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D5.3 GLOBAL PATHWAYS & EU RESPONSE: A 1ST EUROPEAN REGIONAL, NATIONAL AND SECTORAL ASSESSMENT

WP5 – Transforming Europe

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EC Summary Requirements

1. Changes with respect to the DoA

No change with respect to the work described in the DoA. The deliverable was submitted on time (May 31, 2021), and then revised in September 2021 with the finalised Section 3.2.

2. Dissemination and uptake

This deliverable will remain confidential, available only to members of the consortium and the Commission Services, until its content is published in a series of academic journals.

3. Short summary of results

We present the first batch of Paris reinforce models' runs for EU that has implemented the "Where are We Headed" scenario protocol which explores where the World is headed given countries' current climate action. This modelling exercice has been supported by an ensemble of eleven modelling tools and has allowed going through stakeholders' research questions, that have been collected at the beginning of the project. We found that the EU is currently on track to achieving the target of 40% emissions cuts but is still far from its newest ambition of 55% emissions cuts by 2030. We found that the level of CCS deployment appears intertwined with deeper emissions cuts, 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 which is nonetheless significantly outperformed by electrification. Detailed sectoral figures are also delivered thanks to sector specific models. In the building sector, CO_2 emissions decline by about 30% in 2030 and 50% in 2050 in comparison with 1990 equally driven by energy efficiency and fuel switch and in the transport sector, the decarbonisation is based on a rapid diffusion of electric vehicles in passanger cars and on hybrid diesel catenary trucks, for heavy duty vehicles. The literature review on existing quantitative figures for projected GHG emissions from the AFOLU sector shows that net emissions could range between -100 to +170 $MtCO_2$-eq./y in 2050 in EU. Finally, the study of post COVID-19 pandemic implications for the EU energy system shows, despite important short-term impacts, moderated effects in 2030 and the results confirm that behavioural changes observed during the pandemic could alleviate the GHG reduction burden in long-term.

4. Evidence of accomplishment

This report.

Preface

PARIS REINFORCE will develop a novel, demand-driven, IAM-oriented assessment framework for effectively supporting the design and assessment of climate policies in the European Union as well as in other major emitters and selected less emitting countries, in respect to the Paris Agreement. By engaging policymakers and scientists/modellers, PARIS REINFORCE will create the open-access and transparent data exchange platform I^{2}AM PARIS, in order to support the effective implementation of Nationally Determined Contributions, the preparation of future action pledges, the development of 2050 decarbonisation strategies, and the reinforcement of the 2023 Global Stocktake. Finally, PARIS REINFORCE will introduce innovative integrative processes, in which IAMs are further coupled with well-established methodological frameworks, in order to improve the robustness of modelling outcomes against different types of uncertainties.

NTUA - National Technical University of Athens	GR
BC3 - Basque Centre for Climate Change	ES
Bruegel - Bruegel AISBL	BE
Cambridge - University of Cambridge	UK
CICERO - Cicero Senter Klimaforskning Stiftelse	NO
CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici	IT
E4SMA - Energy Engineering Economic Environment Systems Modeling and Analysis	IT
EPFL - École polytechnique fédérale de Lausanne	CH
Fraunhofer ISI - Fraunhofer Institute for Systems and Innovation Research	DE
Grantham - Imperial College of Science Technology and Medicine - Grantham Institute	UK
HOLISTIC - Holistic P.C.	GR
IEECP - Institute for European Energy and Climate Policy Stichting	NL
SEURECO - Société Européenne d'Economie SARL	FR
CDS/UnB - Centre for Sustainable Development of the University of Brasilia	BR
CUP - China University of Petroleum-Beijing	CN
IEF-RAS - Institute of Economic Forecasting – Russian Academy of Sciences	RU
IGES - Institute for Global Environmental Strategies	JP
TERI - The Energy and Resources Institute	IN

Executive Summary

Since the ratification of the Kyoto Protocol in 1997, the European Union has developed climate change mitigation policies and signed in 2015, the Paris Agreement, that aims at keeping global temperature increase well below 2°C and pursuing efforts to limit the increase to 1.5°C. To comply with Paris Agreement, EU updates its climate change mitigation action. In 2020, EU has submitted to the United Nations Framework Convention on Climate Change (UNFCCC) its 2050 Long-Term Strategy that moved the previous 2050 target of at least -80% of GHG emissions in comparison to 1990 to the achievement of a climate neutral EU in 2050. It has been followed by the EU Green Deal strategy launched by von der Leyen Commission in December 2019 and endorsed by the European Council and the European Parliament in May 2021. The EU Green Deal aims, inter alia, reducing GHG emissions by at least 55% in 2030 in comparison with 1990 (European Commission, 2020d) instead of the former 40% milestone. In this document, we present the first batch Paris reinforce models' runs for EU that have focus on the EU current policies, i.e. prior to the EU Green Deal, and that will be used as reference scenarios for analysing Paris Agreement Compliant scenarios for EU. This first set of scenarios has implemented the "Where are We Headed", scenario protocol which explores where the World is headed given countries' current climate action and most recent pledges (Sognnaes et al.) and has been based on a harmonised set of socio-economic and techno-economics parameters (Giarola et al., 2021). This modelling exercice has been supported by an ensemble of eleven modelling tools, two global general equilibrium models (GEMINI-E3 and ICES), two global partial equilibrium models (GCAM and TIAM), three energy system models with two global (MUSE and 42) and one EU level one (EU-TIMES), two macro-econometric models with one global (E3ME) and the other at EU level (NEMESIS) and two EU sectoral models (FORECAST and ALADIN). The modelling work has allowed going through stakeholders' research questions, that have been collected at the beginning of the project and even if the "Where are We Headed" scenario framework does allow dealing with all the questions, we have already studied a good part of them. Among key findings, we found that the EU is currently on track to achieving its the 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. We also complete the EU-wide figures some with some members states level figures, showing for instance the important German contribution to the 2030 EU CO_2 emissions mitigation efforts, between 25% and 30% of the total in 2030 according to models.

The document delivers also some sectoral detailed results for the buildings, industry and transports sectors. In the buildings sector, the EU current policies do not imply drastic changes. By 2050, coal phase-out is complete, whereas heating oil is not yet phased out and biomass and district heating shares increase reaching around 40%. CO_2 emissions decline by about 30% in 2030 and 50% in 2050 in comparison with 1990 equally driven by energy efficiency and fuel switch. In a more ambitious scenario, the CO_2 emissions reduction reach 70% in 2050, in comparison with 1990, the only remaining fossil fuels in the heating fuel mix in EU is the natural gas, with 37%. In the industry sector, the EU total final heating energy demand remains relatively stable between 2015 and 2050, biomass and ambient heat gain substantial market shares from 2015 to 2050 leading to a decrease in fossil energy demand for fuel oil (-70%), coal (-62%) and other fossils and then, CO_2 emissions reduce slightly up 2030, around

-10% in comparison with 2015, and significantly more in 2050, with -40%, despite emissions from industrial processes declining weakly. In the transport sector, the market share of passenger electric vehicles in car registrations in the EU rises rapidly reaching more than 50% before 2030 and almost 90% by 2040. For heavy duty vehicles, the battery electric vehicles will dominate the stock of trucks smaller than 3.5 t similar to passenger cars in 2050. For heavy duty vehicles higher (>12t) hybrid Diesel catenary trucks will be the most cost-efficient alternative (following the assumption that electric overhead lines will be partly constructed on European highways). Hydrogen plays a minor and natural gas a neglectable role. Consequently, the electricity demand by the transport sector raises, from 40 TWh (almost entirely for rail transport) to 170 TWh in 2030 and up 640 TWh in 2050 of which 55% for cars, one third for trucks, the remaining for rail transport.

The last section explores the first elements of deep decarbonisation scenario in the EU and especially the Paris Agreement Compliant scenarios. We performed a large literature review on existing quantitative figures for GHG emissions of the Land Use, Land Use Change and Forestry and the Agriculture sectors. LULUCF can absorb between 240 to 340 $MtCO_2$/y. in 2030 and between 250 and 340 $MtCO_2$/y. in 2050 (and even up to 500 $MtCO_2$/y. with a payment for the carbon capture at 150€/tCO_2). For the GHG emissions from Agriculture, mainly methane and nitrous oxide, decarbonisation is more challenging. The projections for agricultural GHG emissions for 2050 are relatively stable compared to 2015 in current policies scenarios, around 400 $MtCO_2$-eq./y. In a more ambitious decarbonisation scenario, the GHG emissions range between 280 and 230 $MtCO_2$-eq./y. in 2050.

These results mean that in an EU carbon neutral economy in 2050, the negative CO_2 emissions for the LULUCF sector will be, from partially to completely, offset by the remaining agricultural GHG emissions, with a net AFOLU GHG emissions between -100 to +170 $MtCO_2$-eq./y in 2050. Then, it means that CO_2 emissions from energy and industrial process should be nearby zero in 2050 and even negative in some cases, pointing the importance of key technologies such as CCS and negative emissions technologies but also of behavioural changes that could limit the extent of their deployment.

We also study in this last section the potential the impact of the COVID-19 pandemic on European Green Deal scenarios. EU-TIMES and NEMESIS have run several scenarios that combine: (i) two different economic recovery in EU up to 2030 (a full and a limited one), (ii) two European climate ambition (current policies and EU 2030 Climate Target, i.e. -55% with respect to 1990) and (iii) two potential long-lasting behavioural changes (remote working and fligths reduction) resulting from increasing environmental concerns and COVID-19 pandemic. The two models show relatively similar CO_2 emissions pathways to reach -55% GHG emissions reduction in EU in 2030. Behavioural changes lead to converging results between models for specific sectors with lower energy consumption in transport and higher in residential but different results for aggregated figures. In EU-TIMES, they contribute to the reduction of the FEC in climate ambitious scenarios, but not in NEMESIS where their impacts are limited. Finally, both models assessed the investments requirement to achieve the climate target of the European Green deal, that represent 410 billion euro (constant 2010) from 2021 to 2030 in the NEMESIS model, whereas the additional gross investment for the power generation is evaluated around 184 billion euro (constant euro 2010) by the EU-TIMES model. By compring them with the EU Recovery Plan, the Next Generation EU program oriented towards climate action would cover from 55% to 70% of the investments assessed by the two models.

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1 Introduction

Since the ratification of the Kyoto Protocol in 1997, the European Union has developed climate change mitigation policies, starting in 2005 with the implementation of the first phase of the European Union Emissions Trading Scheme (EU-ETS). It has been followed by the 2020 energy climate and energy package (European Union, 2009) that fixed GHG emissions reduction targets for 2020 and the 2030 energy climate and energy framework that fixed, inter alia, a reduction of the EU greenhouse gases (GHG) emissions reduction of 40% in comparison to 1990 (European Council, 2014). To comply with these EU-wide targets and policy objectives, EU has introduced a set of policy: of which the EU Emission Trading Scheme (EU ETS) directive[1], the Effort Sharing Regulation (ESR)[2], the CO_2 Emissions Performance Standards for Cars and Vans[3] and the Land Use, Land Use Change and Forestry (LULUCF) regulation[4] are the main legal texts. The complementary policies on energy efficiency (Energy Efficiency Directive - EED[5]) and renewable energy (Renewable Energy Directive - RED II[6]) are also important cornerstones of the EU climate policies package (a detailed presentation of all EU climate policies is delivered in Annex II of this document).

Nevertheless, as recognised by the scientific community, the current trends will lead to the global warming well above sustainable path and its economic, social and environmental consequences require urgent action at global, regional and local scale. In this context, the European Union has signed, in 2015, the Paris Agreement, that aims at keeping global temperature increase well below 2°C and pursuing efforts to limit the increase to 1.5°C. To comply with Paris Agreement, EU updates its climate change mitigation action. In 2020, EU has submitted to the United Nations Framework Convention on Climate Change (UNFCCC) its 2050 Long-Term Strategy (European Union, 2020a) that moved the previous 2050 target of at least -80% of GHG emissions in comparison to 1990 to the achievement of a climate neutral EU in 2050. It has been followed by the EU Green Deal strategy launched by von der Leyen Commission in December 2019 (European Commission, 2019b). that aims, inter alia, reducing GHG emissions by at least 55% in 2030 in comparison with 1990 (European Commission, 2020d) instead of the former 40% milestone (European Council, 2014). This new GHG emissions targets have been endorsed by the European Council and the European Parliament in May 2021.

In this document, we present the first batch Paris reinforce models' runs for EU that have focus on the EU current policies, *i.e.* prior to the EU Green Deal, and that will be used as reference scenarios for analysing Paris Agreement Compliant scenarios for EU. This first set of scenarios has implemented the "*Where are We Headed*", scenario protocol which explores where the world is headed given countries' current climate action and most recent pledges (Sognnaes et al.) and has been based on a harmonised set of socio-economic and techno-economics parameters (Giarola et al., 2021).

Supported by an ensemble of eleven modelling tools, we present in the first part of this document the main results of the "Where are We Headed" current policies scenario for EU, focusing on CO_2 emissions, the energy mix by sector and fuel but also exploring models' results to answer to stakeholders' research questions that have been collected at the beginning of the project (Nikas et al.). These questions cover technological aspects: potential

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[1] Directive (EU) 2018/410 amending Directive 2003/87/EC to enhance cost-effective emission reductions and low-carbon investments, and Decision (EU) 2015/1814

[2] Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013

[3] Regulation (EU) 2019/631

[4] Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU

[5] Directive (EU) 2018/844

[6] Directive (EU) 2018/2001

failure of key technologies, the role of electrification and storage or the hydrogen's future and more socio-economic ones such as the required investments and their implications. Besides EU-wide analysis of the "Where are We Headed" scenario, this document details also the results for some key sectors: buildings, industry and transports, thanks to two EU sector specific models.

The second part of the document starts to explore Paris Agreement Compliant scenarios. To do so, we perform a large literature review on existing quantitative figures for GHG emissions of the Land Use, Land Use Change and Forestry and the Agriculture sectors in order to assess their potential in supporting Long-term EU strategy of carbon neutrality and well as the 2030 EU Climate target (European Commission, 2020d). And we continue with the presentation and a scenario protocol to model long-term impacts of the COVID-19 pandemic on EU energy system which is based on three layers: a first economic one according to how the European economy will recover after the pandemic, a second on the EU climate action: either the current polices as defined in the previous part of the document or the EU updated ambition, i.e. the European Green Deal, and the third on the potential long-term behavioural changes resulting from the COVID-19 pandemic as well as increasing environmental concerns.

Finally, we conclude this document by summarizing the work and the key results as regards of the next steps.

