renewable based electricity system [18]–[20], highly electrified demand [21]–[24], and synergies with other energy carriers, e.g. green hydrogen [25], become the main policy design driver and transformation pathway behind the *New Players* scenario assumptions.

In the second narrative - *Incumbents' Renewal* - Carbon Capture and Storage (CCS), nuclear power and synthetic and bio-based clean fuels lead to a fundamental reshaping of the energy supply side to provide

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[5] For publications focused on sensitivity analysis of the models used in this work you can refer to Giannousakis et al. (2021) [15], which provides a deeper discussion on REMIND technology costs sensitivity analysis, while Capros et al (2019) [3] develop multiple deep decarbonisation pathways for the EU based on alternative scenario assumptions using the PRIMES model.

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emission-neutral fuels, while the current energy infrastructure and end-use appliances remains largely in place [26]–[30] with limited changes in end-use technologies and infrastructure.

Finally, efficiency measures and reduction in energy consumption combined with circular economy considerations and lifestyle changes are the main drivers behind achieving decarbonization goals under the third and last narrative: *Efficiency and Sufficiency* [31], [32].

The different modelling assumptions in each of the three scenarios mean that the development and deployment pace of specific low-carbon technologies associated with the specific narrative are facilitated. Nevertheless, alternative mitigation options are still made available in the decarbonization strategies portfolio.

2.2. Climate policy and energy system models

Three well established energy system models, extensively used for the analysis of the EU energy and climate policies [3], [33], [34], are applied to simulate the decarbonization pathways narratives: REMIND, PRIMES and ETM-UCL.

The models were tested against a shared CO_2 emissions mitigation target[6]. A European carbon emissions budget of 43 Gt CO_2 is considered for the total allowed emissions between years 2020 and 2050 [33][7]. In the sequence, results will show this budget assumption compatibility with achieving the European Green Deal [1] and the submitted EU UNFCCC Mid-century Strategy [2] ambitions of net-neutrality by 2050 (Figure 2c).

The "Middle of the road" Shared Socioeconomic Pathway scenario assumptions (SSP2, [35]) were used to standardize the main socio-economic scenario assumptions (GDP and population) across all models; these are in line with the assumptions used for European countries (e.g. they follow closely the European Commission Ageing Report [36]). We present a brief description of the models used in our analysis in the sequence. More information about their formulations, parametrization and assumptions can be found in Annex B, in the references below, and in model comparison publications such as [37], [38].

REMIND [39], [40] is a global multi-regional energy-economy-climate model with detailed representation of the energy sector spanning the years 2005–2100. It solves for an intertemporal Pareto optimum in economic and energy investments in the model regions, fully accounting for interregional trade in goods, energy carriers

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[6] This paper analysis is focused on European results only. Whenever relevant for the specific model, other world regions are assumed to respect currently submitted Nationally Determined Contributions (NDCs) and mitigation strategies in line with the Paris Agreement goals.

[7] The 43 Gt CO_2 carbon budget assumption is compatible with the Clean Planet for all strategy Impact Assessment [33, p. 198], where the CO_2 budget over 2018-2050 for the 1.5 scenarios is 48 Gt CO_2.

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and emissions allowances. REMIND enables analyses of technology options and policy proposals for climate change mitigation.

The PRIMES model simulates the energy system of all EU Member States [41]. The model provides projections until 2050 and 2070 of detailed energy demand and supply balances, CO_2 emissions, investments in the energy system, technology deployment, energy prices and costs. PRIMES simulates a multi-market equilibrium by explicitly calculating energy prices which balance demand and supply [34]. The simulation of behaviour of each agent is based on detailed modelling founded on micro-economics and includes technical, engineering-oriented constraints. The PRIMES model has served to quantify energy outlook scenarios for the European Commission [42] and to provide model-based analysis for EU energy and climate policies, including Low Carbon Roadmap [43], Energy Roadmap to 2050 and the recent "Clean Planet for all" long-term strategy [33].

The European TIMES Model at UCL (ETM-UCL) [44], [45] is a dynamic partial equilibrium energy system model with an inter-temporal objective function to minimise total discounted system costs, based on the ETSAP-TIMES model generator [46]. It is a technology-rich, bottom-up model with perfect foresight and covers energy flows across supply-side and demand-side sectors. The model comprises a total of thirty-one countries (EU27 plus UK, Norway, Iceland and Switzerland), grouped into eleven regions. Each region is modelled with supply, power generation and demand side sectors (residential, commercial, industry, transport and agriculture), and are linked through trade in crude oil, hard coal, pipeline gas, LNG, petroleum products, biomass and electricity. In addition there is a "global" region which serves as a simple 'basket of resources' from which other regions may import the above products (except electricity). The model is calibrated to a base year of 2010, with energy service demand projected into the future using the exogenously calculated drivers of GDP, population, household numbers and sectoral output (linked to GDP), for each region.

All models underwent substantial improvements to be able to represent decarbonization components described in the alternative narratives: end-use decarbonization alternatives were extended in key sectors including transport, buildings and industries, and increased spatial detail was developed.

A new version of the REMIND model was developed for this publication with increased European policy and spatial representation: REMIND-EU. REMIND-EU preserves the global coverage of the REMIND model, but extends the previous 12 world regions representation to a total of 21 regions. The enhanced spatial detail is focused in Europe, by introducing a total of nine regions representing European Union and UK, and two additional regions that represent the remaining European countries. The spatial disaggregation introduced followed a trade-off analysis between added mathematical complexity versus better representation of

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European climate zones, energy specific policies, economy characteristics clustering, behavioural assumptions and country specificities.

Modelling improvements realized in PRIMES include the enhanced representation of the buildings sector (with various building types by income class and deep retrofit strategies), the detailed integration of the production, distribution and storage of hydrogen and clean synthetic fuels in the national and EU energy systems (as new energy vectors enabling sectoral integration with the electricity, gas, transport and industrial systems) and the enhanced representation of disruptive mitigation options in specific hard-to-abate industrial sub-sectors (i.e. Hydrogen to produce direct reduced iron - DRI) and transport segments (e.g. freight trucks, aviation, navigation) [47].

ETM-UCL improvements focused on more accurately ground the potential for European energy systems with high shares of variable renewable energy sources. This involved integrating a set of constraints into ETM-UCL that act to parameterise key details of a high spatial and temporal resolution power system model. These included an improved representation of the need for storage and interconnection to support higher variable renewable shares as well as a new formulation that significantly furthers the modelling of renewable curtailment within ETM-UCL. Finally, a geospatial analysis was also conducted to enhance the technical capacity potential for on and offshore wind and solar photovoltaics based on CORINE land cover[8], Natura 2000[9] and CDDA datasets[10].

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3. Results

Figure 1a shows the EU CO_2 emission pathways under the three co-designed Narratives, while respecting the CO_2 emissions climate policy targets. All models are capable of achieving the tight 43 Gt CO_2 budget under all Narratives. Resulting 2050 net emissions are between –334 Mt CO_2 and +63 Mt CO_2, closely reflecting 2050 European net-neutrality goals (Figure 2c).

Achieving these reductions requires carbon prices in the range of 363-946€/t CO_2 by 2050: 11-31€/year increase from 2020 onward (see Figure 1b). As observed, a high carbon price variation between the different deep decarbonization strategies is to be expected due to the different portfolio of supply and demand side mitigation alternatives available at each scenario.

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[8] https://land.copernicus.eu/pan-european/corine-land-cover

[9] https://ec.europa.eu/environment/nature/natura2000/index_en.htm

[10] https://www.eea.europa.eu/data-and-maps/data/nationally-designated-areas-national-cdda-14.

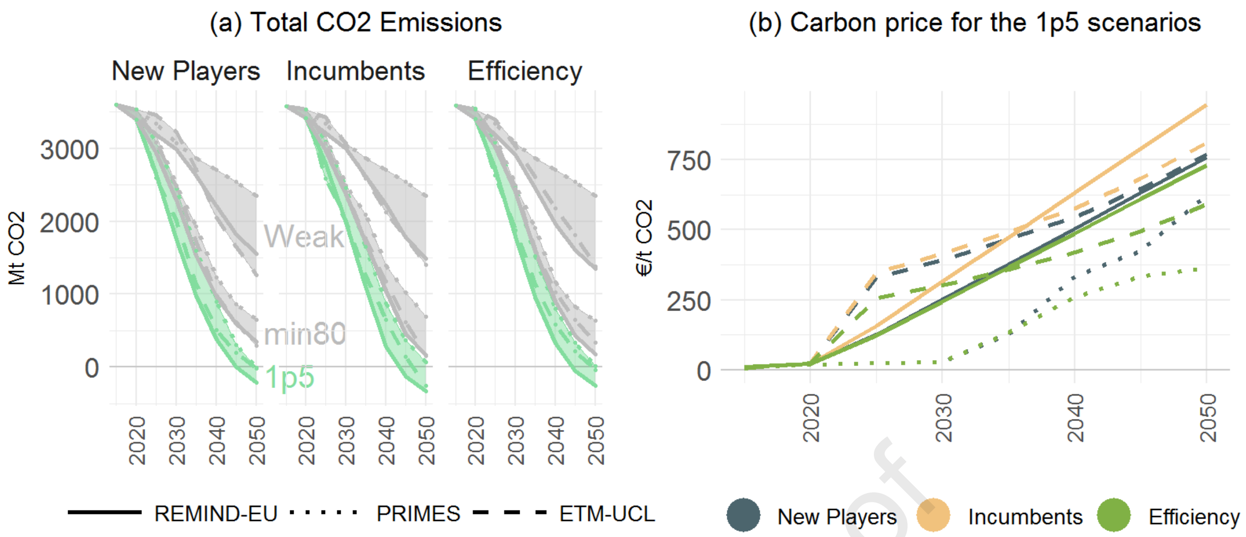

Figure 1. Total CO2 emissions and carbon prices for EU-28 in the 1p5 scenarios[11].

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All three models agree that under a high degree of societal engagement, as portrayed in the *Efficiency and Sufficiency* narrative, the decarbonization transition can be achieved with lower investment requirements in the supply side, lower carbon prices and lower total system costs, representing a less costly process. This future decarbonized energy system require ambitious supporting policies targeting energy and resource efficiency, including deep renovation, lifestyle changes, energy savings, circular economy and shared mobility not necessarily directly promoted through carbon pricing.