2 Where is the EU Headed?

2.1 Where is the EU headed given its current climate policy? A co-created model intercomparison[7]

2.1.1 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., 2017) 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-Sanchez 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

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[7] This section takes to Nikas, A., Elia, A. Boitier, B., Koasidis, K., Doukas, H., Cassetti, G., Anger-Kraavi, A., Bui, H., Campagnolo, L., De Miglio, R., Delpiazzo, E., Fougeyrollas, A., Gambhir, A., Gargiulo, M., Giarola, S., Grant, N., Hawkes, A., Herbst, A., Koberle, A., Kolpakov, A., Le Mouël, P., McWilliams, B., Mittal, S., Moreno, J., Neuner, F., Perdana, S., Peters, G. P., Plötz, P., Rogelj, J., Sognnaes, I., Van de Ven, D.J., Vielle, M., Zachmann, G., Zagamé, P., & Chiodi, A. (2021). Where is the EU headed given its current climate policy? A stakeholder-driven model inter-comparison. *Science of the Total Environment, 793*, 148549.

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 to 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. (2019) 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; van Soest et al., 2019; 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 co-created with stakeholders, and significant socioeconomic and technoeconomic 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., 2021). 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.). 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 2.1.2 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 2.1.3 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 2.1.4 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 2.1.5 discusses the conclusions, caveats, and next steps of the study.

2.1.2 Methods and tools

2.1.2.1 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-creation 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 hours 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^{2}AM 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 minutes explaining each potential research area to the audience, then allowing participants to vote (via sli.do[8]) 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 minutes 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 Figure 1.

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

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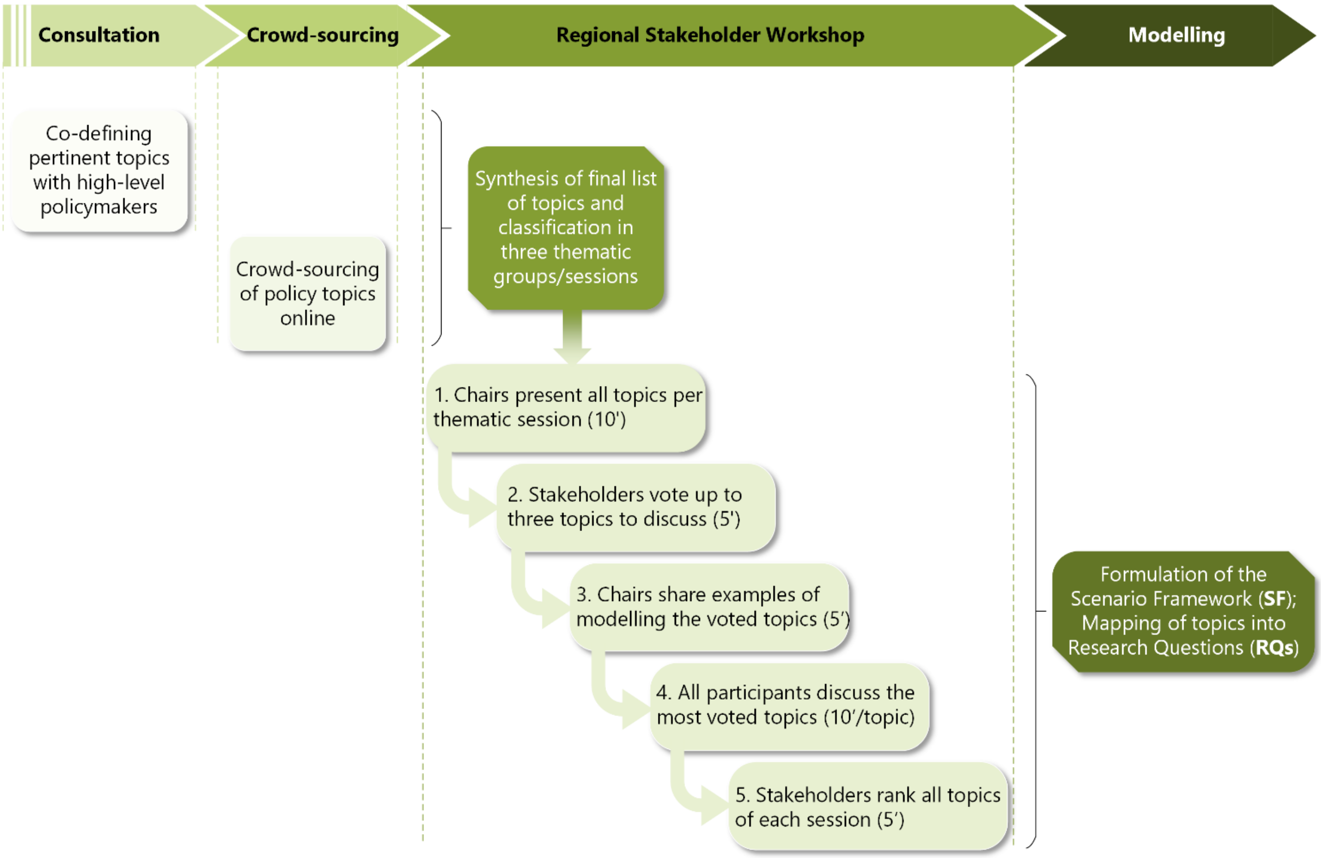

Figure 1: Stakeholder engagement process and co-creation of scenario framework and research questions

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, the topic was then prioritised 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 2.1.1. 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. To interpret and measure its 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, 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. and Box 1). 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.

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 2.1.3)
	- Potential failure of key technologies	**RQ2a**: What is the role of carbon capture and storage as a game changer? (Section 2.1.4.1) **RQ2b**: What is the role of import dependency in Europe? (Section 2.1.4.1)
	- Game-changing innovations	
	- Behavioural and lifestyle changes	*N/A; see 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 2.1.4.2) **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 2.1.4.2)
	- Hydrogen's future in industry, transport, & energy	
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 2.1.4.3)

Box 1: The 'Where are We Headed?' 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 "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., those recorded in 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 2030 emissions of 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.

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2.1.2.2 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 Table 2; full documentation of the eleven models can be found in the I^{2}AM PARIS platform[9].

Table 2: The eleven models used in the study (including type, coverage, and description)

Type	Model (version)	Coverage	Description
General equilibrium	GEMINI-E3 (European)	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. The European version of GEMINI-E3 is used (Vielle, 2020; Babonneau et al., 2020).
	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 across government 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.
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).
	TIAM (Grantham)	World	*TIAM* is a multi-region, global version of TIMES, a modelling platform for local, national or multi-regional energy systems, providing a technology-rich basis for estimating how energy system operations will evolve over time (Loulou and Labriet, 2008); it operates on a "perfect foresight" welfare cost-optimisation basis: all

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[9] http://paris-reinforce.epu.ntua.gr/main

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			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., 2014).
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 the EU Member States and neighbouring countries, where each country is modelled as one region (Simoes et al., 2017). It can consider policies affecting the entire energy system, sectors, group of or individual technologies/commodities (Sgobbi et al., 2016, Blanco et al., 2018, Nijs et al., 2019).
	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 (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.
	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., 2014b) 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.
	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).
Sectoral	ALADIN	Europe	*ALADIN* (Plötz et al., 2014a) is an agent-based simulation model for assessing market diffusion of alternative fuel (passenger and heavy-duty) vehicles in Germany and

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			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).

2.1.2.3 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. (2021), focusing on Europe (EU-27, plus UK, EU hereinafter) (Table 3)[10].

Table 3: Modelling assumptions

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 updating the CD-Links project database (Roelfsema et al., 2020).

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[10] A detailed harmonisation heatmap can be found in the I^2AM PARIS workspace of this analysis, available at: http://paris-reinforce.epu.ntua.gr/pr_wwh/harmonisation_table

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. (2021). 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.

2.1.3 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, but not 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.

2.1.3.1 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 (Figure 2-a). 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, 2019a; 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). All nine models show the EU will reach the former -40% milestone, while most even display overperformance. 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 higher flexibility in terms of available mitigation options in these models, considering the availability of advanced decarbonisation technologies 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 (Figure 2-b) 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

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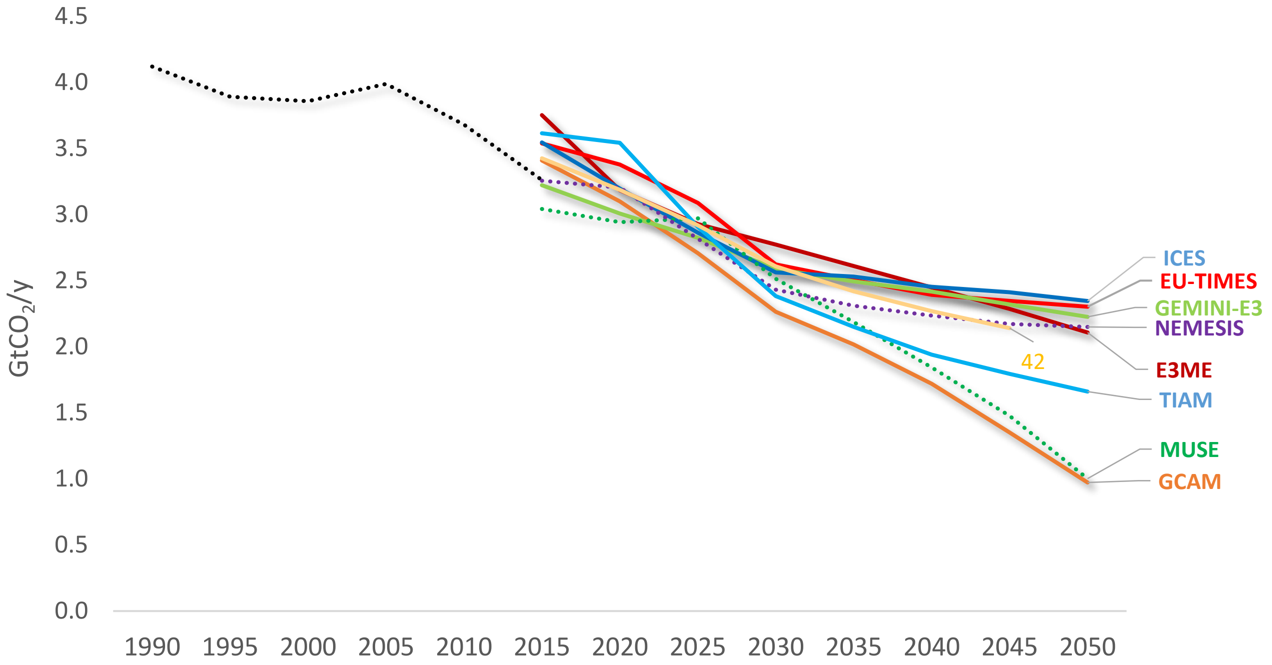
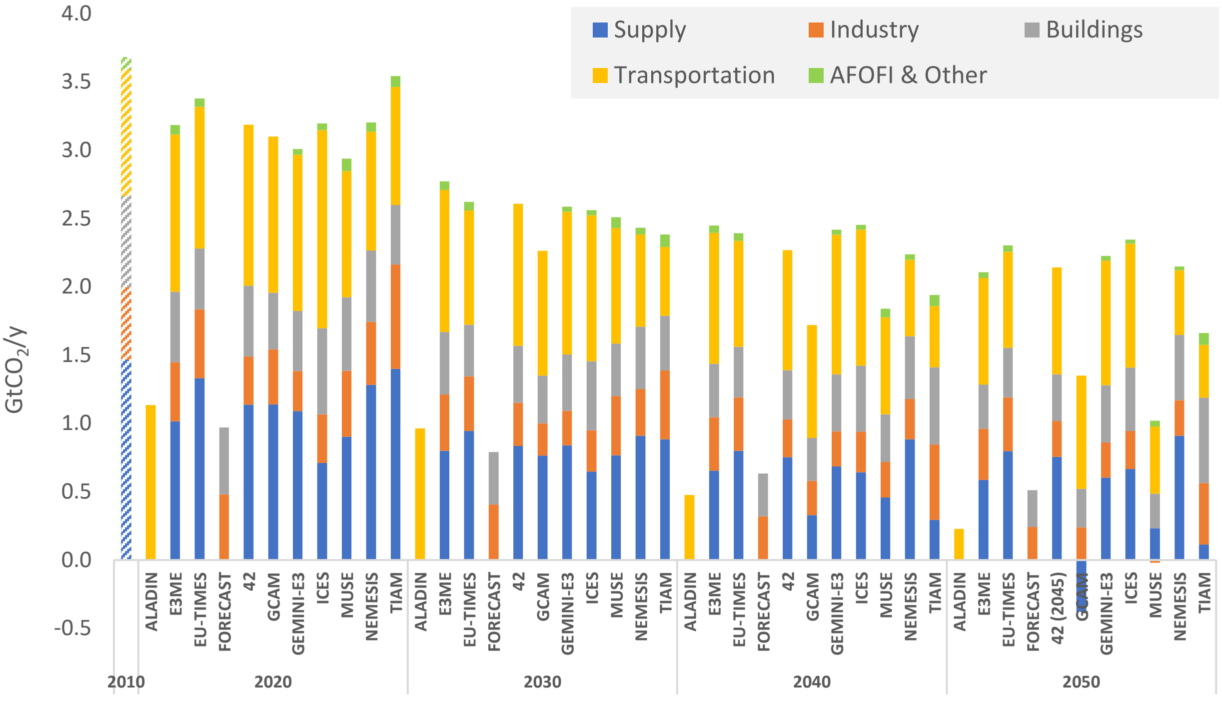
EU energy supply declines by 47% between 2020-2050. Median decarbonisation rates in industry (42%), buildings (30%) and transport (32%), between 2020 and 2050, are relatively similar but differ significantly across models. It is noteworthy that the two sector-specific models, FORECAST (buildings and 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.



(a) Trajectory of total energy CO₂ emissions



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

Figure 2: CO$_2$ emissions from energy in the EU across models (a) total, (b) by sector

(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 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.

Three models deliver results for EU Member States: EU-TIMES and NEMESIS for all individually and ICES for nine individual Members States (Czechia, Finland, France, Germany, Greece, Italy, Poland, Spain, Sweden) and the United Kingdom, as well as two aggregates (Benelux, in Belgium, the Netherlands and Luxembourg; and all other EU Member States). Figure 3 synthesises the contribution of the six major European emitters (France, Germany, Italy, Poland, Spain and the United Kingdom, representing about 70% of the total EU CO_2 emissions between 1990 and 2010) and of the other Member States to the deviation with respect to 1990 of the EU total CO_2 emissions from energy (detailed results by Member State are available in

					2020			2030			2040			2050		
	2000	2005	2010	2015	EU-TIMES	ICES	NEMESIS	EU-TIMES	ICES	NEMESIS	EU-TIMES	ICES	NEMESIS	EU-TIMES	ICES	NEMESIS
Austria	2.9	14.6	7.0	0.6	21.8		-0.6	2.1		-13.6	0.8		-16.9	-2.7		-19.5
Belgium	2.8	2.5	-4.0	-16.5	-12.6		-25.0	-21.6		-28.1	-29.0		-35.1	-26.9		-36.4
Bulgaria	-29.4	-24.3	-23.9	-24.5	-32.1		-23.7	-34.5		-35.6	-34.7		-38.0	-40.4		-43.7
Croatia	-3.3	0.0	-1.8	-4.9	-1.3		-4.4	-4.7		-8.3	-4.9		-9.2	-5.2		-9.9
Cyprus	2.4	3.2	3.5	2.1	3.7		2.5	3.5		1.5	2.2		0.9	2.2		0.8
Czechia	-33.4	-34.2	-41.9	-54.2	-39.2	-39.3	-54.6	-70.5	-60.8	-76.9	-86.8	-59.6	-92.6	-84.3	-60.7	-99.5
Denmark	0.5	-2.2	-3.7	-17.9	-1.0		-20.8	-28.7		-31.4	-26.6		-34.0	-33.1		-35.6
Estonia	-21.3	-19.6	-17.5	-20.4	-22.0		-15.8	-30.0		-20.1	-29.6		-22.0	-29.4		-23.1
Finland	0.2	0.1	6.6	-12.9	18.8	-32.1	-15.8	-4.7	-32.6	-27.7	-11.1	-32.9	-32.9	-24.3	-34.3	-36.1
France	17.2	28.0	-5.5	-52.9	-62.7	-107.3	-54.8	-148.1	-157.3	-132.9	-150.9	-163.0	-124.7	-173.6	-156.5	-97.5
Germany	-150.0	-177.7	-205.1	-240.2	-244.2	-189.2	-253.5	-384.6	-460.2	-458.7	-570.9	-482.9	-507.9	-581.0	-514.7	-532.7
Greece	19.4	29.6	16.1	-5.4	-0.7	-0.7	-13.4	-29.9	-22.6	-29.9	-40.8	-26.1	-33.5	-40.2	-26.9	-34.6
Hungary	-12.2	-10.6	-17.9	-23.3	-20.8		-19.5	-32.5		-31.7	-28.2		-30.4	-28.2		-31.8
Ireland	11.6	14.8	9.6	5.9	10.4		13.4	-4.0		7.0	-1.5		4.9	-2.6		2.1
Italy	34.2	62.8	3.7	-63.1	-71.4	-158.7	-103.9	-146.1	-177.5	-183.9	-166.4	-206.9	-220.5	-187.0	-237.5	-229.3
Latvia	-11.6	-10.9	-10.5	-11.8	-10.3		-11.0	-11.1		-11.6	-10.7		-11.9	-10.4		-12.3
Lithuania	-21.8	-19.7	-19.7	-21.6	-17.6		-22.3	-24.3		-26.2	-25.2		-27.5	-28.2		-28.5
Luxembourg	-2.2	1.2	0.4	-1.4	4.4		-1.2	-0.1		-3.3	-2.2		-3.9	-2.0		-4.4
Malta	0.1	0.2	0.2	-0.7	0.4		-1.1	-0.1		-1.5	-0.1		-1.5	0.1		-1.6

Netherlands	9.0	15.0	19.9	4.1	-6.2		2.4	-31.4		-30.2	-27.0		-40.3	-40.4		-42.0
Poland	-56.8	-49.6	-38.1	-61.4	-44.3	27.8	-25.9	-137.3	-45.6	-121.5	-136.1	-108.6	-152.7	-130.8	-123.0	-186.8
Portugal	19.1	23.4	8.4	8.0	9.0		3.8	-4.3		-7.1	-6.7		-11.5	-9.1		-13.3
Romania	-63.2	-60.8	-72.5	-77.7	-76.3		-76.8	-79.0		-90.9	-79.2		-93.2	-79.6		-95.0
Slovakia	-19.5	-18.9	-22.6	-27.0	-26.0		-28.7	-32.3		-32.9	-30.0		-34.3	-27.6		-35.2
Slovenia	0.6	1.9	1.7	-1.1	1.3		-0.1	-4.4		-1.4	-5.0		-1.9	-6.1		-4.4
Spain	76.2	130.7	52.4	41.8	34.7	39.4	45.5	-6.9	6.8	-4.4	3.6	1.5	-14.7	-8.2	-5.9	-16.6
Sweden	-2.9	-4.0	-4.8	-14.0	12.8	-14.1	-14.6	-1.8	-20.1	-23.8	-3.4	-21.2	-28.1	-1.9	-24.0	-29.8
United-Kingdom	-29.8	-27.1	-79.2	-168.6	-171.1	-223.4	-196.6	-230.4	-282.3	-262.9	-227.2	-281.4	-270.5	-216.6	-290.3	-273.8
Other EU (ICES)						-226.7			-271.3			-263.2			-255.8	
EU	-261.5	-131.4	-439.2	-858.8	-742.5	-924.3	-916.5	-1 497.9	-1 523.6	-1 688.1	-1 727.4	-1 644.2	-1 883.8	-1 817.5	-1 729.7	-1 970.6

– Annex I).

In 2000, historical CO_2 emissions were slightly higher than in 1990 for France and Italy, with +17.2, +34.2 $MtCO_2$ and have raised significantly in Spain with +76.2 $MtCO_2$ (+36% compared with 1990). In Germany, Poland, the United Kingdom and the aggregate of other Member states, the CO_2 emissions from energy decline in comparison with 1990 from -150 $MtCO_2$ in Germany and *Other EU* to -30 $MtCO_2$ in the UK. In 2010, the CO_2 emissions were trending downward. Only Spain, with +52$MtCO_2$, had increasing CO_2 emissions in comparison with 1990, the others showed important reductions such as in Germany with -205 $MtCO_2$ and or an equivalent level as for Italy.

In 2020, models project that EU current policies will reduce the total EU emissions between -743 (EU-TIMES) to -924 $MtCO_2$ (ICES) in comparison with 1990. This reduction is not homogeneous between Member States, for a part due to the design of the EU climate policies (burden sharing between EU Emissions Trading System and the Effort Sharing Regulation—European Council, 2014), but in all models, Germany and the aggregate "Other EU" are the main contributors to the total CO_2 emissions reduction. The reduction of the CO_2 emissions in Germany, with respect to 1990, ranges between 190 to 254 $MtCO_2$, according to models and the reduction in the region "Other EU" between 327 and 184 and 237 $MtCO_2$. In "Other EU", countries like Czechia (between -39 to -71 $MtCO_2$), Romania (-77 to -80 $MtCO_2$) or Slovakia (-29 to -32 $MtCO_2$) have the largest CO_2 emissions reductions. The United Kingdom, Italy and France reduce significantly their CO_2 emissions up to 224, 158 and 107 $MtCO_2$ respectively in ICES where the deviations are the largest. The three models project an increase of the Spanish CO_2 emission from energy in 2020 in comparison to 1990 (from +35 to +45 $MtCO_2$) but to a lesser extent than in 2000 and 2010.

In 2030, the models expect that the six European major emitters will reduce their CO_2 emissions in comparison with 1990, except for Spain in the ICES model, the cumulate CO_2 emissions reduction for these six countries reaches between 1.05 and 1,16 $GtCO_2$. German CO_2 emissions reduction declines up to 460 $MtCO_2$ in ICES and NEMESIS, up to 282 $MtCO_2$ in the United Kingdom in ICES and up to 184 $MtCO_2$ in Italy in NEMESIS. Spain still has almost no CO_2 emissions reduction in comparison with 1990.

Finally, in 2050, the EU CO_2 emissions reductions are slightly higher than in 2030 reaching 1.73 Gt in ICES; 1.82 Gt in EU-TIMES and 1.97 Gt in NEMESIS. According to models, the aggregate "Other EU" and Germany are both the largest contributors to the EU CO_2 emissions reduction. Emissions in Germany are expected to decline by more than 500 $MtCO_2$ in all models (from 515 in ICES to 581 $MtCO_2$ in EU-TIMES). In the region "Other EU", the models project a decline of CO_2 emissions from energy in comparison with 1990 ranging from 402 (EU-TIMES) to 634 $MtCO_2$ (NEMESIS) with between 80 and 95 $MtCO_2$ from Romania, 33 to 35 $MtCO_2$ from Denmark and 35 to 41 $MtCO_2$ from Greece.

The three models with EU Member States either individually or grouped show relatively similar results. Among the six major EU CO_2 emitters, Germany's CO_2 emissions reductions represent around one third of the total EU CO_2 abatement, the United Kingdom covers around 15%, whereas France and Italy around 10%. The Polish contribution to the EU CO_2 reduction is about 7%, whereas CO_2 emissions projections for Spain display no reduction in comparison with 1990, but with approximately 200 Mt CO_2 emissions from the energy sector in 2050, it represents, even so, a reduction of about 40% in comparison to 2005, where Spanish CO_2 emissions reached their maximum (339 $MtCO_2$).

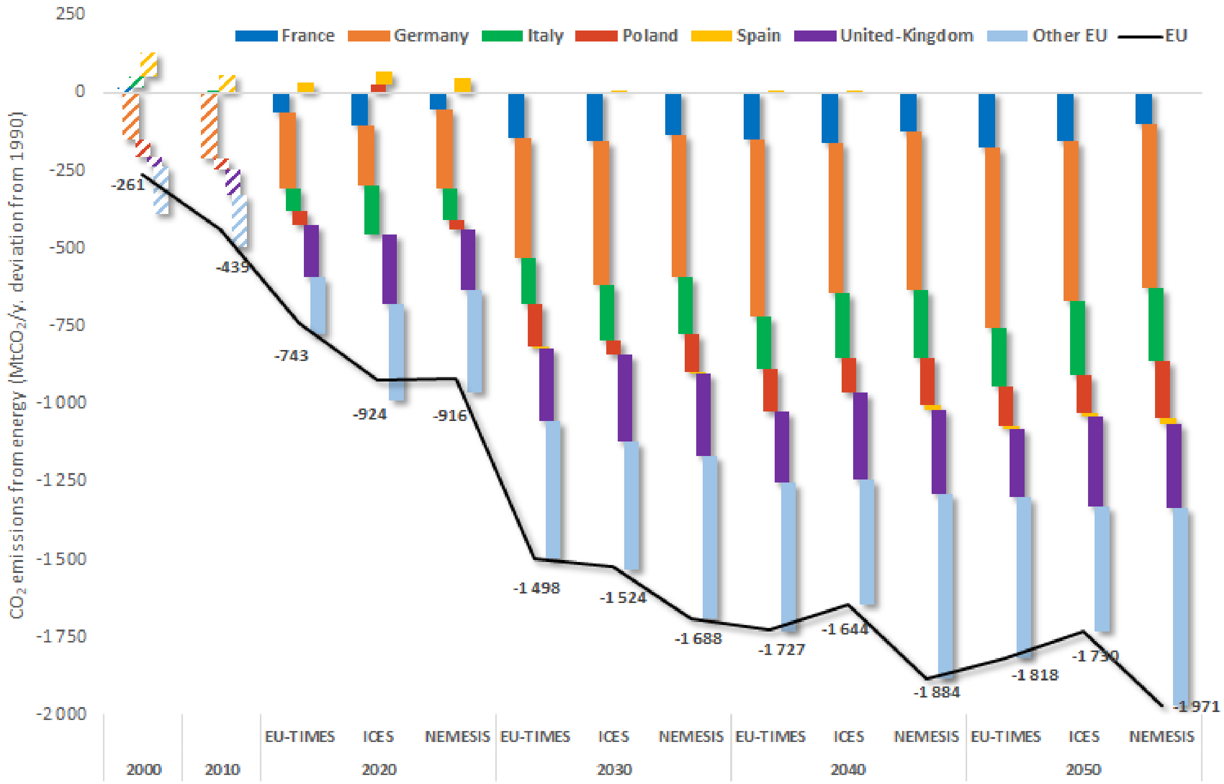


Figure 3: Deviation of CO_2 emissions from energy in MS across models

Hatched bar: historical data from European Environmental Agency (2020); Other EU: Austria, Belgium, Bulgaria, Cyprus, Czechia, Denmark, Estonia, Finland, Croatia, Greece, Hungary, Ireland, Lithuania, Luxembourg, Latvia, Malta, The Netherlands, Portugal, Romania, Sweden, Slovenia and Slovakia (see

	2000	2005	2010	2015	2020			2030			2040			2050		
					EU-TIMES	**ICES**	**NEMESIS**	**EU-TIMES**	**ICES**	**NEMESIS**	**EU-TIMES**	**ICES**	**NEMESIS**	**EU-TIMES**	**ICES**	**NEMESIS**

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Austria	2.9	14.6	7.0	0.6	21.8		-0.6	2.1		-13.6	0.8		-16.9	-2.7		-19.5
Belgium	2.8	2.5	-4.0	-16.5	-12.6		-25.0	-21.6		-28.1	-29.0		-35.1	-26.9		-36.4
Bulgaria	-29.4	-24.3	-23.9	-24.5	-32.1		-23.7	-34.5		-35.6	-34.7		-38.0	-40.4		-43.7
Croatia	-3.3	0.0	-1.8	-4.9	-1.3		-4.4	-4.7		-8.3	-4.9		-9.2	-5.2		-9.9
Cyprus	2.4	3.2	3.5	2.1	3.7		2.5	3.5		1.5	2.2		0.9	2.2		0.8
Czechia	-33.4	-34.2	-41.9	-54.2	-39.2	-39.3	-54.6	-70.5	-60.8	-76.9	-86.8	-59.6	-92.6	-84.3	-60.7	-99.5
Denmark	0.5	-2.2	-3.7	-17.9	-1.0		-20.8	-28.7		-31.4	-26.6		-34.0	-33.1		-35.6
Estonia	-21.3	-19.6	-17.5	-20.4	-22.0		-15.8	-30.0		-20.1	-29.6		-22.0	-29.4		-23.1
Finland	0.2	0.1	6.6	-12.9	18.8	-32.1	-15.8	-4.7	-32.6	-27.7	-11.1	-32.9	-32.9	-24.3	-34.3	-36.1
France	17.2	28.0	-5.5	-52.9	-62.7	-107.3	-54.8	-148.1	-157.3	-132.9	-150.9	-163.0	-124.7	-173.6	-156.5	-97.5
Germany	-150.0	-177.7	-205.1	-240.2	-244.2	-189.2	-253.5	-384.6	-460.2	-458.7	-570.9	-482.9	-507.9	-581.0	-514.7	-532.7
Greece	19.4	29.6	16.1	-5.4	-0.7	-0.7	-13.4	-29.9	-22.6	-29.9	-40.8	-26.1	-33.5	-40.2	-26.9	-34.6
Hungary	-12.2	-10.6	-17.9	-23.3	-20.8		-19.5	-32.5		-31.7	-28.2		-30.4	-28.2		-31.8
Ireland	11.6	14.8	9.6	5.9	10.4		13.4	-4.0		7.0	-1.5		4.9	-2.6		2.1
Italy	34.2	62.8	3.7	-63.1	-71.4	-158.7	-103.9	-146.1	-177.5	-183.9	-166.4	-206.9	-220.5	-187.0	-237.5	-229.3
Latvia	-11.6	-10.9	-10.5	-11.8	-10.3		-11.0	-11.1		-11.6	-10.7		-11.9	-10.4		-12.3
Lithuania	-21.8	-19.7	-19.7	-21.6	-17.6		-22.3	-24.3		-26.2	-25.2		-27.5	-28.2		-28.5
Luxembourg	-2.2	1.2	0.4	-1.4	4.4		-1.2	-0.1		-3.3	-2.2		-3.9	-2.0		-4.4
Malta	0.1	0.2	0.2	-0.7	0.4		-1.1	-0.1		-1.5	-0.1		-1.5	0.1		-1.6
Netherlands	9.0	15.0	19.9	4.1	-6.2		2.4	-31.4		-30.2	-27.0		-40.3	-40.4		-42.0
Poland	-56.8	-49.6	-38.1	-61.4	-44.3	27.8	-25.9	-137.3	-45.6	-121.5	-136.1	-108.6	-152.7	-130.8	-123.0	-186.8
Portugal	19.1	23.4	8.4	8.0	9.0		3.8	-4.3		-7.1	-6.7		-11.5	-9.1		-13.3
Romania	-63.2	-60.8	-72.5	-77.7	-76.3		-76.8	-79.0		-90.9	-79.2		-93.2	-79.6		-95.0