The Incumbents' Renewal strategy by contrast is on the higher side of the required carbon price levels. This scenario focus on the supply side transformation, with limited demand side action and reduced end-user energy carriers change. As consequence, carbonaceous energy carriers decarbonization rely more heavily on the innovation, development and diffusion of more uncertain and currently immature technologies such as hydrogen, e-fuels, Carbon Capture and Utilization (CCU) or Carbon Dioxide Removal (CDR) to fully decarbonise the economy. The higher marginal abatement cost of the last unit of carbon emissions, under a stringent climate target as achieving 2050 net-neutrality, require surpassing additional costs on scaling up and promoting these alternative decarbonization strategies in order to achieve market maturity in the limited time frame available.

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[11] The shaded area in figure 1a correspond to the range of emissions results of the three models for three different climate target European budgets: weak=82 $GtCO_2$ (representing previous European climate policy target ambitions), min80=57 $GtCO_2$ (calculated from a ~80% reduction of EU GHG emissions in 2050) and 1p5=43 $GtCO_2$ (used in this work analysis and in line with mid-century carbon net-neutrality). The shaded green area underline the scenario evaluated in this paper, the 1p5 scenario.

Regarding models variations, we can observe a substantial difference on the short-term mitigation pace. ETM-UCL and REMIND-EU CO_2 require prices already by 2030 in the range of 244-415€/tCO_2, while PRIMES projects much lower CO_2 prices of about 50€/tCO_2. This difference can be mainly explained by two factors. Firstly, PRIMES shows lower emission reductions in 2030 of 46% in the 1p5 scenario, while the two other models see stronger reductions of 56-61% (in relation to 1990 emissions). Although this paper analysis does not enforce intermediate mitigation targets, REMIND and ETM-UCL emission reduction trajectories respect recently set European emission reduction targets for the next decade[12]. The higher 2030 carbon prices observed in these models reflect directly the associated costs with speeding up the decarbonization process. Secondly, price levels are highly dependent on concurrent supporting policies, such as efficiency standards for example. As previously mentioned, the model's parametrization regarding these policies was not harmonized in order to provide a more robust test against common results observed from the different model results. In this case, PRIMES shows a substantial influence of other supporting policies, related to renewable energy and energy efficiency in line with the recent revisions of the Energy Efficiency Directive and Renewable Energy Directive, while the other two models achieve the target mainly through carbon pricing.

3.1. How to achieve European carbon neutrality

The feasibility of the alternative future energy systems is an important result as it is confirmed by all models under different scenarios. However, the way that the transition to carbon neutrality is achieved in different model-based scenarios can be considered even more important.

Figure 2a shows that all scenarios and models massively reduce CO_2 emissions from energy demand and supply, but still rely on a certain amount of negative emissions to compensate for residual fossil emissions in hard-to-abate sectors and reach their mitigation goals. This is in line with previous research highlighting the relevance of at least some negative emissions to achieve very tight mitigation targets [48]. This result points to the need to support research and demonstration projects for CDR technologies, especially in light of the limited success of these technologies over the last decade.

Mid-century capture and sequestration management (Figure 2b) is consistently done in the form of Bio-Energy with Carbon Capture and Storage (BECCS), in all scenarios and models. Biomass promotes decarbonization mainly in power, heat, hydrogen and upstream via Fischer-Tropsch processes for producing synthetic fuels.

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[12] EU member states and the EU Parliament agreed recently upon a carbon emissions reduction of at least 55% by 2030, compared with 1990 levels.

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Fossil Carbon Capture and Storage (CCS) also contributes to emission reductions especially in the *Incumbents* scenario. Limited demand mitigation options in this case forces the system to adapt to higher 2050 residual emissions. Pre-emptive policies focused on promoting future CCS availability, costs reduction and public acceptance are a must to make this residual emission compensation feasible in the *Incumbents* scenario.

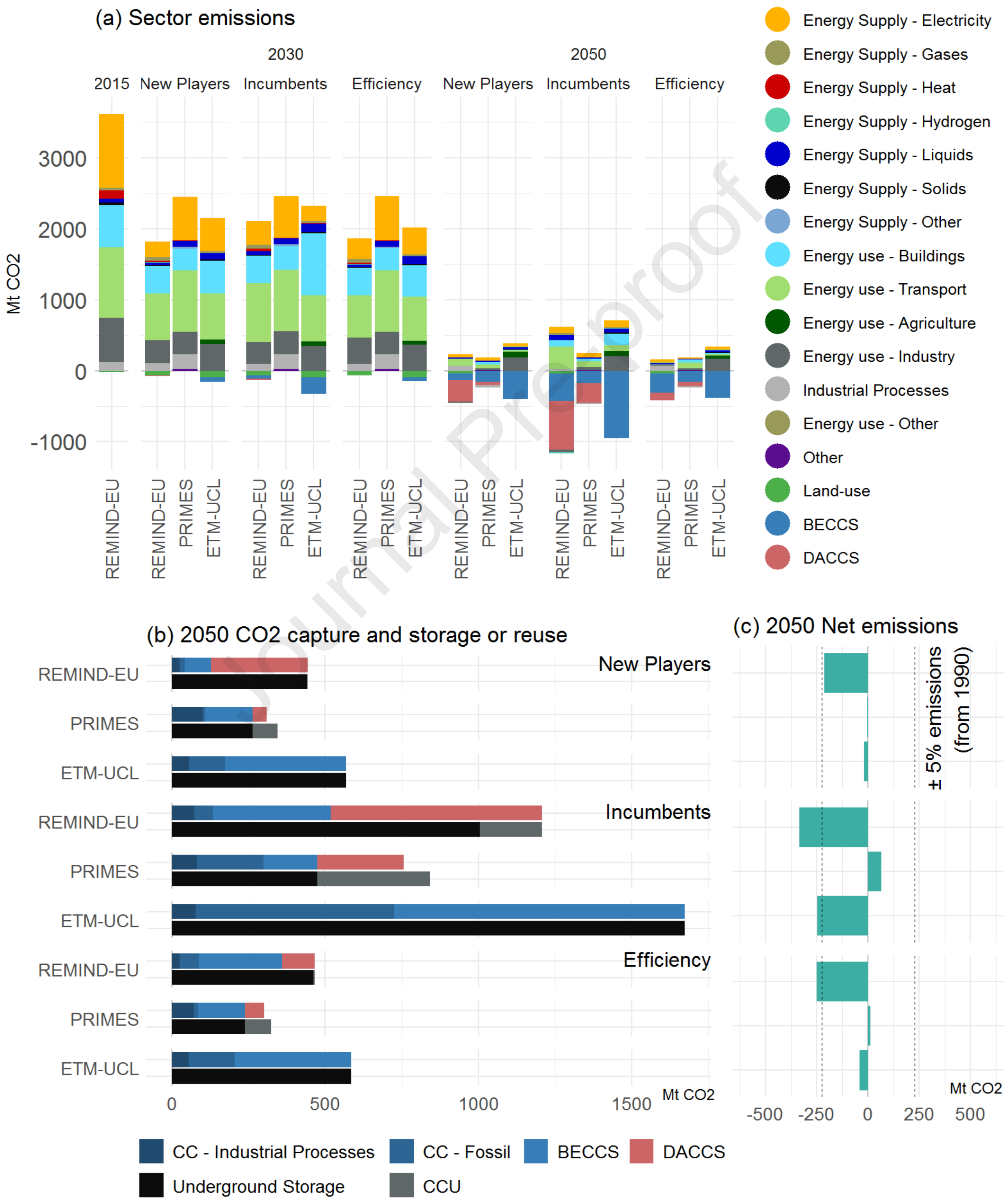

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Figure 2. Emissions per sector (a), 2050 CO2 capture and storage or reuse (b) and 2050 net emissions (c) for EU-28.
(Mt CO2 per year)

The emergence of BECCS underlines the importance of biomass for the decarbonized energy system by 2050. Biomass sources cover energy crops (grassy and woody crops grown specifically for energy purposes) and bio solids (woody residues from forestry and agriculture). However, limited European bio-energy resources and high land-use competition may limit the bio-energy role in the transition process to a decarbonized economy (Figure 3).

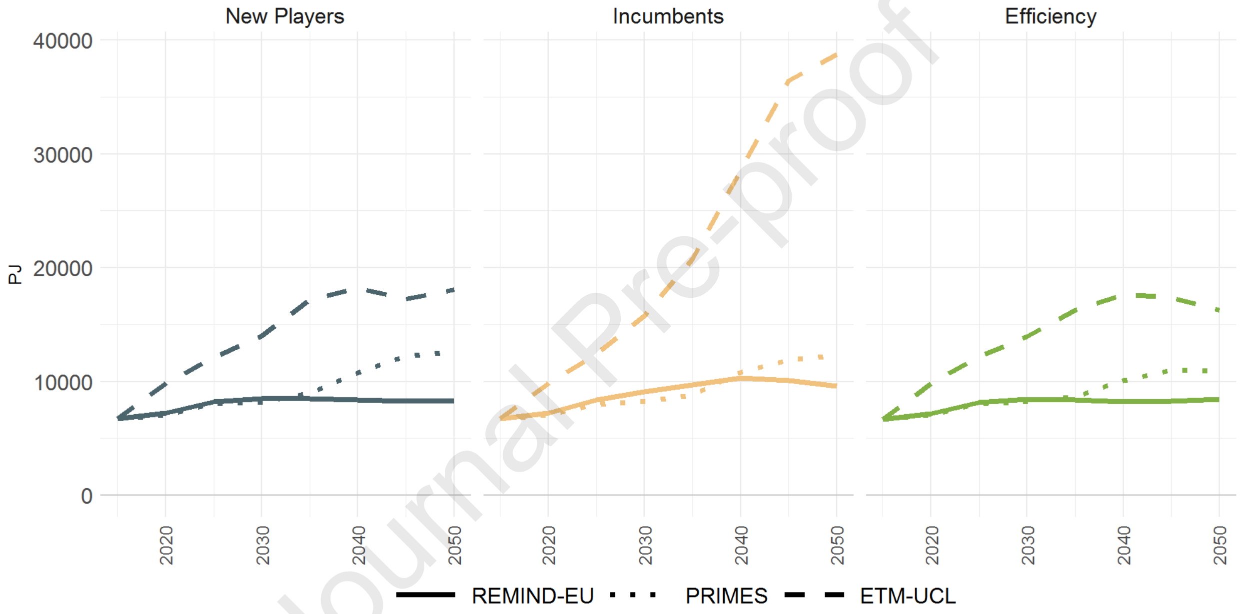

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Figure 3. Biomass primary energy use in EU-28. (PJ per year)

PRIMES and REMIND assumed a relatively limited contribution of biomass use potential due to the limits of European own production and imports requirements. As consequence, Direct Air Carbon Capture and Storage (DACCS), together with CCU for the incumbent's case, rises as relevant mitigation back-stop technologies. In the ETM-UCL scenarios, which assume a larger bioenergy supply, the use of biomass increases substantially in the *Incumbents* scenario. Here, while domestic production is in line with the boundaries proposed by Ruiz et al. [49], the EU draws on sizable biomass imports to promote decarbonization. Biomass is also used for solids energy use; synthetic bio-fuels production to partially decarbonize hard-to-abate sectors – mainly freight transport, aviation and high heat industrial demand –; and as an alternative bridge low carbon technology in the short-term (see 2030 biomass electricity generation capacity in Figure 5).

Results show that final energy electrification combined with large-scale expansion of renewable energy and storage capacities is a robust strategy under all scenarios analysed (Figure 4a). Electrification increases by two

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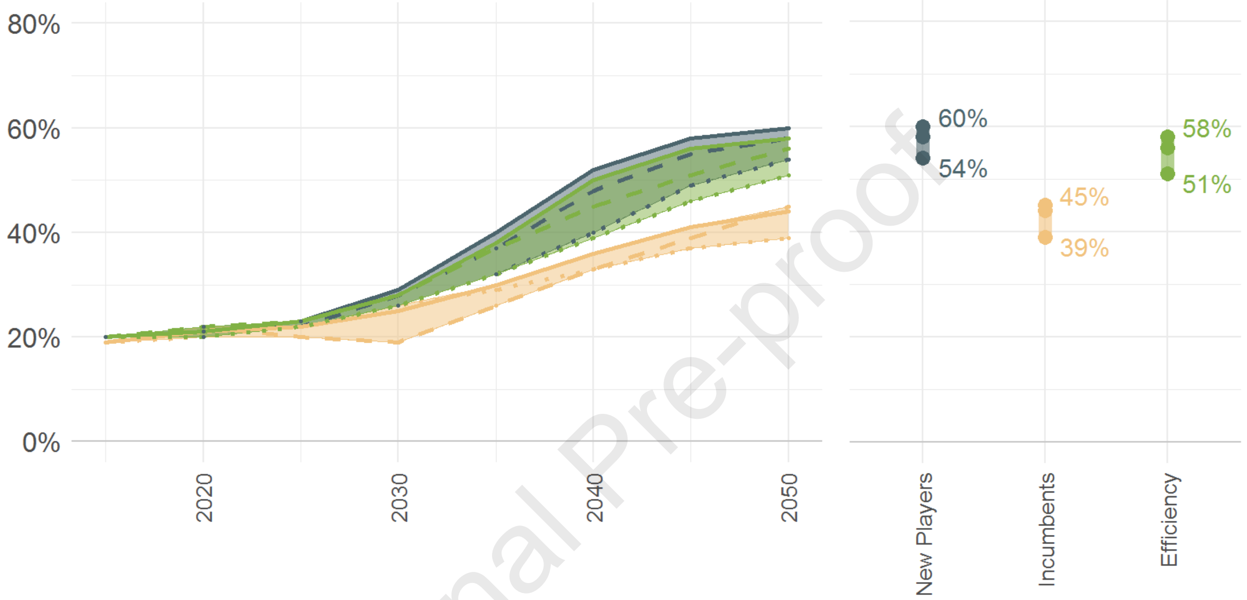
to three times relative to current levels across model-based scenarios in 2050. The highest electrification shares are observed in the *New Players* scenario– up to 60% of the final energy consumption by 2050 –, but even under the *Incumbents* scenario electrification shares double compared to 2015, to 39-45%. The residential and commercial sectors see the highest electrification potential by mid-century, up to 76%-83% of total final energy, largely driven by the expansion of heat pumps (Figure 4b).

(a) Total final energy electricity Share



(b) Sectoral final energy electricity Share

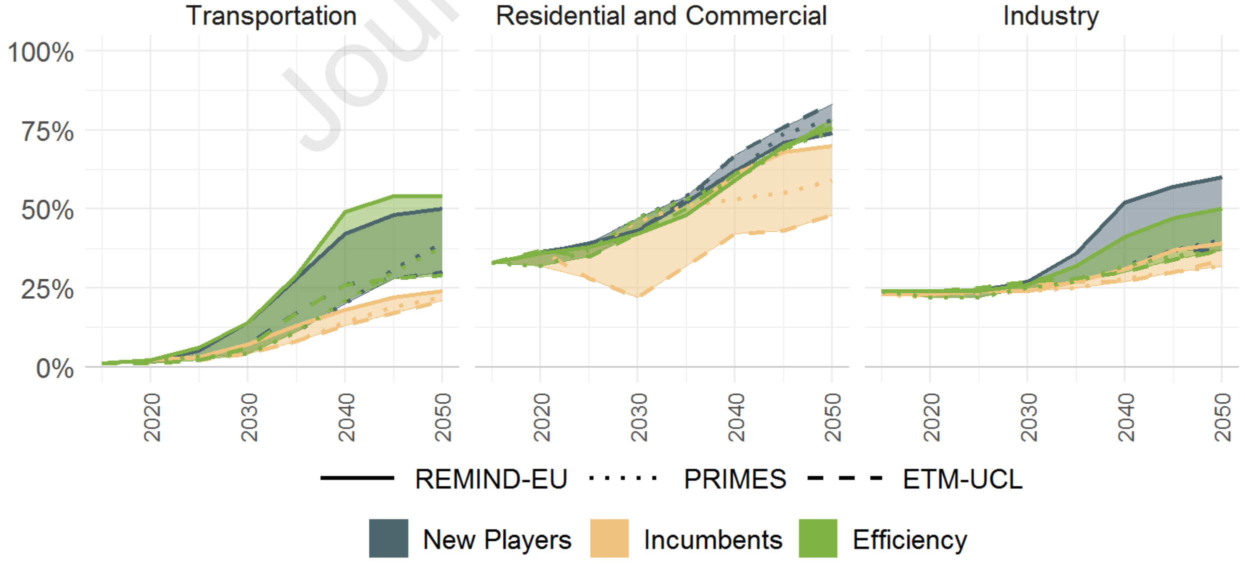


Figure 4. Electricity Share on Final Energy (%) in EU-28[13]

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[13] The shading area in figure 4a and 4b indicates the range of results between the three different energy system models used in this analysis.

As can be seen in Figure 5, total electricity production present similar levels between all models, which can be considered a major finding given the differences in formulation and assumptions across the three models. The high increase of electricity requirements in all scenarios, either due to electrification or due to the production of green hydrogen and synthetic fuels, all of which require large amounts of electricity, pose some stresses in renewable energy potentials.

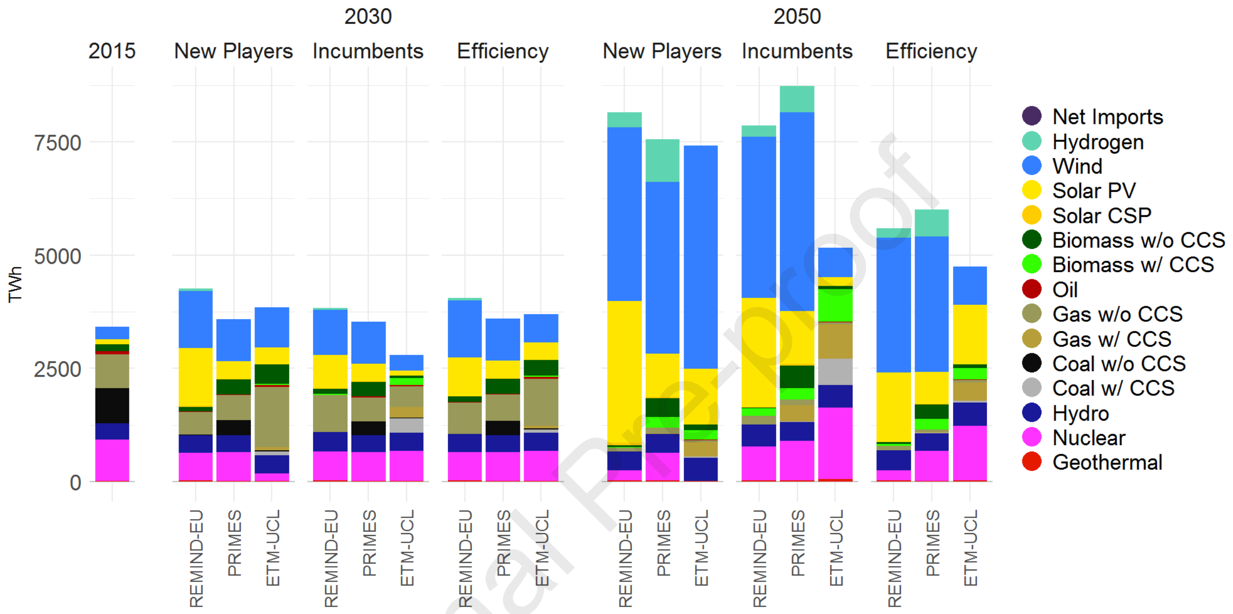

Figure 5. Electricity Generation in EU-28 (TWh per year)

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New electricity generation is heavily dominated by variable renewables, namely wind and solar PV. This effect is smaller in the *Incumbents*' scenario, where nuclear power plants coexist as an alternative solution in politically favourable countries (e.g. those that have not imposed limitations in nuclear energy[14]) and favourable developments of carbon capture allow gas – and in ETM-UCL even coal – based generation to be used in the electricity production.