Slovakia	-19.5	-18.9	-22.6	-27.0	-26.0		-28.7	-32.3		-32.9	-30.0		-34.3	-27.6		-35.2
Slovenia	0.6	1.9	1.7	-1.1	1.3		-0.1	-4.4		-1.4	-5.0		-1.9	-6.1		-4.4
Spain	76.2	130.7	52.4	41.8	34.7	39.4	45.5	-6.9	6.8	-4.4	3.6	1.5	-14.7	-8.2	-5.9	-16.6
Sweden	-2.9	-4.0	-4.8	-14.0	12.8	-14.1	-14.6	-1.8	-20.1	-23.8	-3.4	-21.2	-28.1	-1.9	-24.0	-29.8
United-Kingdom	-29.8	-27.1	-79.2	-168.6	-171.1	-223.4	-196.6	-230.4	-282.3	-262.9	-227.2	-281.4	-270.5	-216.6	-290.3	-273.8
Other EU (ICES)						-226.7			-271.3			-263.2			-255.8	
EU	-261.5	-131.4	-439.2	-858.8	-742.5	-924.3	-916.5	-1 497.9	-1 523.6	-1 688.1	-1 727.4	-1 644.2	-1 883.8	-1 817.5	-1 729.7	-1 970.6

in Annex for results by Member State).

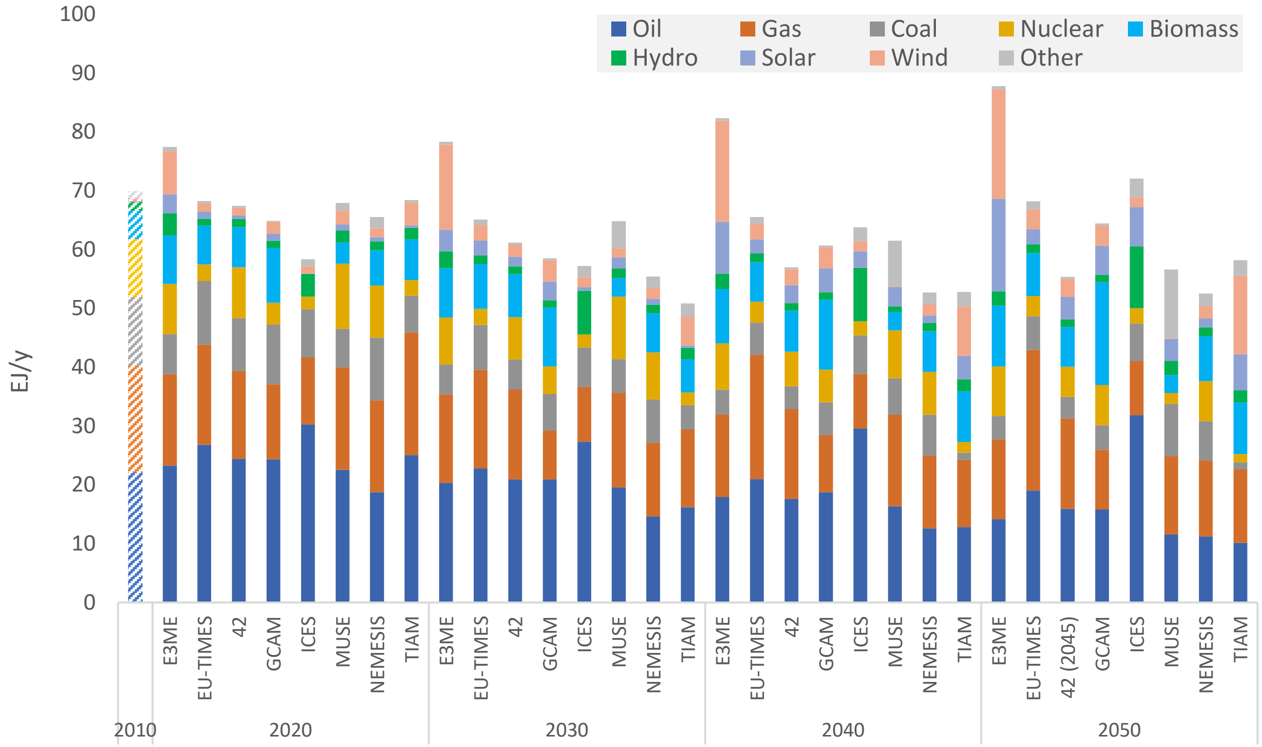
2.1.3.2 Primary and final energy

From an energy perspective, eight models detail EU primary energy by fuel (Figure 4-a). 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).

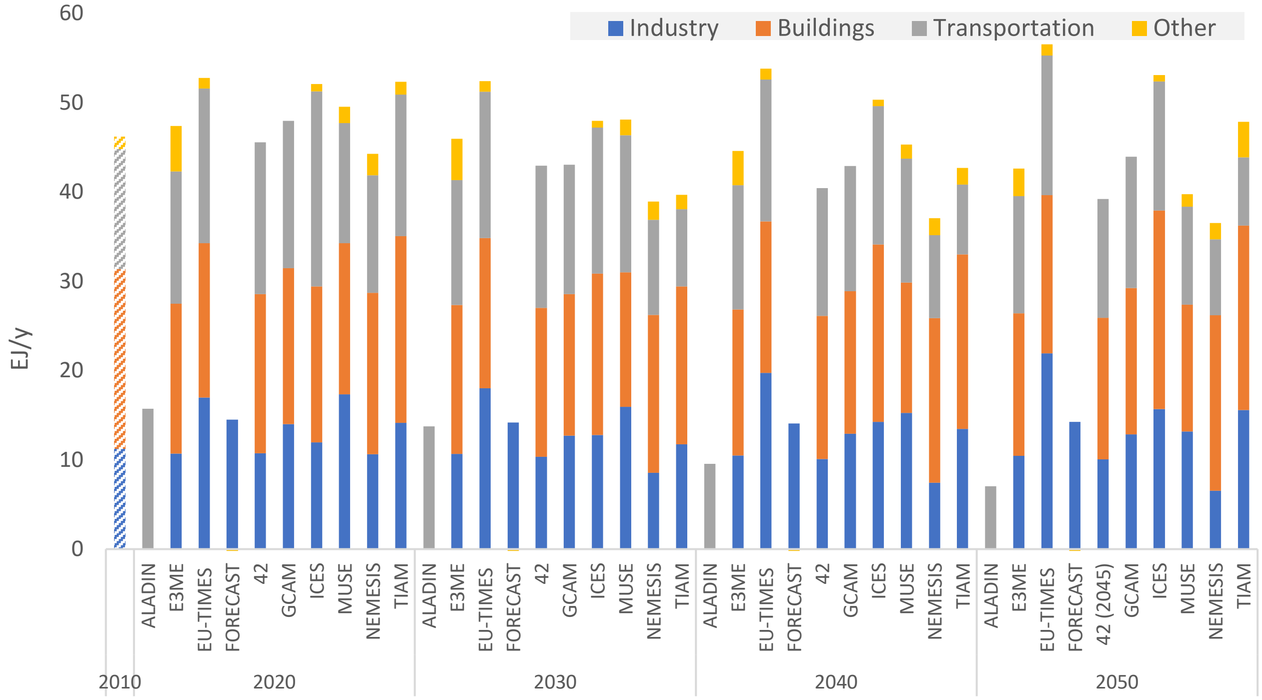
Projections of primary energy consumption by fuel show similar behaviour as far as the evolution of the shares of fossil fuels and renewable energy sources (RES) in the EU primary energy mix is concerned. The former declines in all models, from 59-86% in 2020 to 36-71% in 2050. As the EU is a net importer of fossil fuels (especially 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 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 significant 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. Whilst 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%) (Figure 4-b). 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. All models show significant CO_2 emissions reductions in 2030, in line with the EU's outdated -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.



(a) Primary energy consumption by fuel



(b) EU final energy consumption by sector

Figure 4:The EU energy system in 2010, 2020, 2030, 2040 and 2050 (a) primary energy by fuel; (b) final energy by sector

(a) primary energy consumption by fuel ('other' may include municipal/industrial solid waste, etc.); and (b) final energy consumption by sector. Historical values calculated by authors based on (Eurostat, 2021a). 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.

2.1.4 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.

2.1.4.1 Potential failure of key technologies

- *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 (Figure 5-a). 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 2.1.3, 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). To trace the contribution of CCS to reducing overall emissions, we calculate the ratio of annual captured CO_2 to the emissions that would be delivered if no reduction in 2020 emissions intensity was assumed (Table 4).

Table 4: Emissions intensity and CCS contribution per model

Emission intensity [$MtCO_2$/MWh (PEC)]	E3ME	EU-TIMES	GCAM	MUSE	TIAM
2020	0.16	0.18	0.18	0.16	0.19
2030	0.14	0.15	0.15	0.15	0.17
2040	0.12	0.14	0.11	0.11	0.13
2050	0.10	0.13	0.06	0.07	0.10
CCS contribution	**E3ME**	**EU-TIMES**	**GCAM**	**MUSE**	**TIAM**
2030	2%	0%	0%	3%	0%
2040	2%	3%	14%	12%	6%
2050	3%	5%	27%	33%	16%

PEC stands for Primary Energy Consumption

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 CO2 capture rates with CO2 emissions cuts compared to 1990 (Figure 5-b) 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

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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).

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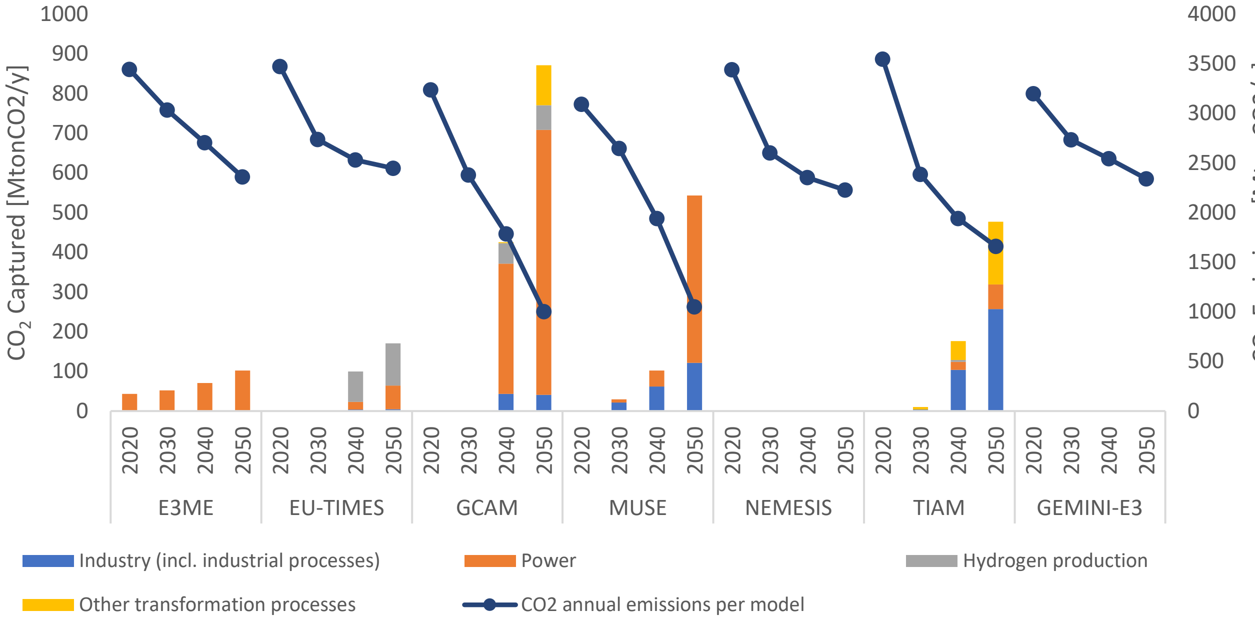
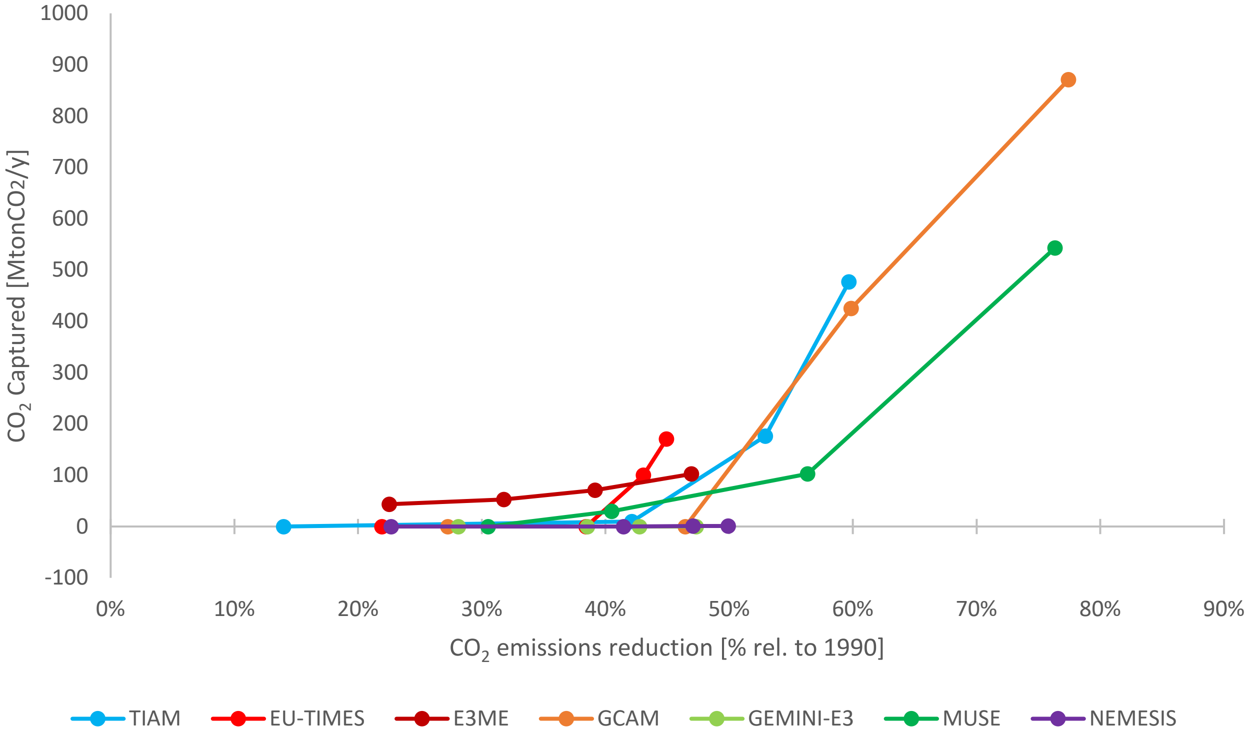


(a) CCS-captured CO$_2$ by sector vs. CO$_2$ emitted



(b) CCS-captured CO$_2$ - CO$_2$ reduction levels ratio

Figure 5: 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)

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).