Carbonaceous energy carriers (solids, liquids and gases) are strongly reduced, but still used by 2050 (see Figure 6.a). Although highly decarbonized, the total amount in 2050 is less than half the level in 2015 in the *Incumbents*' scenario and goes down to less than a third in the *New Players* and *Efficiency* scenarios. Advanced solid biofuels promote the solids decarbonization process. Liquids and gaseous biofuels replace fossil liquids and gases carriers. Under high renewables penetration, clean gases (e.g. green hydrogen) can potentially

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[14] Models formulation consider current policies in place regarding nuclear phase-out and limitations to new capacity installation. Country specific societal acceptance for relevant mitigation technologies, like for example nuclear power plants, is also considered either through hard-coded constraints or additional adjustment costs on technology diffusion and new capacity investments.

decarbonize industry gases demand and replace transportation liquids use. Under the presence of pushing policies (*Incumbents*' scenario), synthetic fuels assist the remaining liquids and gases energy carriers decarbonization. Fossil energy carriers remain present in the system mainly in difficult to decarbonize sectors (e.g. industry) and under scenarios with limited demand-side changes and/or favourable CCS and CCU assumptions (*Incumbents*' scenario).

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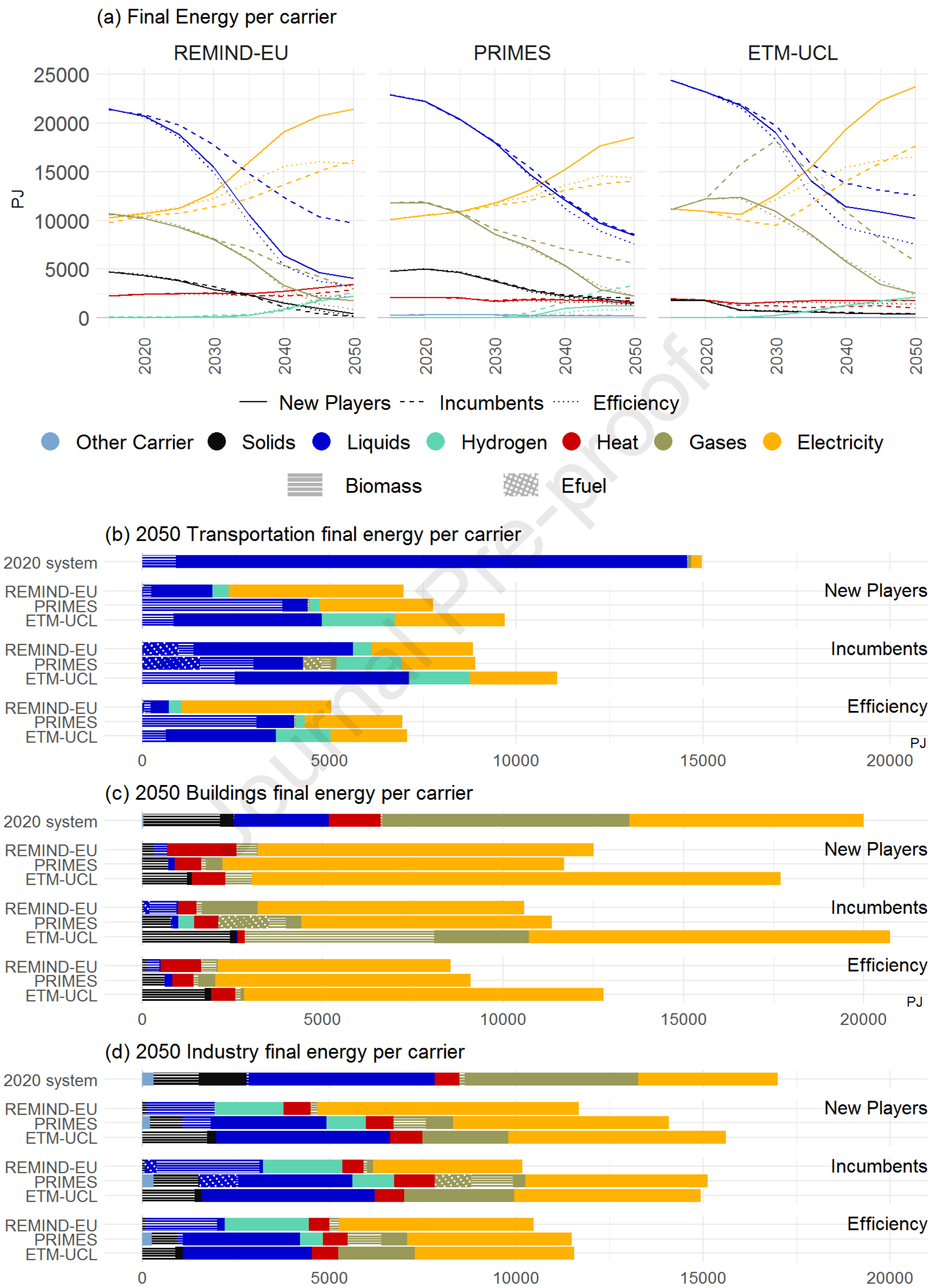

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Figure 6. Final energy per carrier (a). Final energy per sector and carrier in 2050: Transportation (b), Buildings (c) and Industry (d) in EU-28. (units: PJ per year)

The first decade of the decarbonization process is dominated by no-regret mitigation measures, mainly energy efficiency measures and electrification of light duty transport and buildings heating. Electricity continuously replaces the use of fossil energy carriers like liquids, gases and solids during the decarbonization process until its potentials are gradually exhausted.

In situations where electrification is uncertain or impractical, such as technical processes requiring high energy density or those requiring very high temperature heat, alternatives to electrification such as bioenergy, hydrogen and e-fuels become relevant. While the first faces the already mentioned challenges related to biomass availability in Europe, the latter two require specific policies to become competitive, as the related technologies are currently immature and have high costs.

Hydrogen becomes a relevant energy carrier after 2030. Currently, hydrogen is still an immature energy carrier, hindered by its high production and transportation costs, low market penetration, logistics challenges and lack of production infrastructure. Nevertheless, strong supporting policies can potentially create the necessary push to transform it into a feasible low-emission alternative (especially if produced from renewable-energy-system based electricity) to decarbonise demand sectors for the future[15].

All models' results show green hydrogen being deployed in high energy density heavy freight and passengers transport (Figure 6.b). Hydrogen also replaces a substantial share of the gases used in high-temperature industrial processes in both REMIND and PRIMES results by mid-century, and can be also deployed in direct reduced iron production (Figure 6.d). Heat pumps and district heating competitiveness limit the hydrogen use in the residential and commercial sector, being only relevant under PRIMES assumptions for the *Incumbents*' scenario, which include natural gas network adaptations and additional end-user appliances deployment and conversion policies (Figure 6.c).

Finally, energy efficiency improvements in end-uses and reduction of demand is an important mitigation option as identified by all participating models across scenarios, substantially reducing the strain on the energy supply system and the pressure on renewable energy potential. This is directly observed in the *Efficiency and Sufficiency* scenario throughout all results in this paper. Higher societal engagement in the decarbonization

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[15] Hydrogen specific pushing policies could increase its competitiveness against fossil based established energy carriers by, for example: promoting skilled labour training and availability for end-user installation and appliances conversion; supporting investments in pipeline network adaptations, conversion and/or hydrogen blending increase; scaling-up the supply chain to increase its dissemination rate and re-supply station network deployment, allowing competitiveness in the heavy duty transport activity; supporting the emergence of international supply chain H_2 trading flows, reducing supply costs and taking advantage of specific regional capabilities; increasing industrialisation of fuel cell and hydrogen tank manufacturing; increasing renewables penetration and allowing the emergence of secondary revenue sources from power system supply stabilization and storage services provided by hydrogen activities; etc.

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process can substantially reduce: the scale of the electrification effort (Figure 5), allowing mitigation targets to be achieved even under lower than expected renewable deployment rates; required carbon prices (Figure 2b); the need for residual mid-century emissions compensation (Figure 2b); transportation decarbonization requirements (Figure 6b); bio-energy resources requirement and land-use competition; and so on. Although *Efficiency and Sufficiency* decarbonization policies can be at a certain degree more uncertain by relying in behavioural change of millions of individuals, they clearly provide a no regret option reducing the burden of the decarbonization process if successfully coordinated and implemented.

3.2. National strategies

As seen so far, although important mitigation measures on the road to net-zero emissions can be identified, there is no single strategy that dominates the EU decarbonization process in the evaluated scenarios. The same is true also when assessing national decarbonization strategies results.

Figure 7 show the 2050 electric power generation for the two biggest continental EU economies: Germany and France.

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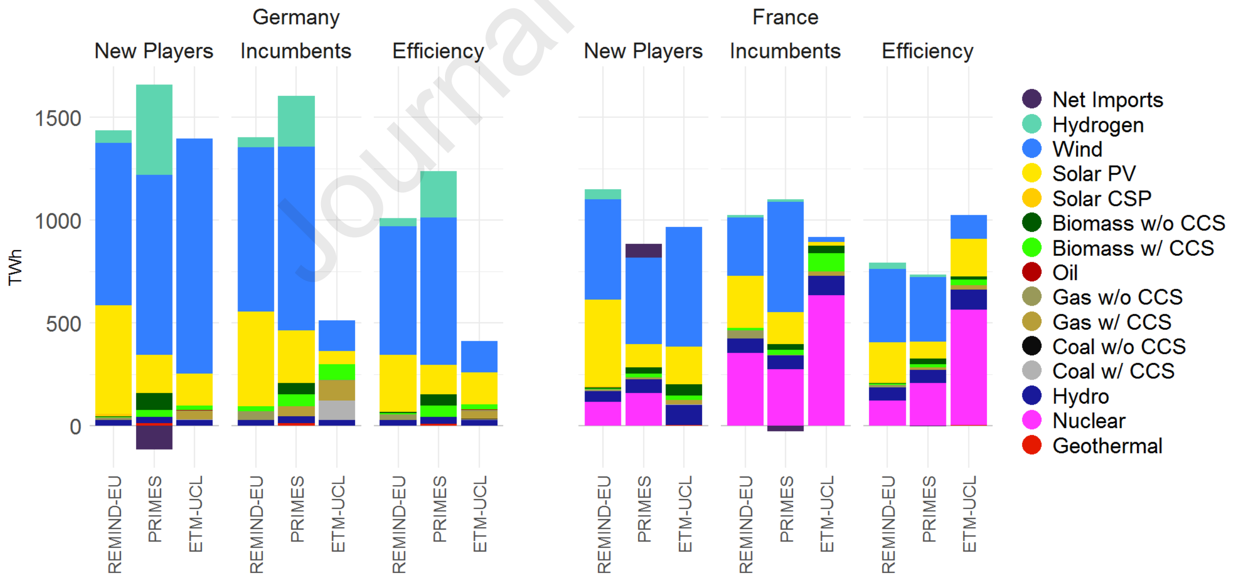

Figure 7. 2050 Electricity Generation (TWh per year)

Variable renewables are more broadly used in the German electric power system as the main mitigation option to reduce electricity-related emissions; meanwhile France electric power generation portfolio relies in a more heterogeneous mix including substantial nuclear power participation, even under non-nuclear favourable scenarios, albeit at lower levels than today. This result portrays the fact that national strategies can differ, but still coexist, in the same scenario in a 2050 decarbonized Europe.

This is an important insight for current policy design as, even considering the same model and decarbonization narrative, under a perfect foresight modelling approach, looking ahead 30 years in the future, and considering an integrated European decarbonization strategy (as implicit in the modelling assumptions that differ between scenarios), national specificities and priorities remain relevant for the decarbonized system by mid-century, as highlighted in recent research of low-carbon pathways in eleven major-emitting economies [50].

4. Summary and conclusions

In this study, we have analysed European mid-century carbon net-neutrality targets under three stakeholder-designed narratives that represent possible future energy system developments. The stakeholders' narratives were translated into specific techno-economic expectations and represented in the modelling tools through a dedicated set of assumptions on policies, technologies and dynamic interaction. A model comparison exercise using three state of art energy system models provided quantitative simulations of the resulting alternative decarbonization pathways for European countries. Special focus was on (1) analysing feasibility and the transformation pathways of quite different, and highly decarbonized, future energy systems; and (2) identify if there are robust strategies that are relevant across narratives to achieve the low-carbon transition by 2050.

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To reach ambitious mitigation goals within the *New Players and System* narrative, electrification of energy services needs to be significantly upscaled, which requires that customers actively embrace new electricity-based end-use technologies like battery-electric vehicles and heat pumps.

In the *Incumbents* scenario, the key challenge is the upscaling of carbon capture and storage, nuclear power and synthetic and bio-based fuels, which are needed for the fundamental reshaping of the energy supply side to provide emission-neutral fuels that allow end users to continue using energy equipment and infrastructure as they are used to.

The *Efficiency and Sufficiency* scenario shows that ambitious supporting policies targeting energy and resource efficiency, including deep renovation, lifestyle changes, energy savings, circular economy and shared mobility may lower the need for supply-side investment and reduce the required carbon price.

The major findings from a policy design perspective were: (1) Stringent climate policies (represented in the modelling as high carbon prices of 300-900€/tCO_2) are needed in all scenarios to achieve carbon net neutrality in 2050; (2) Demand-side electrification, combined with significant upscale of variable renewables and storage, is key under all strategies: the electrification share at least doubles compared to 2015, and can go as high as

60% of total final energy in 2050; (3) No matter which strategy, both demand and supply sectors have to fundamentally change: all three carbonaceous energy carriers (solids, liquids and gases) are reduced to less than half their 2015 usage, even under the *Incumbents*' scenario that limits demand-side changes to a minimum; (4) Carbon Dioxide Removal plays an important role for contributing the last 200-400 Mt CO_2/yr emission reductions towards achieving net CO_2 neutrality targets under all strategies; under limited demand-side changes in *Incumbents*, the contribution can be as high as 1074Mt CO_2/yr. Given the very limited deployment so far, there is a current necessity for early policy action to develop and upscale CDR options in the next decade; (5) Biomass is primarily used as mid-century negative emissions provider, in the form of BECCS, under a limited biomass supply case; and as an important alternative to carbonaceous decarbonization (biofuels) if supply is available; (6) Under favourable assumptions or the presence of supporting policies, hydrogen can become an important contribution to mid-century mitigation especially in hard-to-abate sectors such as high-temperature industrial processes and heavy-duty transport. The same is true for the synthetic fuels that can be used to provide carbon-free fuels in transport, industries and buildings; (7) Energy efficiency improvements in end-uses and demand reductions is a relevant mitigation option in all sectors, substantially reducing the strain on the energy supply system and the pressure on renewable energy potential; (8) Mid-century national strategies can differ, but still coexist, in the same decarbonization scenario, as national policy priorities and specificities play a key role in the development of national low-carbon transition strategies.

However, there is still much further work that needs to be done to better understand the trade-offs of different decarbonization strategies for the EU. While the modelling demonstrates the techno-economic feasibility of the narratives, questions remain about the social dimensions and political feasibility of such rapid change. The group of European policymakers we engaged through our scenario workshops felt that the pathways were plausible routes for European decarbonisation. However, they also raised a range of potential barriers to success, including many issues that cannot be easily analysed using E3 model results analysis.

Key issues of concern raised by policy stakeholders focused in particular on political challenges, particularly those related to the potential for climate policies to generate political backlash by groups or regions that are negatively affected. They stressed the importance of policies that support a 'just transition' to avoid such outcomes. There was also concern about the potential for political populism to undermine public consent for strong climate policies.

Stakeholders were also concerned about the potential for innovative developments to be stymied by social and political reactions to change. For example, data-enabled solutions could be held back by privacy concerns, while support for renewables could be undermined if system operators fail to maintain grid reliability as the penetration of variable sources reaches ever higher levels. At the same time, policy stakeholders discussed the

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potential for social movements to play an important and supportive role in driving shifting social norms and life-styles, and in influencing the actions of governments and corporate actors to change.

From the modelling side, improved representation of national policies, path dependencies and societal differences can improve energy system models capacities on addressing the European decarbonization strategies. Relevant policy design dimensions as national mitigation burden sharing and socio-economic and distributional consequences of the possible transition pathways remain to be evaluated under the narratives framework. Also, a key assumption behind all three narratives was a strong cooperation across all of the EU, with a common goal and strategy. It would be important to provide a quantitative assessment of a fourth narrative that came up in the stakeholder process, in which different Member States follow explicitly different targets and strategies: a Europe of multiple speeds.

In summary, our results show that different strategies can lead to a decarbonized EU energy system in 2050, thus current policy choices on which technologies and options to support may strongly shape the future energy system. Still, a number of robust commonalities emerge across all strategies and models, pointing out no-regret options important for all analysed strategies, such as accelerated renewables deployment, electrification of end uses and bringing CDR technologies and e-fuels to maturity. Fast implementation of these no-regret options is a cornerstone of any mitigation strategy that will succeed in achieving the European 2030 and 2050 targets.

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A. Scenarios taxonomy and model assumptions

Table 2. Scenarios taxonomy and model assumptions.

	Narrative techno-economics	Model Assumptions
New Players and systems	Widespread electricity fuel switching in heating and in industrial sectors	Cost reduction and higher uptake of heat pumps and electric boilers in buildings. Strong electrification: heating processes, heat generation and industrial processes. Increased electricity price elasticity.
	Higher rates of transport electrification	Stronger innovation lowering Electric Vehicles (EV) battery costs. Increased learning in batteries. Increasing EV market acceptance. Extensive and timely development of battery recharging infrastructure.
	Renewables penetration	High solar and wind deployment. Increased learning potential for variable renewables. Reduce adjustment costs due to parallel supporting policies to renewables. Demand response facilitates renewables integration. Increased storage competitiveness. Increased smart grids and transmission network capability to integrate variable renewables.
	Hydrogen importance on more challenging decarbonizing activities: aviation, heavy-duty transportation and certain industries	Green hydrogen takes advantage of renewables high penetration and potential curtailment.
	Incumbent technologies	Limitations to nuclear power new investments. Limitations in bioenergy deployment in the power sector
	Hurdles to CCS realization make CCS use more expensive and slower to scale up	Increased adjustment costs for CCS based technologies. Postponed CCS investments (2035).
Incumbents' renewal	Concern for 'just transition' drives strong government support for building energy measures for lower-income consumers and regions	Lowered electricity price elasticity. Heat networks increased penetration in relation to heat pumps.
	Passenger car remains the dominant form of personal mobility, with a relatively slow adoption of electric vehicles.	Technology progress and cost reduction of fuel cells for transportation. Biofuel as competitive alternative. EVs slower penetration.

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	Narrative techno-economics	Model Assumptions
Incumbents 'Renewal (cont.)	Wind, solar, storage and transmission grid development is not in the focus, so costs reduce more slowly, and renewables integration is more challenging	Increase adjustment costs to renewables. Reduced learning gains.
	End-use energy carriers do not substantially change, rather the supply side changes: solids, liquids and gases are supplied from bio-energy and power-to-x	Incumbent technologies supply side driven substitution.
	Synthetic liquid/gaseous fuels become important energy carrier substitutes	Maximization of the learning potential of Power-to-X technologies. Economies of scale leading to cost reduction for H2 and clean synfuels. Increased public and political acceptance of synthetic fuels. Facilitation of investments in the production of synthetic fuels and H2.
	Hydrogen potentially displaces traditional fuels in network infrastructures where conversion of end uses is easy: gas boilers in industry and buildings are replaced; Gas-infrastructure owners push 'green-gas' options – including biogas as well as hydrogen	Technology progress and cost reduction for hydrogen production technologies. Higher share of H2 can be mixed with natural gas in gas grids for buildings demands. Faster development of hydrogen refuelling stations and grid.
	Incumbents use their continued power to ensure that some of their CO_2-intensive plants are shielded from policy measures, thus running for 5-10 years longer than in the other scenario/ optimal based on CO_2 prices	Countries with nuclear tradition keep using a higher share of this technology. Investment cost incentives to retrofitting incumbents technologies extend their lifetime. More optimistic assumptions for CCS technologies (for costs and public acceptance). Earlier CCS availability in regions with current projects. Centralized heat is pushed in building and industry. More bioenergy use in residential and commercial space and water heating.
Efficiency and sufficiency	Very high levels of efficiency in buildings, and saturation of energy service demands– resulting in substantially reduced final energy demand (and reduced energy service demands) against the baseline.	Final energy reduction through efficiency measures. Increased rate and deepness of Renovation in buildings. Eco-design standards for the appliances are tightened. Changes in consumer behaviour and adoption of environmentally-friendly lifestyles. Reduced costs for heat pumps and electrified water heating in residential and commercial buildings.