- *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 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 5).

Table 5: 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%

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, the 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 (Figure 6-a). 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. Figure 6-b shows that, in the global partial equilibrium models, import dependency decreases in time, in line with decarbonisation efforts, thereby attesting to future low-carbon

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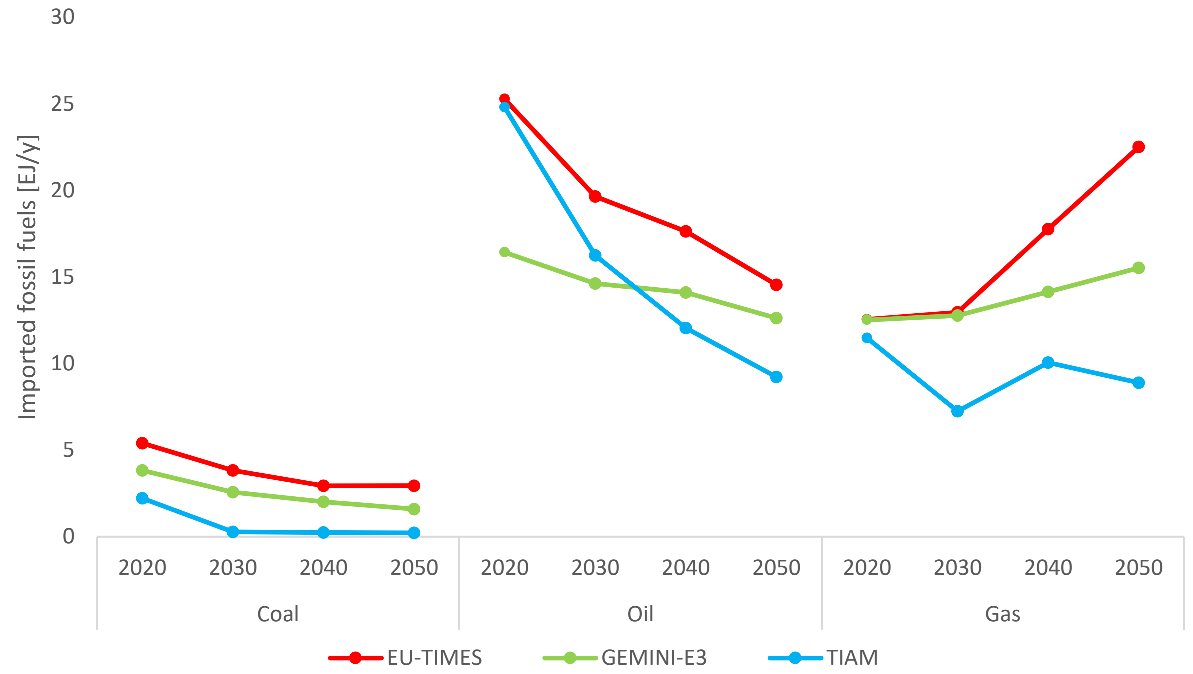
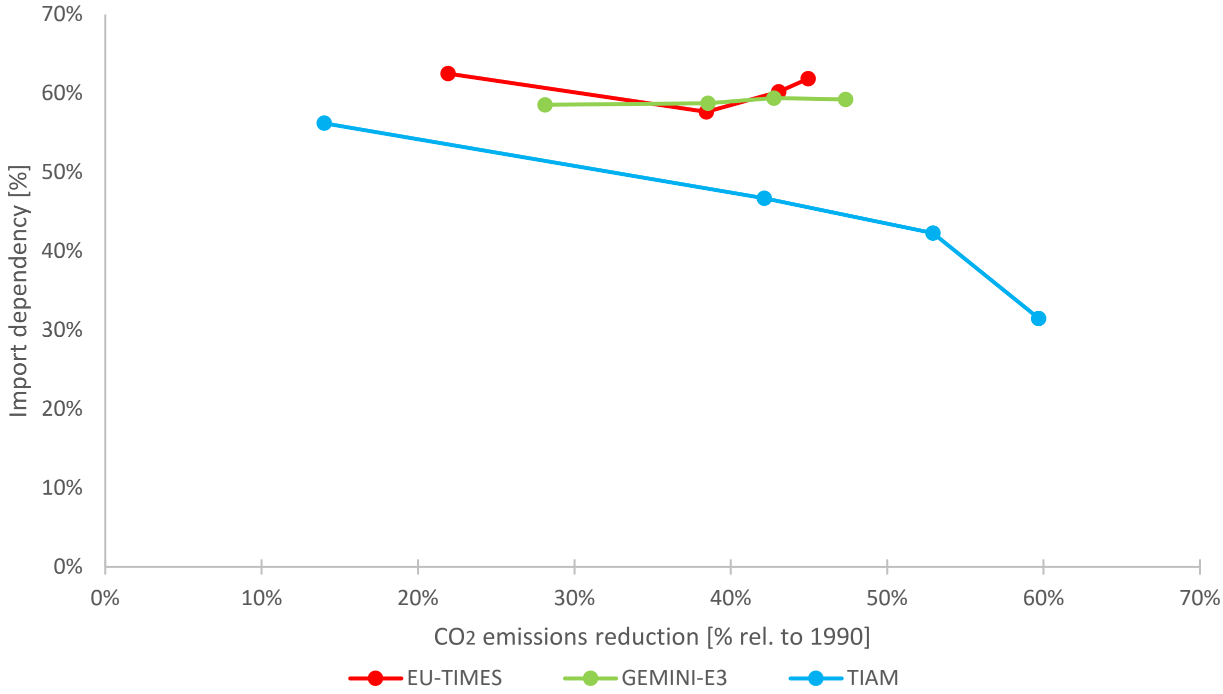
energy systems relying less and less on imports, substituted primarily by energy savings and domestic energy resources. It is noteworthy that costs of fossil fuels in other regions are calculated endogenously in global models, but exogenously in the regional model.



(a) Fossil fuel imports



(b) Imported fuels and CO_2 reduction levels

Figure 6: Fossil fuel imports under current policy efforts

(a) imported fuels until 2050; and (b) import dependency in relation to CO2 emissions reduction levels (since 1990, based on European Environmental Agency, 2019)

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2.1.4.2 Electrification and hydrogen

- *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 (Figure 7-a). 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. Figure 7-b 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.

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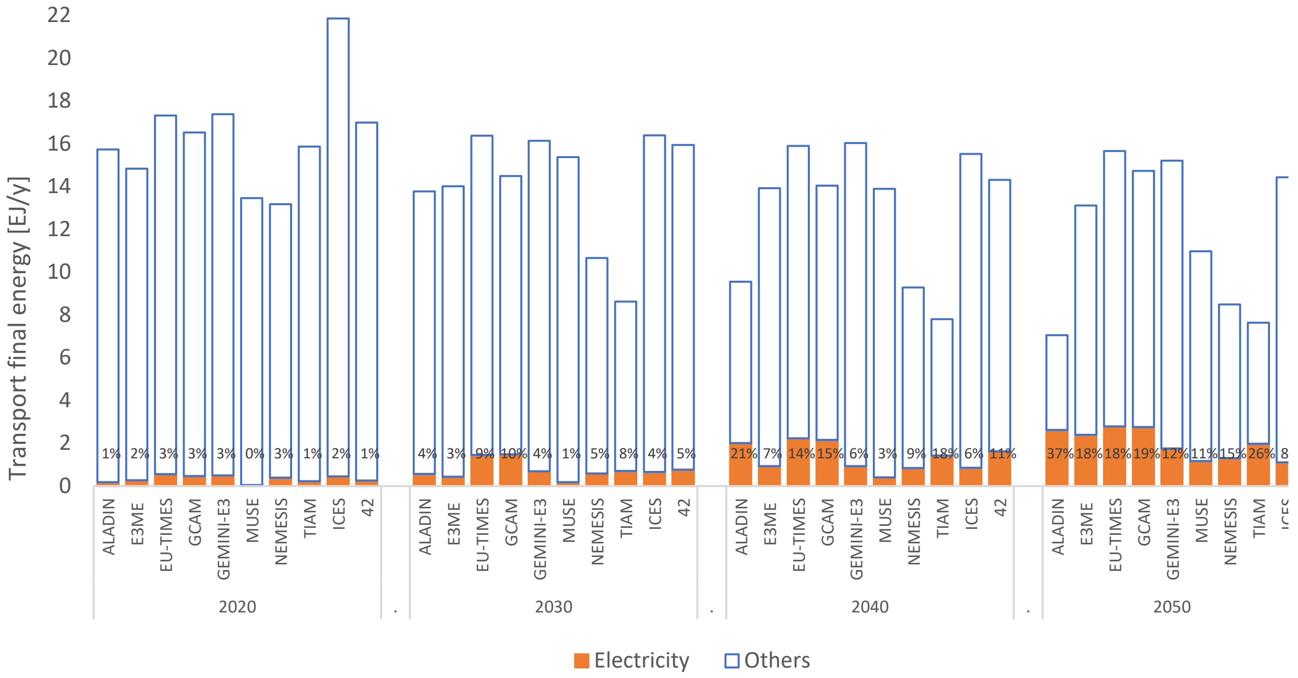
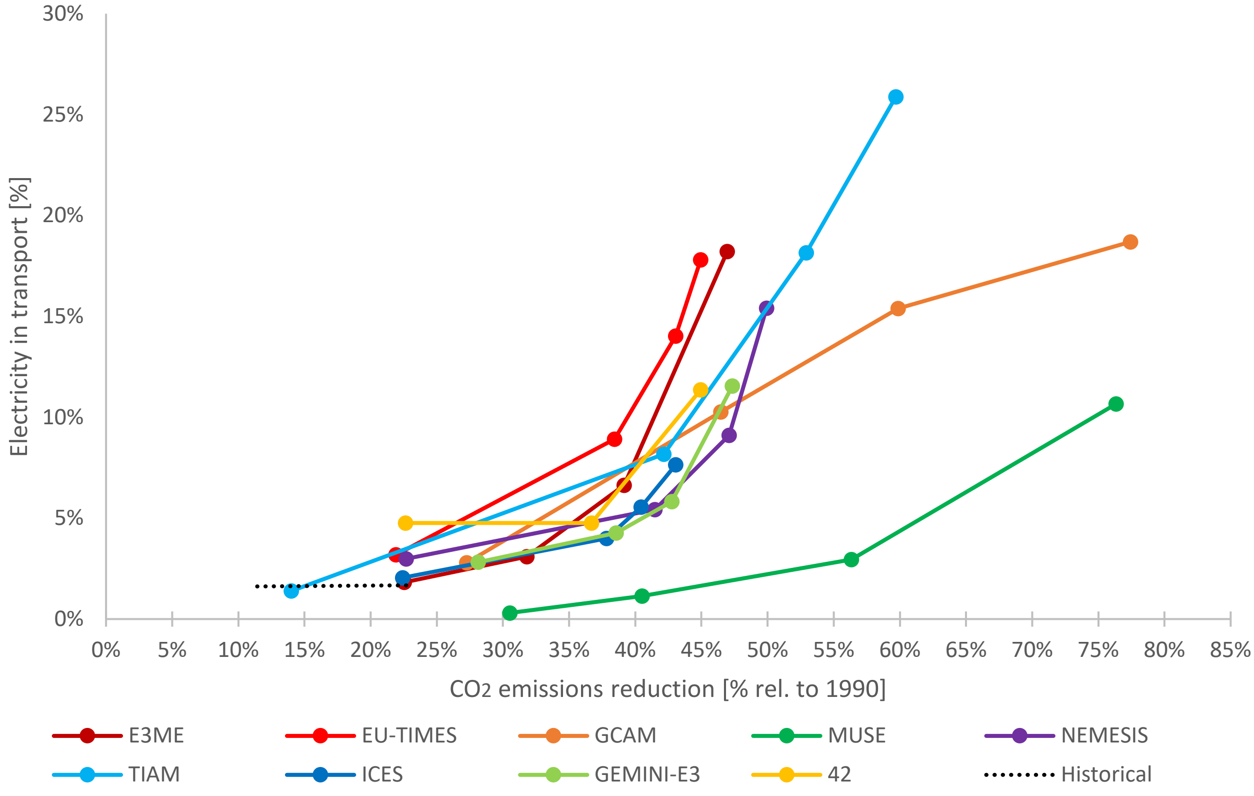


(a) Electricity in EU transport final energy consumption



(b) Transport electrification vs. CO_2 emissions cuts

Figure 7: 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)