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	Narrative techno-economics	Model Assumptions
Efficiency and sufficiency (cont.)	Dietary shift to lower red meat and dairy consumption, largely driven by health concerns and shifting social norms in some societies. This involves a continuation of long-term trend away from beef so that beef consumption is 50% lower in 2050 than in 2015; significant but less dramatic reductions in dairy, with growth in poultry& plant-based protein	Final energy reduction through new lifestyle change.
	Circular economy: Lower industrial energy demand by 2050: e.g. at least 10%reduction against baseline in demand for cement, at least 15% reduction in demand for steel in 2050; at least 10% reduction against baseline in demand for plastics	Application of advanced Best Available Techniques in industry. Significant energy efficiency effort and heat recovery in industry.
	Shift towards greater mode shares for walking, cycling, e-bikes and public transport. Vehicles see strong electrification	Modal shifts in transport sector (e.g. use of public transport) and emergence of shared mobility. Rapid replacement of conventional inefficient cars. Increased EVs penetration.
	Local freight transport demand does not decrease, and may increase slightly relative to baseline: lower overall demand for material goods, but more complex reverse logistics supply chains.	Reduced domestic and international aviation.

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B. Models description

This section presents a description of the models used in this paper analysis.

B.1 REMIND

REMIND (Regional Model of Investments and Development) is a global multi-regional energy-economy-climate model spanning the years 2005–2100. Figure 1 illustrates its general structure. The macro-economic core of REMIND is a Ramsey-type optimal growth model in which inter-temporal welfare is maximized.

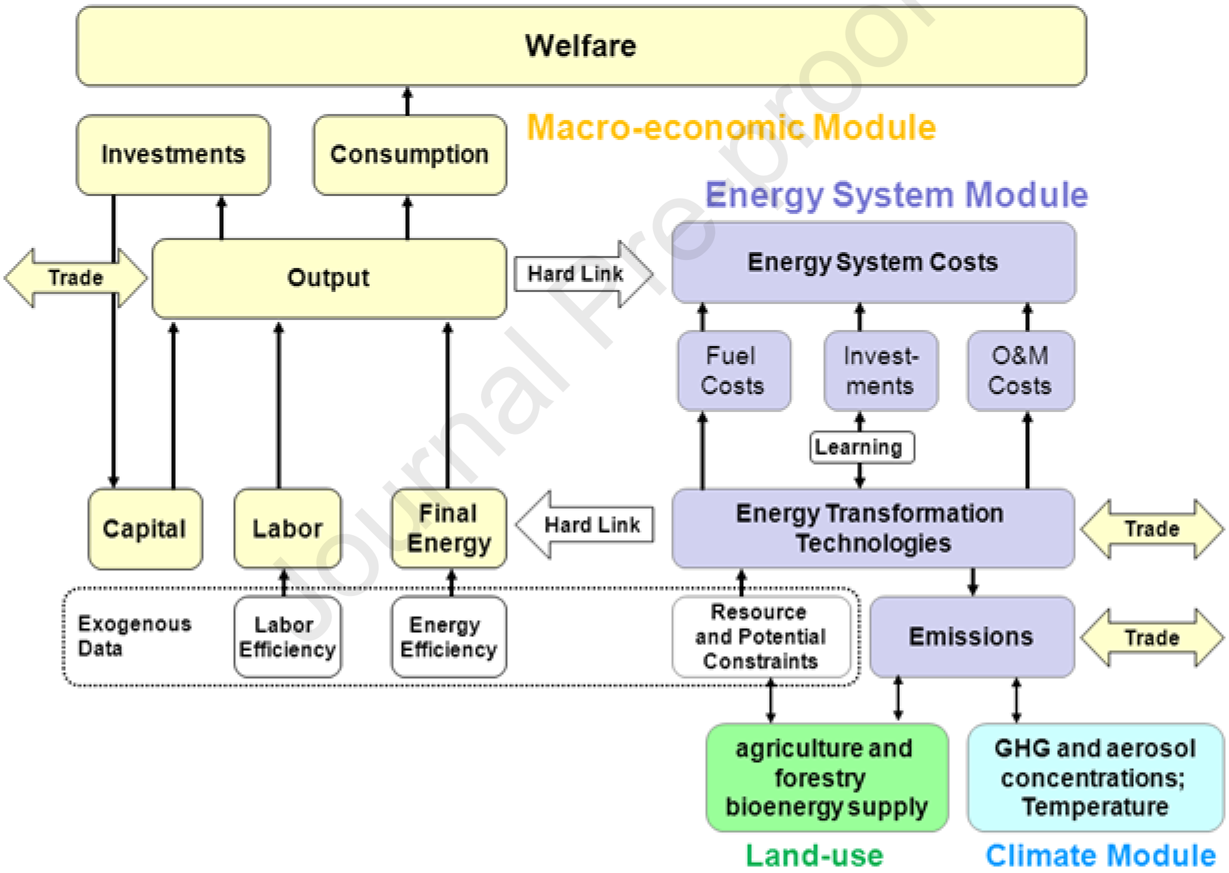

Figure 1. General structure of the REMIND model.

The REMIND-EU model version, developed specifically for this assessment, extends the traditional REMIND formulation of 12 world regions to 21 regions (see Figure 2), introducing a total of nine regions representing European Union and UK, and two additional regions that represent the remaining continental European countries.

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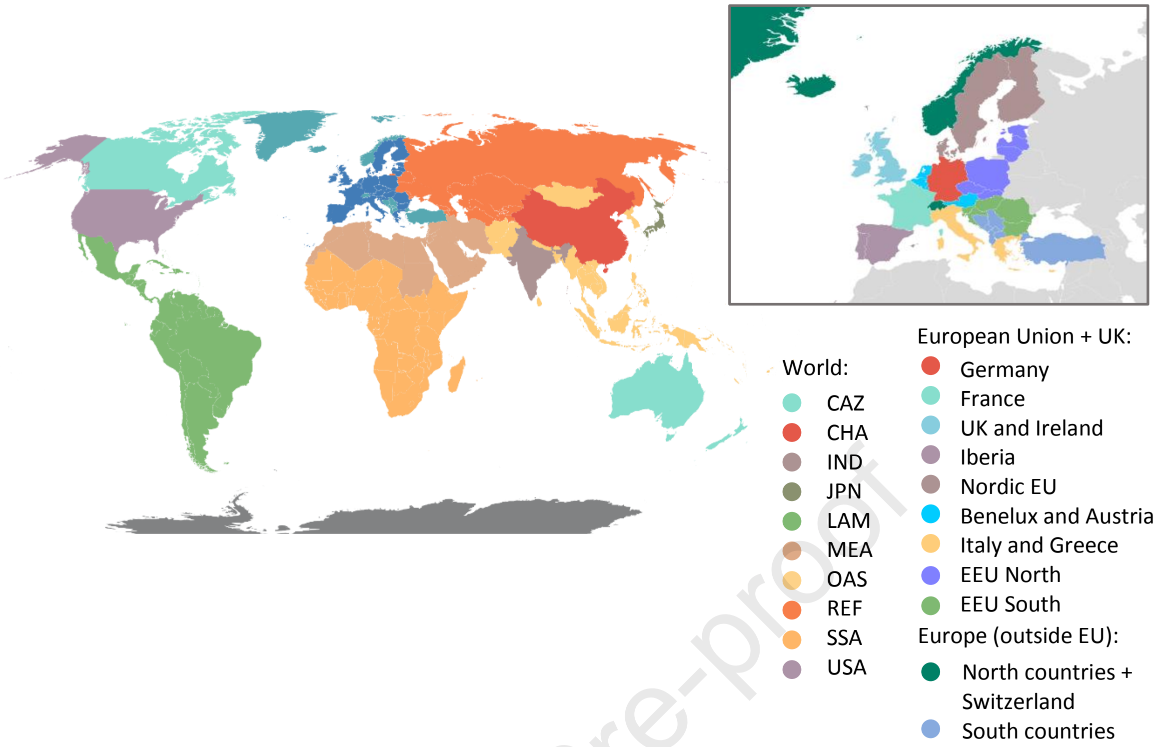

Figure 2. REMIND-EU regions.

The model computes the market equilibrium either as a Pareto optimal solution in which global welfare is maximized (cooperative solution assuming all externalities are internalized), or as a non-cooperative Nash solution in which welfare is optimized on the regional level without internalization of interregional externalities. The model explicitly represents trade in final goods, primary energy carriers, and in the case of climate policy, emissions allowances. Macro-economic production factors are capital, labor, and final energy. REMIND uses economic output for investments in the macro-economic capital stock as well as consumption, trade, and energy system expenditures.

The macro-economic core and the energy system module are hard-linked via the final energy demand and costs incurred by the energy system. Economic activity results in demand for final energy such as transport energy, electricity, and non-electric energy for stationary end uses. A production function with constant elasticity of substitution (nested CES production function) determines the final energy demand. The energy system module accounts for endowments of exhaustible primary energy resources as well as renewable energy potentials. More than 50 technologies are available for the conversion of primary energy into secondary energy carriers as well as for the distribution of secondary energy carriers into final energy.

REMIND uses reduced-form emulators derived from the detailed land-use and agricultural model MAgPIE to represent land-use and agricultural emissions as well as bioenergy supply and other land-based mitigation options. REMIND can also be run in fully coupled mode with the MAgPIE model.

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The model accounts for the full range of anthropogenic greenhouse gas (GHG) emissions, most of which are represented by source. The MAGICC 6 climate model is used to translate emissions into changes in atmospheric composition, radiative forcing and climate change.

In terms of its macro-economic formulation, REMIND resembles other well established integrated assessment models such as RICE and MERGE. However, REMIND is broader in scope and features a substantially higher level of detail in the representation of energy-system technologies, trade, and global capital markets. In contrast to RICE, REMIND does not monetize climate damages, and therefore is not applied to determine a (hypothetical) economically optimal level of climate change mitigation ("cost-benefit mode"), but rather efficient strategies to attain an exogenously prescribed climate target ("cost-effectiveness mode").

Table 3 provides an overview of REMIND's key features.