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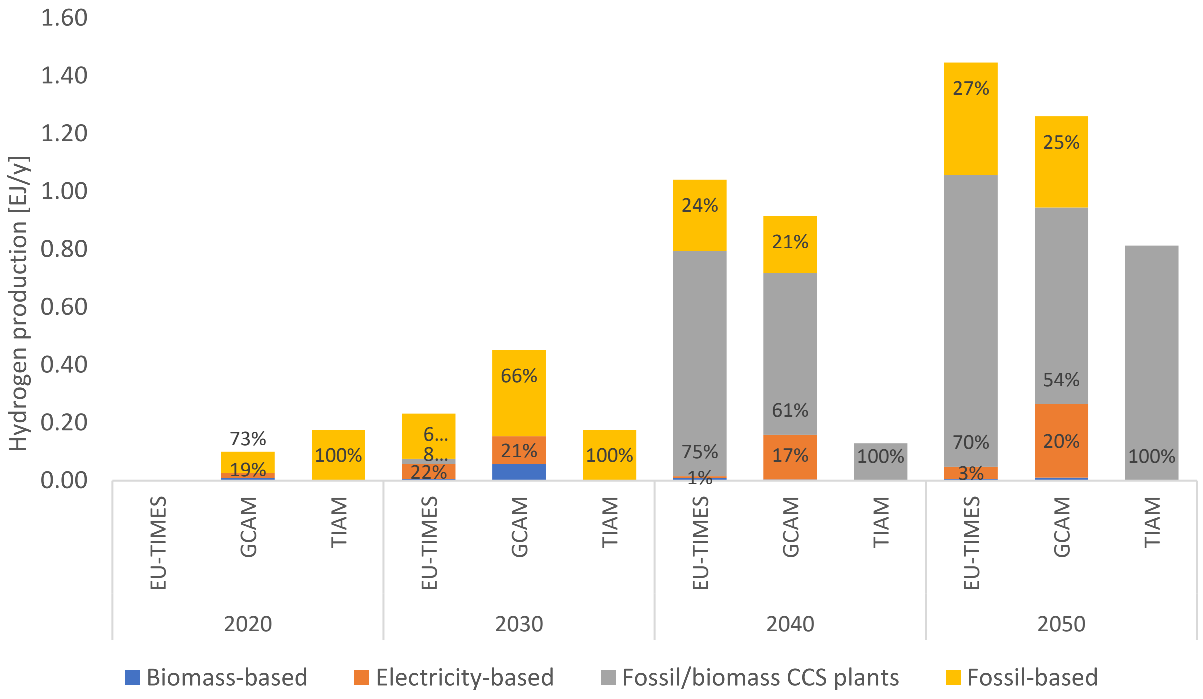
- *The future of hydrogen in the EU, given its current policy efforts*

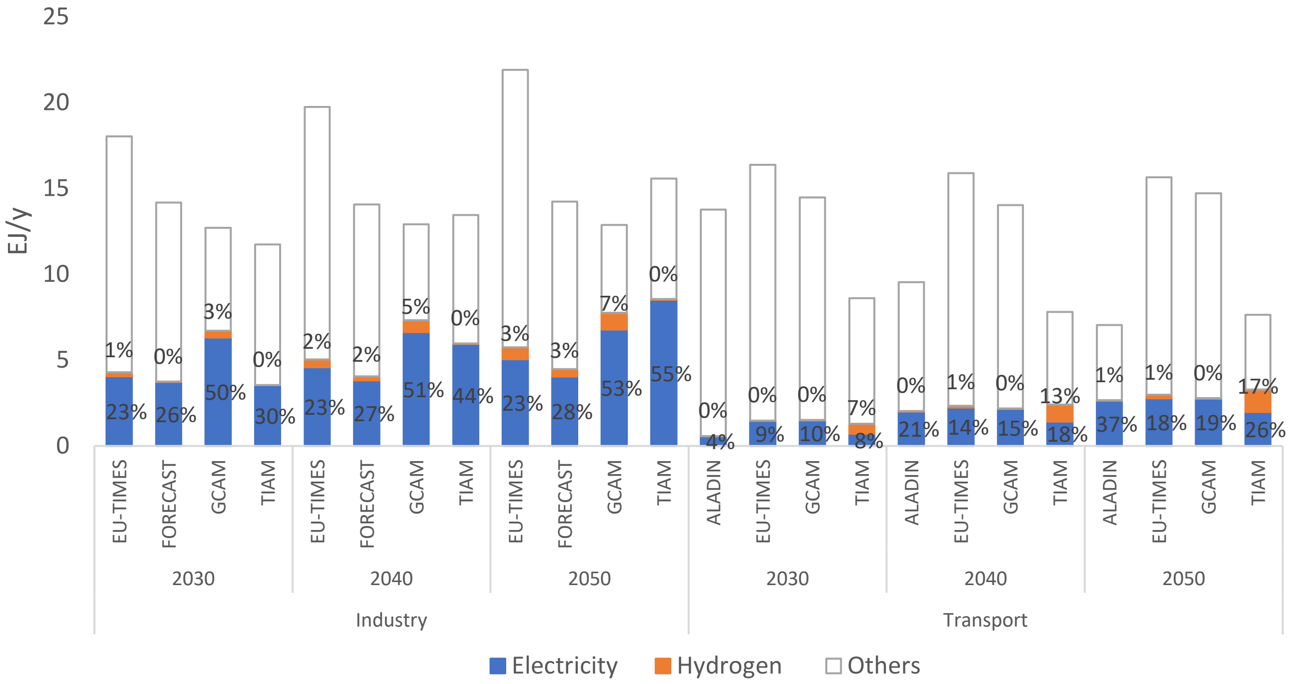
Most hydrogen is currently used in oil refining and chemical production, produced with fossil fuel processes, namely grey/brown hydrogen. In a low-carbon future, hydrogen is generally expected to grow, becoming a leading energy vector to sustain decarbonisation of hard-to-electrify demand sectors, like 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.

Here, we use modelling results to address this research question coming from stakeholders and investigate what role, in the 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: 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 (Figure 8-a) 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 the 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 (Figure 8-b), 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 (Figure 8-c) shows that hydrogen comes into play with a 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.



(a) Hydrogen production by fuel



(b) Electricity & hydrogen final demand

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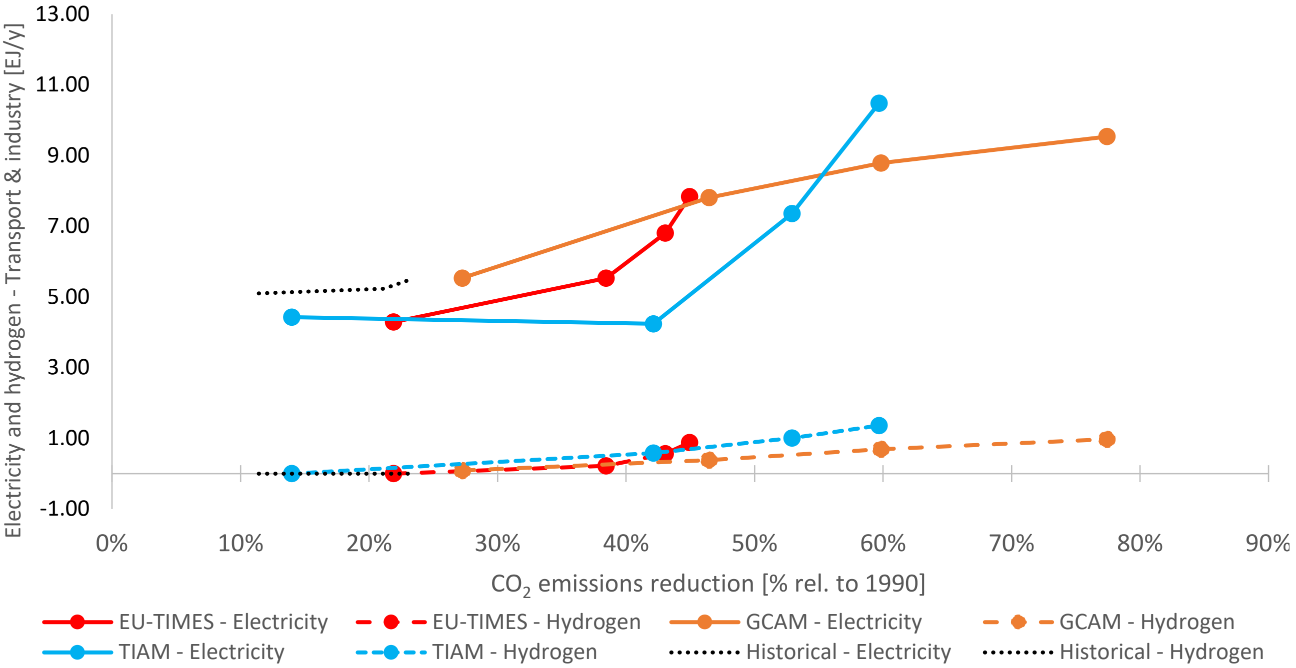

(c) Electricity & hydrogen use vs. CO_2 emissions cuts

Figure 8: 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)

2.1.4.3 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, 2019; 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, meaning that no other counterfactual scenario is designed, employed, and compared against. That said, the macroeconomic models of the employed ensemble can deliver information on the policy costs of the scenarios modelled, referring to their own reference 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, 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, 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 a 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.

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 Figure 9-a). 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 2.1.3). 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 (Figure 9-b). In accordance with fuel evolution (see section 2.1.3), 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 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 2.1.4.1).

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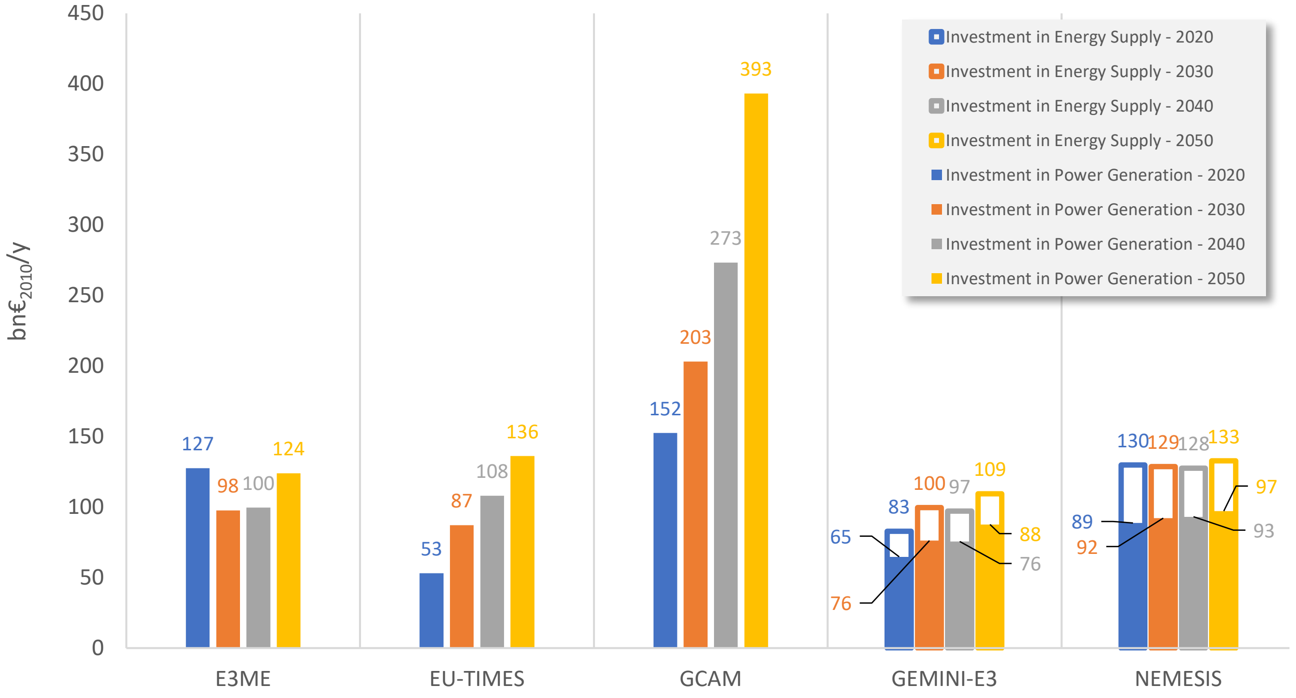
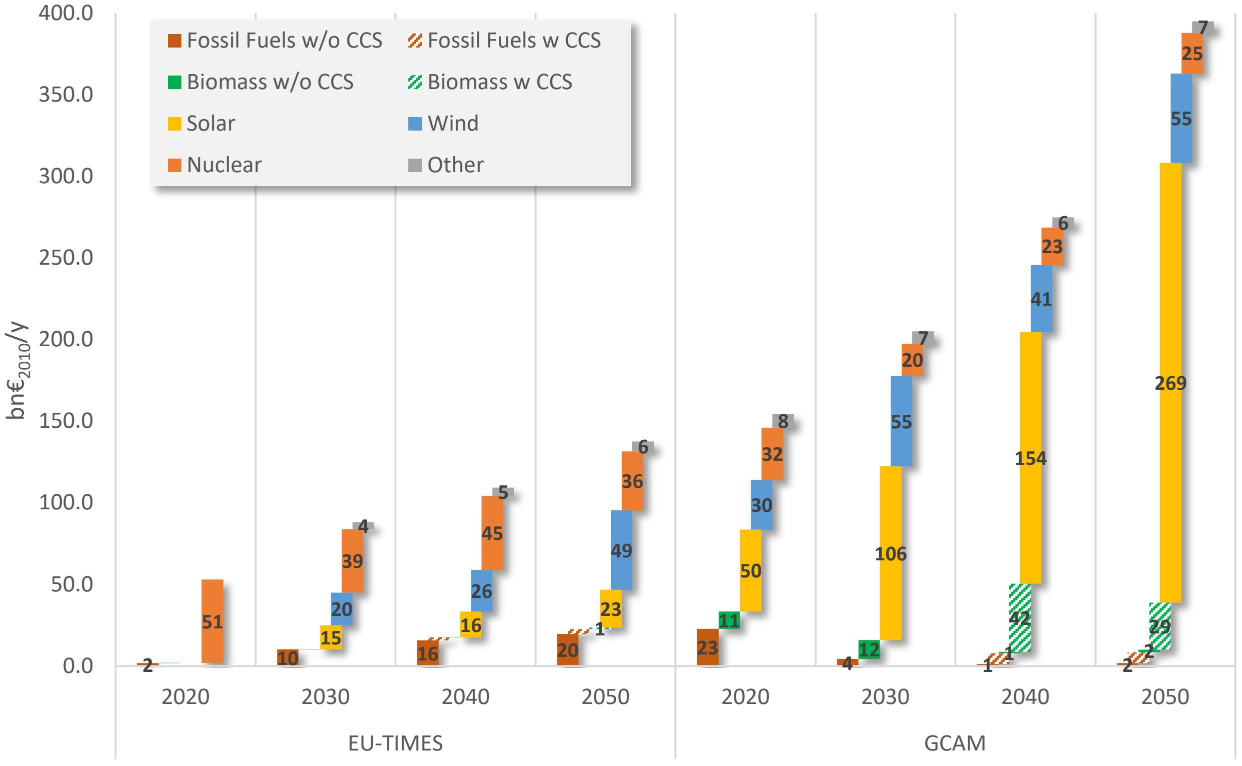


(a) Investments in energy supply and power generation



(b) Investment in electricity by power generation technology

Figure 9: Investments

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

2.1.5 Concluding remarks

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 co-created model inter-comparison exercise, both the scenario logic behind and the research questions of which were co-formulated with stakeholders. 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 achieving its outdated 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. Finally, our exercise highlighted that the EU could benefit from deeper decarbonisation in terms of energy security and jobs, with some sectoral employment losses in energy supply and energy-intensive industries, and that moderate-to-high investment needs are foreseen, mostly dominated by RES.

The co-creative approach employed, in which stakeholders' concerns and questions co-formulated the scenario framework and drove the scope of the exercise, allowed to adopt a scenario logic that is underrepresented in the literature and to explicitly frame common research questions in this context. But, even in terms of questions that have been explored in recent literature, our stakeholder-driven setting allowed us to do so in a way that promotes openness of and inclusiveness in the scientific process, emphasising principles of open (Pfenninger et al., 2018; Morrison, 2018) as well as comprehensive and comprehensible science (Nikas et al., 2021), thereby legitimising and building trust in the tools and their results. This does not mean we were able to explore all prioritised topics and address all communicated concerns. For example, 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. Others, like possible failure of CCS, could only partially be addressed in this scenario, as running the models with technological constraints to clearly respond to this would be outside the main scope of assessing implications of current policy projection; however, our study showed that failure of key technologies could bring us to a more static representation of the energy-economy system described by macroeconomic models. Finally, questions on behavioural/lifestyle change-related issues are acknowledged as currently hard-to-model (Trutnevyte et al., 2019). Nonetheless, there are ways to incorporate such dimensions that are aligned with the transdisciplinary and co-creative approach employed (Nikas et al., 2020a), as an ambitious next step of our study. Aside from intensifying efforts to further reinforce harmonisation, which there is always room to improve, a key prospect lies in employing the same co-creative setting, to follow up on these underexplored concerns and further co-define the most pertinent questions regarding decarbonisation and increased ambition, and assessing these against the reference trajectory produced in this study.

2.2 In-depth analysis of “Where is the EU Headed?” scenarios at sectoral level

The following section presents the results of a set of scenarios, based on the “Where are We headed” scenario framework but adapted to each modelling tool and to the specificities of each sector. Three sectors are highlighted here: buildings, industry and transport. For the two previous sectors, the FORECAST model (Fleiter et al., 2018, Table 2) has been used whereas for the transport the results are based on the ALADIN model (Plötz et al., 2014a, 2019, Table 2), both models being developed and managed by the Fraunhofer ISI.

2.2.1 Buildings

The EU buildings are responsible for 37% of the total final energy demand of the EU with approximately 5000 TWh (Eurostat, 2019a). In residential buildings, the space heating demand alone makes up almost 65% of the final energy demand (Eurostat, 2018). In 2019, fossil fuels provided 58% of this final energy demand of buildings (Eurostat, 2019a & 2019b). Even though coal use for building heating has already decreased to low levels, residential buildings still rely heavily on natural gas, oil and electricity, while, the demand of the tertiary sector is mostly met by electricity and natural gas (European Commission, 2018a). Setting aside the emissions resulting indirectly from the electricity consumption, European buildings need to decarbonize their heat consumption. Improving the energy performance of the building envelope, installation of efficient equipment, fuel switch to renewables and smart operation of buildings are important measures to reduce emissions in the buildings sector (European Commission, 2018a).

Nearly 80% of today’s buildings will exist in the building stock of 2050 (European Commission, 2018a). This means that renovation has high importance and priority over demolishing old buildings and building new ones. Considering the technological development of better performing building components, as well as the low compliance rate of old buildings with the relevant standards at the time, nearly all buildings built before 2010 would need renovation until 2050 (ECOFYS, 2012). The pace of the renovation wave is essential in defining how quickly buildings reach their long-term low to zero emission targets. The European and related national building codes and directives provide the path of building renovation. However, challenges remain, as there is a disconnection between regulations and end-users. Mainly, the communication of and guidance on knowledge about renovation to end-users is insufficient; investment costs are high and up-front, while, rates of investment return are slow; evaluation of subsidy requirements are complicated and the application procedures are unclear or difficult; and, the incentives are unevenly distributed between property owners and tenants. In addition, strict implementation/monitoring of high compliance rates are needed; however, in a case where building function can be interpreted differently for each different code class, the implementation is not always straightforward (European Commission, 2018a, Herbst et al., 2021).

Replacement of less efficient technologies with the most up-to-date efficient equipment has an important role in the energy demand reduction as well. To incentivize the fast diffusion of efficient technologies, especially more efficient and climate-neutral heating equipment such as heat pumps and biomass boilers, could also be challenging in cases where the inefficient/carbon-intensive stock is relatively young or far from the technical end-of-life.

Along with energy demand reduction in buildings, fuel switch is also essential to reaching the long-term targets. Since fossil fuel technologies currently dominate in serving the heating demand of buildings, renewable heat production capacities should increase and be accessible to European buildings. In addition, the renewable heat carriers should also be economically competitive against the widely used and conveniently priced fossil fuels. The options for the fuel switch such as district heating and heat pumps have the pre-requisite that the central source of production must be renewable, *i.e.* heat distributed in the district heating networks as well as electricity in the grid must be generated from renewable sources. Furthermore, biomass as another fuel switch option is demanded in other sectors as well, and the usage capacity in the buildings sector would be limited.

Probable bottlenecks caused by the construction and skilled labour market in this transition should also be considered and action should be planned and taken accordingly.

2.2.1.1 Scenario definition and assumptions

In the following two WHH scenarios are described:

- ***Current Policy (CP) scenario***: the policies that are currently applied until 2030 stay as is for longer term (*i.e.* until 2050).
- ***Stated Policy (SP) scenario***[11]: member states apply policies in line with the nationally determined contributions (NDCs) and policies to cap the carbon emissions and the fossil fuel demand.

Table 6: Quantitative description of the assumptions used for the building sector in the framework of the WWH.

	Current Policies (CP)	Stated Policies (SP)
National efforts	MS efforts frozen at 2025 level until 2050	MS efforts as declared for short-term and continued until 2050
Building efficiency	Building standards and renovation rates stay at current level	Higher building standards and more ambitious renovation depths
Energy carrier price	Fossil fuel prices expected to rise, as per definition (IEA, 2019)	Fossil fuel prices expected to rise, as per definition (IEA, 2019)
CO_2 price	Application of non-ETS CO_2 price only by the states that currently apply it or scheduled to start applying it by 2025 (at the price development that the state has declared)	Application of non-ETS CO_2 price by all MS. If there is no indication on the start date and price declared by the MS, application is assumed to start by 2025 at the price that a neighbouring MS with a similar economy uses

The scenarios use the Paris Reinforce harmonised set of assumptions on the socio-economic context developed for the "*Where are We Headed*" scenario framework (Giarola et al., 2021 and Table 3). For the building sector, the main assumptions to describe these differences are summarised in detail in Table 7, which describes the most important sector-specific measures. This includes the diffusion of building efficiency standards, compliance rates, renovation rates and depths, the applied non-ETS sector CO_2 price, regulations and willingness to pay for renewable heating options. The national building directives and regulations extending from the Energy Performance of Buildings Directive (EPBD) require certain shares of renewables to be applied in buildings. Accordingly, the preference for renewable heating technologies and the willingness to pay for them is an important measure in modelling the fuel switch. In this analysis, we assume limited capacity for biomass supply for buildings and therefore a higher preference for heat pumps and district heating in comparison to biomass. District heating is assumed to be used to its full expansion potential and will be produced via renewable resources such as large-scale heat pumps (Paardekooper et al., 2018). Decentral heat pumps are attractive where district heating networks are not projected to expand.

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[11] The Stated Policy scenario is also called NDC scenario later.

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Table 7: Summary of important measures related to the buildings sector according to scenarios

	Current Policies (CP)	Stated Policies (SP)
Building standards	Building standards improve at the current pace, moderate compliance rates.	Building standards improve at a faster pace. Compliance rates are higher.
Renovation/ Refurbishment	Refurbishment rates and depths stay at the current level	New building standards diffuse into refurbishment targets quicker. Refurbishment rates slightly increase with incentives.
Non-ETS CO_2 Price	Scheduled prices by 2030 are continued in the long-term. Member states who did not declare any prices in the short-term lower the EU28 price average to 40€/t in 2030 and 60€/t in 2050.	Scheduled prices by 2030 are continued in the long-term. Member states who did not declare any prices are assumed to apply the price that a neighbouring MS with a similar economy uses. EU28 price average is 50€/t in 2030 and 80€/t in 2050.
Technology preference	Willingness to pay for RE technologies stay at current levels as current incentives.	Willingness to pay for RE technologies increase. Ban of coal heating systems, and ban of oil heating systems after 2025.
Regulation	Ban of coal heating systems.	Ban of coal heating systems. Ban of oil heating systems in new buildings after 2025, and in renovation after 2040.
Lifetime of heating systems	Technologies are used until the end of their lifetimes.	Coal and oil heating systems have a shorter lifetime to be replaced faster.

Coal and oil heating technologies are replaced earlier than the end of their lifetime, according to national policies such as bans or replacement subsidies. Some member states such as Austria scheduled to ban the installation of natural gas boilers in new buildings starting from 2025 as well (World Bank, 2020).

2.2.1.2 Heating demand of European buildings

The European buildings under the current policies (CP) reduce their final energy demand for heating by 20% in 2050 compared to the 2015 level. Despite the increase in water heating needs, in line with the projected population and GDP increase, the overall demand decreases to 2700 TWh is due to the 28% demand reduction in space heating. Under the implementation of the stated policies (SP) by the EU Member States, the final energy demand for heating would further reduce by around 27% in 2050 compared to 2015 levels. Thanks to the higher determined compliance rates than the currently realised rates and the diffusion of higher building standards both in new and refurbished buildings, this improvement in the demand reduction is possible.

To understand what the heating demand reduction means for the development of direct CO_2 emissions of the buildings, the energy carrier composition of the demand must be observed. Figure 1 shows the heating demand in the CP scenario by the combusted fuels. By 2050, the coal phase-out is complete, but heating oil is still used. It is important to note that due to the sluggish technology switch away from fossil fuels, coal and oil demand are still higher than desired in 2030, and meaningful change happens only after 2040. This means that the CO_2 emission reductions will be delayed. Member States that have not declared nation-specific policy measures on how to abolish oil boilers out of the sector cause uncertainty on whether they will take action in time to reach the short- and long-term goals. This is why the specific measures that the states have not yet declared are not visible in the CP scenario projections.

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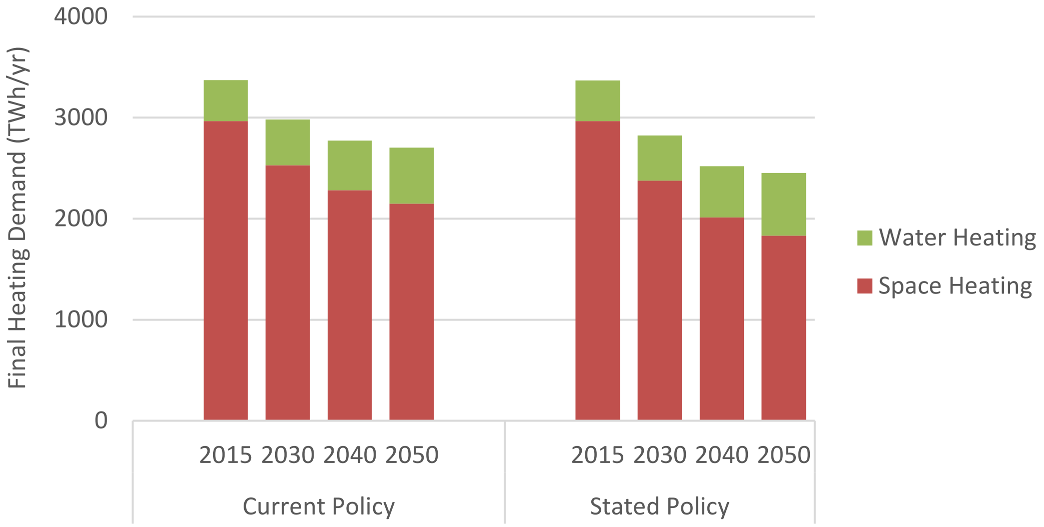

Figure 10: Final heating energy demand development of EU28 in buildings by energy service type

Source: FORECAST model

The switch to renewable fuels of solar thermal and heat pumps are visible in the CP scenario again after 2040. The biomass and district heating take-up is evident towards 2050. However, the share of natural gas remains almost constant in 2050 at the level of 2015. This means that more significant measures than the currently applied ones are needed in order to mitigate natural gas demand, as well as to install solar thermal and heat pump technologies. Coal and oil phase-out are achieved by 2050 under the SP, and the natural gas share has dropped to around 37% in 2050 (see Figure 11). Biomass and district heating are satisfying the majority of the heating demand and heat pumps and solar thermal systems are more visible in the energy mix. Even though the willingness to pay for RE technologies is higher and incentives to switch to renewable fuels are in place, natural gas demand is still significant due to the low price of the fuel itself, which makes the operational fuel costs attractive during the lifetime of the technology. It shows that non-ETS CO_2 price has a decisive role here to decrease the demand for natural gas further.