Table 3. Key features of REMIND

Macro-economic solution concept	Ramsey-type growth model with inter-temporal optimization of welfare
Discounting	Endogenous interest rate in the international capital market reflects the pure time preference rate (default 3%), as well as the marginal utility of consumption which diminishes with increasing per-capita consumption in line with the Keynes-Ramsey-Rule. This gives rise to a model endogenous interest rate of around 5-6%.
Expectation formation	Default: perfect foresight.
Cooperation	Either cooperative pareto-optimal solution with maximization of global welfare (Negishi), or non-cooperative Nash solution maximizing welfare for each individual regional.
Economic sectors, macro-economic production system	Closed-economy growth model with a detailed energy sector. Nested CES production function: a generic final good is produced from capital, labor, and different final energy types.
International macro-economic linkages / Trade	Single market for all commodities (energy resources, final good, permits).
Investment dynamics	Capital motion equations, vintages for energy supply technologies, adjustment costs for acceleration of capacity expansion.
Link between energy system and macro-economy	Hard-linked hybrid model. Economic activity determines final energy demand. Energy system costs (investments, fuel costs, operation, and maintenance) are included in the macro-economic budget.
Representation of end-use sectors	Stationary (which aggregates industry, residential and commercial), transport.
Energy production system and substitution possibilities	Linear substitution between competing technologies for secondary energy production. Supply curves for exhaustible resources (cumulative extraction cost

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	curves) as well as renewable potentials (grades with different capacity factors) introduce convexities.
Technological Change / Learning	Endogenous technological change through learning-by-doing with a global learning curve for wind, solar PV and solar CSP (cf. Section 3.2.1), as well as hybrid, electric and fuel cell vehicle technologies (cf. Section 3.3.1). Labor productivity and energy efficiency improvements are calibrated to reproduce historic patterns.
Implementation of climate policy targets	Pareto-optimal achievement of policy targets on GHG concentration, radiative forcing, or temperature levels under full when-flexibility. Allocation rules for distribution of emissions permits among regions. Other options: emissions caps and budgets, greenhouse gas taxes.
Land-use	Representation of bioenergy supply, land use CO_2 and agricultural non-CO_2 emissions based on a detailed land use model.

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B.2 PRIMES

The PRIMES (Price-Induced Market Equilibrium System) energy model simulates the European energy system and markets on a country-by-country basis and across Europe for the internal electricity and gas market. The model provides projections of detailed energy balances, CO_2 emissions, investment in demand and supply, energy technology penetration, energy prices and costs over the period from 2015 to 2070 in 5-years intervals. The PRIMES model covers individual projections for the EU Member States, and for neighbouring countries including Norway, Switzerland, Turkey and the Balkans.

PRIMES is a large scale applied energy system model that provides detailed projections of energy demand, supply, prices and investment to the future, covering the entire energy system including emissions. The distinctive feature of PRIMES is the combination of behavioural modelling (following a micro-economic foundation) with engineering aspects, covering all energy sectors and markets. The model represents a variety of instruments for policy impact assessment related to energy markets and climate, including market drivers like the ETS, efficiency standards, and targets for renewable energy or CO_2 reduction by sector or overall. It handles multiple policy objectives, such as GHG emissions reductions, energy efficiency, renewable energy targets and provides pan-European simulation of internal electricity and gas markets.

PRIMES is designed to analyse complex interactions within the energy system in a multiple agent-multiple markets framework. It simulates a multi-market equilibrium solution for energy supply and demand and for ETS and other potential markets (e.g. gas, hydrogen) by explicitly calculating prices which balance demand and supply. PRIMES simulates demand and supply behaviour by agent and sector under different assumptions regarding socio-economic development, emission and other policy constraints, technology change, international energy prices, development of network infrastructure, consumption patterns and other drivers.

PRIMES offers the possibility of handling market distortions, barriers to rational decisions, behaviours and market coordination issues and it has full accounting of costs (CAPEX and OPEX) and investment on infrastructure needs. Decisions by agents are formulated based on microeconomic foundation (utility maximization, cost minimization and market equilibrium) embedding engineering constraints and explicit representation of technologies and vintages; optionally perfect or imperfect foresight for the modelling of investment in all sectors is included. PRIMES is well placed to simulate medium and long term transformations (rather than short term) for the transition towards climate neutrality by mid-century and includes non-linear formulation of potentials by type (resources, sites, acceptability etc.) and endogenous technology learning for all energy supply and demand technologies.

PRIMES determines the equilibrium by finding the prices of each energy form such that the quantity producers find best to supply match the quantity consumers wish to use. The market equilibrium is forward looking and includes dynamic relationships for capital accumulation and technology vintages in energy supply and demand sectors. The model formulates agents' decisions according to microeconomic theory, at the same time representing, in an explicit and detailed way, the available energy demand and supply technologies as well as pollution abatement technologies.

The formation of energy prices reflects considerations about market competition economics, industry structure, energy and climate policies and regulation. Information about alternative policy options is also included at a considerable level of detail. The model is designed to handle renewable, energy efficiency and climate change mitigation targets, with representation of various possible policy instruments. The model produces detailed analysis of technology uptake, investment requirements, energy system costs and other implications of policies as required by impact assessment analysis.

Typical Inputs to the PRIMES Model	**Typical Outputs of the PRIMES Model (per country and time period)**
GDP and economic activity per sector	Detailed energy balances (EUROSTAT format)
World energy supply outlook – world prices of fossil fuels	Detailed balance for electricity and steam/heat
Tax and subsidy policies	Production of new clean fuels
Interest rates, risk premiums, etc.	Transport activity, modes/means and vehicles
Environmental policies and constraints	Association of energy use and activities
Gas and electricity network infrastructure	Investment, technologies and vintages in supply and demand sectors

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Technical and economic characteristics of energy technologies	Energy costs, prices and investment expenses per sector and overall
Energy consumption habits and comfort parameters	CO_2 Emissions from energy combustion and industrial processes
Cost-supply curves of potential for primary energy, potential of sites for new plants, energy efficiency potential, renewables potential per source type, etc.	Policy Assessment Indicators (e.g. energy efficiency improvement, shares of renewable energy, emission reductions etc)

The full suite of PRIMES comprises the following sectoral models that are closely interlinked:

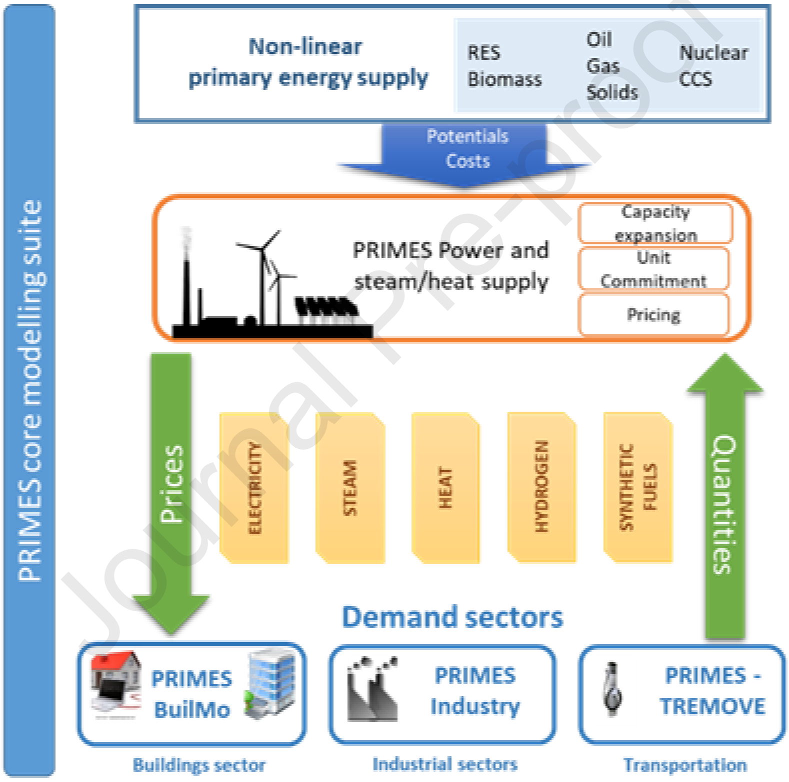

Figure 3. The PRIMES modelling suite.

PRIMES-TREMOVE transport model:

It includes passenger and freight transportation and all transport modes (road, rail, aviation, inland navigation) and several transport types (e.g. cars, two-wheelers, trains, airplanes etc.) in different areas (metropolitan, rural, motorway, etc.). Each transport type is characterised by a variety of vehicle technologies and fuel options. The model represents alternative fuel infrastructure including LPG, CNG, LNG, various biofuel blends as well as electricity and hydrogen, while behavioural elements are also simulated including range anxiety. It is recently enhanced to include linkage to synthetic fuels and hydrogen and to detailed spatial projections of transport activity and route assignment.

PRIMES BuiMo residential and services model:

New model with high resolution representation of the housing and office building stock embedded in an economic-engineering model of multi-agent choice of building renovation, heating system and equipment/appliances by energy use. The model is designed to simulate different building types and income classes and can thus be used to assess the impacts of energy efficiency and climate policies on energy poverty. It includes different end-use processes (e.g. space heating, water heating, cooking) and a variety of electrical durable goods (e.g. refrigerator, washing machine, television), while the modelling of renovation in the building stock has been significantly enhanced to capture deep retrofitting strategies in buildings.

PRIMES-Industry model:

The recently enhanced version of the very detailed industrial PRIMES model includes 12 industrial sectors (focusing on energy and carbon-intensive industries, including iron and steel, cement, chemicals, paper and pulp, non-ferrous metals), subdivided into 26 sub-sectors using energy in 12 generic processes (e.g. air compression, furnaces). The PRIMES-Industry model includes a high resolution split of industrial consumption by sector and type of industrial process and the possibility of using hydrogen and synthetic fuels directly, extended possibilities of electrification, the potential deployment of Carbon Capture Use and Storage options and the possible emergence of non-fossil hydrocarbon feedstock in the chemicals

PRIMES Biomass supply model:

Detailed biomass supply model that includes land use constraints, many types of biomass and waste feedstock/resources, sustainability regulation and endogenous learning and industrial maturity of a large number of potential biomass to biofuels conversion technologies. It computes the optimal use of biomass/waste resources and investment in biomass transformation processes so as to meet a given demand of final biomass/waste energy products;

PRIMES Electricity and Heat/Steam supply and market model:

Fully new model version which includes the hourly unit commitment model -with pan-European market simulation of the electricity market over the grid constraints and detailed technical operation restrictions, the long-term power system expansion model, the costing and pricing electricity and grid model, the integration of heat supply and industrial steam supply with synchronised hourly operation

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PRIMES Gas Supply and Market model:

It can be used in stand-alone version or linked with PRIMES system model and represents in detail the gas supply infrastructure (field production facilities, transmission pipelines, LNG Terminals, Gas Storage, Liquefaction Plants) in the Eurasian and Middle-East area and the internal European market of gas within an oligopoly model embedding engineering gas flow modelling

PRIMES new Fuels and storage model

The PRIMES new Fuels module includes a detailed representation of Hydrogen production and transport, clean Synthetic fuels, Power-to-X options, CO_2 capture from the air and biogenic, CCS/CCU and process-emissions modelling to enhance and perform sectoral integration aiming at simulating a zero-CO_2 system towards the climate neutrality transition by mid-century

PRIMES IEM model:

A simulation tool for the internal EU electricity market; it aims to simulate in detail the sequence of operation of the European electricity markets, namely the day-ahead market, the intraday and balancing markets and finally the reserve and ancillary services market or procurement.

The PRIMES energy system model (and its linkages with GEM-E3 macroeconomic model and PROMETHEUS for world energy markets) is regularly used to support benchmark climate policy impact assessments for the European Commission, including the recent “Clean Planet for all” long-term strategy, the Climate Package for all Europeans, the “Energy Roadmap 2050” and the “Roadmap for moving to a low-carbon economy in 2050”. Aside for the European Commission the model is used for providing services to several governmental agencies in Europe (France, Belgium, Portugal, Slovakia, Spain, Greece, Romania, Slovenia and others) and to business associations including Eurogas and Eurelectric.

B.3 ETM-UCL

The European TIMES Model at UCL (ETM-UCL) is a partial equilibrium linear optimisation energy system model with an inter-temporal objective function to minimise total discounted system costs, based on the ETSAP-TIMES model generator[16]. It is a technology-rich, bottom-up model with perfect foresight and covers energy flows and infrastructure investment from the supply of primary energy through various secondary

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[16] https://iea-etsap.org/index.php/etsap-tools/model-generators/times

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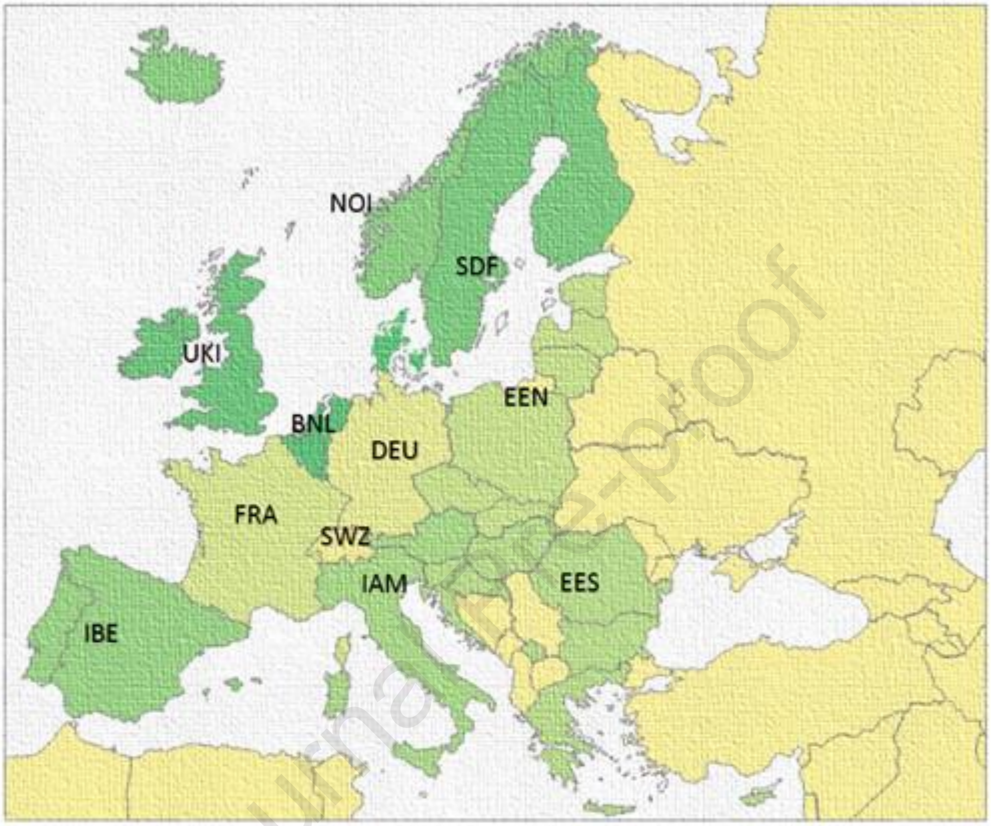
energy processing sectors to five demand-side sectors, i.e. residential, commercial, industry, transport and agriculture. The model comprises a total of thirty-one countries (EU28 plus Norway, Iceland and Switzerland), grouped into eleven regions (see Figure 4).



Region Code	Region Name	Countries Within Region
BNL	Benelux	Belgium, Netherlands and Luxembourg
SWZ	Switzerland	Switzerland
DEU	Germany	Germany
FRA	France	France
IAM	Italy, Austria, Malta	Italy, Austria and Malta
IBE	Iberia	Spain and Portugal
NOI	Norway and Iceland	Norway and Iceland
SDF	Sweden, Denmark, Finland	Sweden, Denmark and Finland
UKI	United Kingdom and Ireland	UK and Ireland
EEN	Eastern Europe – North	Estonia, Lithuania, Latvia, Czech Republic, Slovakia and Poland
EES	Eastern Europe - South	Slovenia, Hungary, Romania, Bulgaria, Greece, Cyprus and Croatia

Figure 4. Regional definition in ETM-UCL

Each region is modelled with primary and secondary energy and demand side sectors, and are linked through trade in crude oil, hard coal, pipeline gas, LNG, petroleum products, biomass and electricity. In addition, there is a “global” region which serves as a simple ‘basket of resources’ from which other regions may import the above products (except electricity). The model is calibrated to a base year of 2010, with energy

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service demands projected into the future using the exogenously input drivers of GDP, population, household numbers and sectoral output (linked to GDP), for each region. The countries that form these regions have been aggregated or modelled as single-country regions considering several factors: geographic proximity, relevance in terms of energy production and/or consumption to the EU28 system and gas and electricity transmission networks. The trade-offs of this configuration have also considered achieving policy goals without too much additional burden on the model computation.

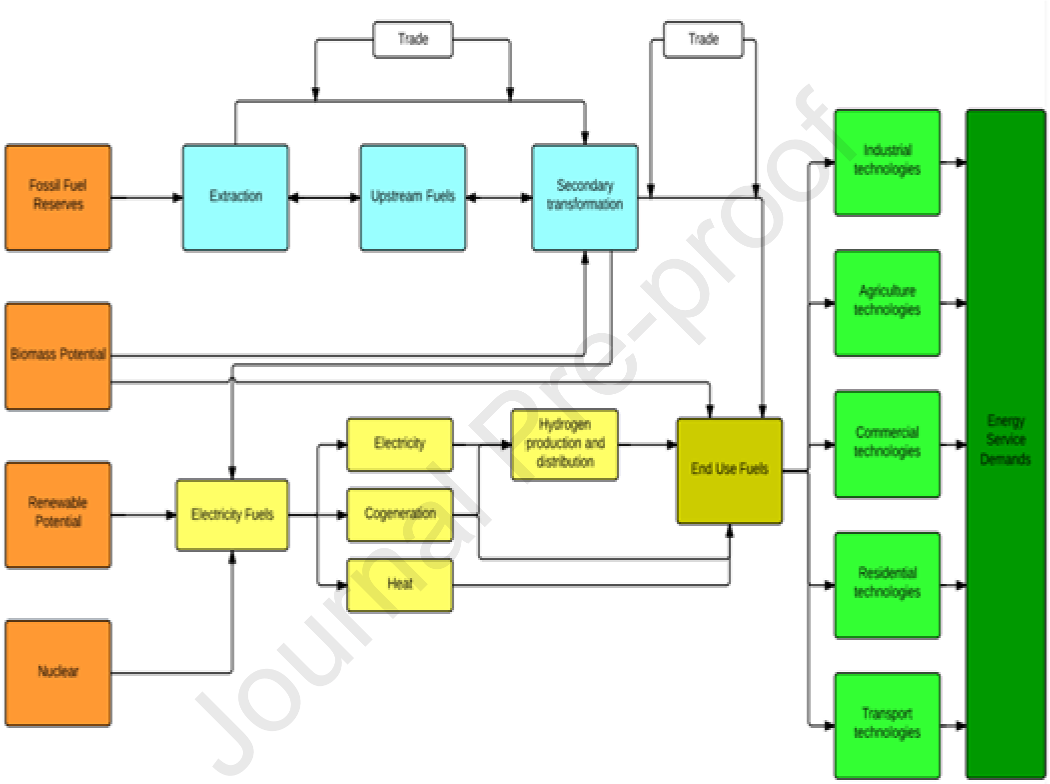

Figure 5. A simplified representation of Reference Energy System in ETM-UCL.

ETM-UCL models the evolution of the European energy system from 2010 to 2050 subject to a range of techno-economic and policy based constraints which can be adjusted and/or added based on the particular scenario being modelled. A simplified version of the reference energy system in ETM-UCL is shown in Figure 5 and depicts the energy flows that may occur within the model. For further details, see the full online documentation[17] and model publications [18,19].

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[17] https://www.ucl.ac.uk/energy-models/models/etm-ucl

[18] Techno-Economic Scenarios for Reaching Europe's Long-Term Climate Targets. CECILIA 2050. Optimal EU Climate Policy. Accessed September 7, 2020. https://cecilia2050.eu/publications/214.html

[19] Rodriguez, Baltazar Solano, Paul Drummond, and Paul Ekins. "Decarbonizing the EU Energy System by 2050: An Important Role for BECCS." Climate Policy 17, no. sup1 (June 1, 2017): S93–110. https://doi.org/10.1080/14693062.2016.1242058

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Narrative-driven alternative roads to achieve mid-century CO_2 net neutrality in Europe

Renato Rodrigues[*], Robert Pietzcker, Panagiotis Fragkos, James Price, Will McDowall, Pelopidas Siskos, Theofano Fotiou, Gunnar Luderer and Pantelis Capros

Highlights

- Multi-model assessment of three stakeholder-designed EU decarbonization narratives.
- There is not a single decarbonized future alternative, but prompt action is necessary.
- High carbon prices, 300-900€/tCO2, are needed to achieve 2050 EU carbon neutrality.
- Energy efficiency, electrification and large-scale renewables are no-regret decisions.
- CO_2 removal is important to net-neutrality; H_2 and synfuels to hard-to-abate sectors.

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Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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