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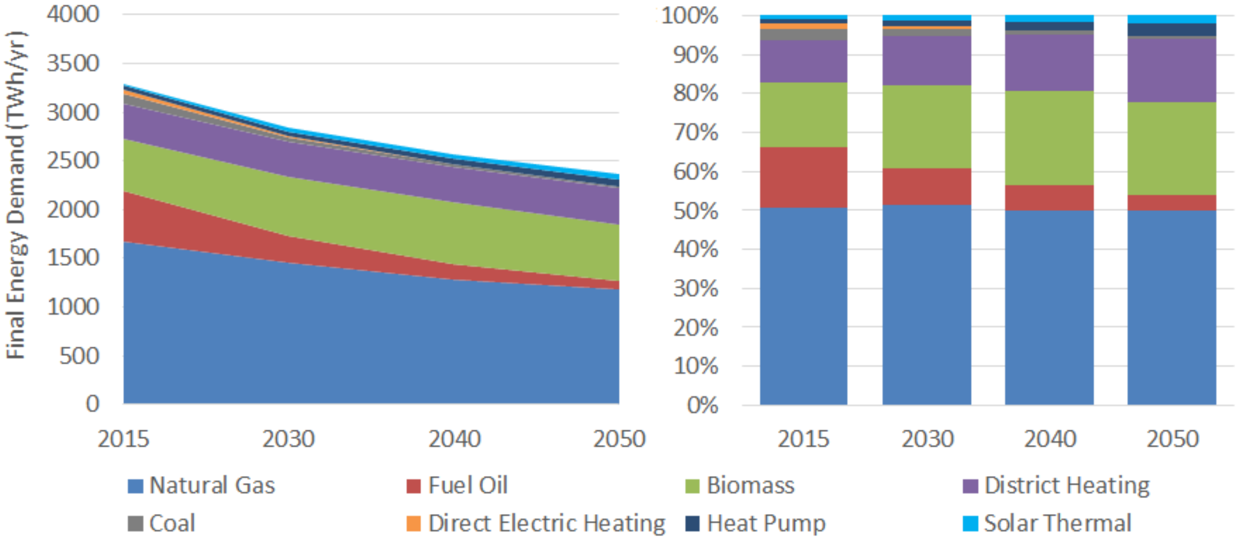

Figure 11: Final heating energy demand of buildings by energy carriers in Current Policy scenario (EU28)

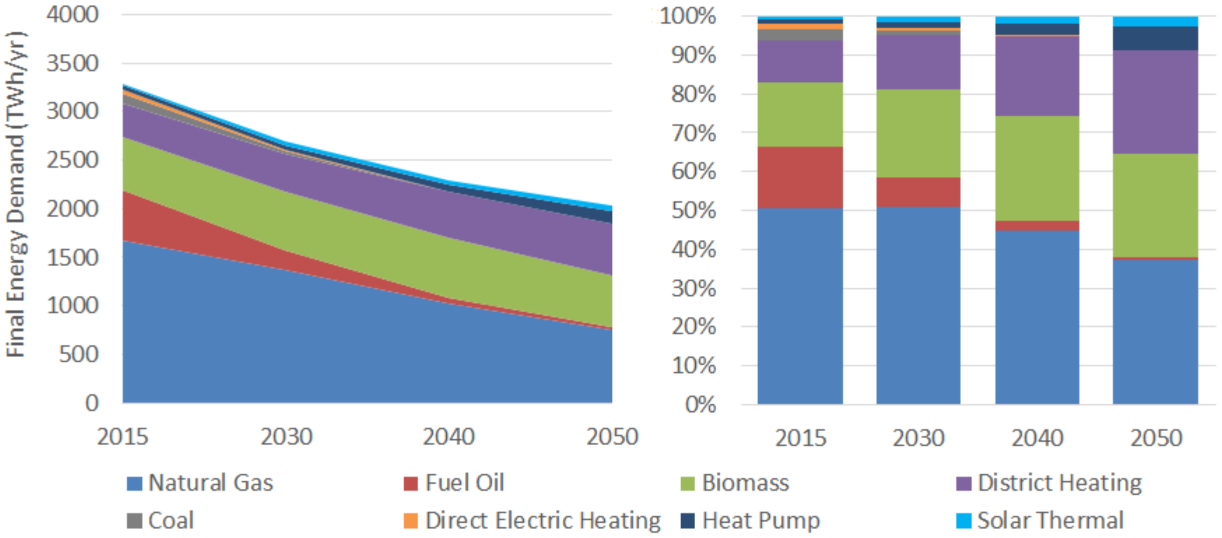

Figure 12: Final heating energy demand of buildings by energy carriers in Stated Policy scenario (EU28)

Source: FORECAST model

Related to the energy mix discussed previously, Figure 13 shows the direct emissions resulting from the heating needs of the residential and tertiary buildings. While the conditions under the CP scenario lead to emission reduction by slightly below 50%, the measures under the SP scenario decrease the emissions in 2050 by around 70% of the 2015 levels. The energy demand reduction and the fuel switch success of the SP measures reduce the source of direct building heating demand emissions to only natural gas. In addition, the indirect emissions resulting from the not yet carbon neutral electricity and district heating network grids should always be kept in mind, and the efforts to decarbonize these networks should be progressing simultaneously. However, this analysis is out of the scope of the sector.

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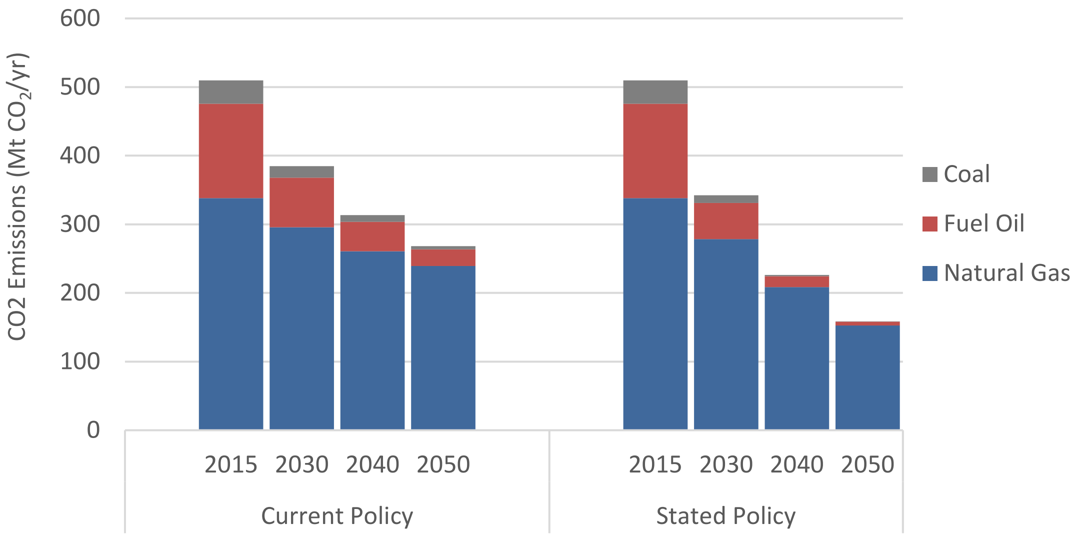

Figure 13: Direct CO2 emissions from fossil fuels consumed in building heating (EU28)

Source: FORECAST model

Nevertheless, the progress achieved in the short-term by 2030 under these scenarios is not enough to meet the European GHG emission reduction targets to reduce emissions to at least 50-55% of 1990 levels. Moreover, the long-term goal of achieving carbon neutrality is also delayed at this rate. Consequently, not only the efforts need to be more ambitious in the short- and long-term, the overall efforts should also pace up in order to achieve higher emission reductions that already start by 2030.

Table 8: Total direct CO2 emissions by residential and tertiary sector buildings

MtCO$_2$/y.		1990	2015	2030	2040	2050
Current Policies		536	510	385	314	268
	Reduction wrt. 1990		-5%	-28%	-42%	-50%
Stated Policies		536	510	343	226	158
	Reduction wrt. 1990		-5%	-36%	-58%	-71%

2.2.1.3 Electricity demand for appliances and processes

Excluding the final energy demand for heating, the remaining final energy demand of the buildings stems from the energy consumption of appliances, ventilation and cooling processes, and lighting. The energy efficiency increase in the equipment is well underway as guided by the efficiency standards (e.g., Ecodesign Directive 2009/125/EC). Even if the electricity consumption does not cause direct CO_2 emissions by the sector itself, it is less burdening to the power generation system and more responsible towards the environment to have reductions in the final electricity demand as well.

The electricity consumption of the tertiary sector buildings is especially significant, as this consumption makes up 47% of the final energy demand (Eurostat, 2019a). Therefore, the energy efficiency increases and energy demand reduction from the electrical applications have high relevance in these buildings. The challenge of the tertiary sector is that the efficiency gains through technology improvement have to compete with the growing GDP and sector activities that require more energy.

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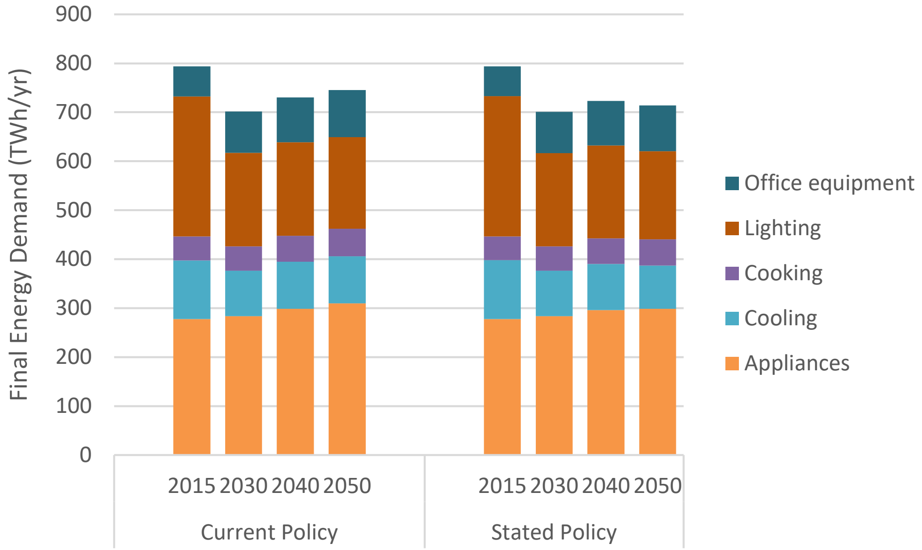

Figure 14: Final electricity demand of appliances and processes in the EU28 tertiary sector, excluding heating (EU28)

Source: FORECAST model

Figure 14 shows that most of the electricity demand reduction in the EU28 tertiary sector buildings is projected to be achieved by 2030. The rate of increase in the electricity demand of appliances slows down under SP compared to the CP, and the lighting demand decreases more in the SP scenario than the decrease projected in the CP scenario. This is a result of the higher compliance rates that are expected under the SP. Cooling demand slightly decreases after 2040 under the SP scenario, whereas, it keeps increasing under the CP scenario. This could be attributed to the achievement of better building envelopes under the SP scenario. In both WWH scenarios, no significant reduction is possible on the overall electricity demand under the current or planned policy measures after 2030. The sectoral activity increases in line with population and GDP growth; so, the measures to achieve further reduction in the non-heating electricity demand have to be more ambitious. Closer guidance or better incentives on the diffusion of efficient electrical equipment, smart management of buildings, and change towards eco-friendly user behaviour could bring more reductions in the non-heating energy demand of the tertiary buildings.

2.2.2 Industry

In Europe, around a quarter of emissions stem from the industrial sector (Eurostat, 2019a). The majority of these emissions stem from energy-intensive industries such as steel, cement and basic chemicals.

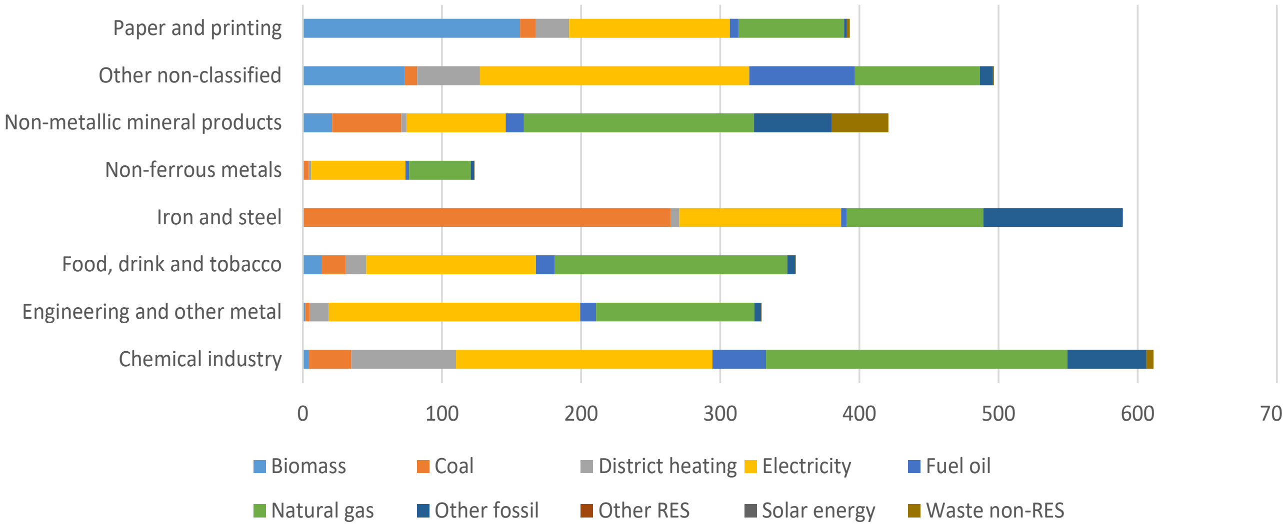

Figure 15: Final energy demand by sector and energy carrier in 2018 for the EU28

Source: FORECAST, Eurostat (2019a).

In terms of end-uses, most industrial GHG emissions are from high-temperature process heat, either in the form of steam or hot water or from the direct firing of various types of furnaces. The high temperatures and the specific requirements of furnaces limit the use of renewable energies here to biomass or secondary energy carriers. In addition to their high energy intensity, energy-intensive production processes are also characterised by a variety of chemical, physical and biological processes that also generate process-related greenhouse gas emissions and are used continuously and in high throughput quantities (e.g. cement). Process-related emissions account for about 20% of all direct emissions. With available technologies, it is technically difficult or even impossible to mitigate them at present. Finally, even the provision of space heating is responsible for ~10% of industrial GHG emissions (Herbst et al., 2018). While there is broad consensus on the goal of (nearly) CO_2-neutral industrial production by 2050, the sector-specific technology paths, as well as the policy framework and instruments, are still under discussion. Decarbonisation strategies include, for example, the electrification of process heat, a switch to hydrogen or green gas, the increased use of biomass, the market introduction of low-CO_2 processes, the use of CCS as well as the recycling of CO_2 and along the entire value chain, an expansion of the circular economy as well as the efficient use of materials. According to the production processes used and the sector structure, these strategies are differently suitable for the different industrial sectors. In addition, new carbon-neutral technologies in the industry sector differ in maturity and distance from the market as well as their dependence on resources and infrastructure.

2.2.2.1 Scenario definition and assumptions

In the Current Policy scenario (CP), existing technologies are used and complete diffusion of today's best available technologies is assumed. Fuel switch is mostly driven by prices and takes place towards natural gas and biomass. Fast development of the circular economy is assumed which leads to higher shares of recycling. In addition, initial uses of hydrogen are introduced in the iron and steel industry and as feedstock for ammonia production, which take into account the considerations of the EU hydrogen strategy in combination with the PARIS REINFORCE scenario framework. In the Stated Policy (or NDC) (SP) scenario a balanced mix of mitigation options is assumed. The scenario aims at a higher emission reduction between 75 to 80% compared to 1990.

For the industrial sector, the main assumptions by scenario are summarised in Table 9, which is categorised by mitigation option.

Table 9: Scenarios' assumptions for the industrial sector

	Current Policies	Stated Policies
Energy Efficiency	Fast deployment of Best-Available-Techniques (BAT) efficiency	Fast deployment of BAT efficiency + innovations >= TRL 5
Fuel switch	Fuel switch driven by prices	Financial support for RES and electricity
CCU/S	No CCU/S	Optional - for High-Value Chemicals (HVC)
Process innovation	First use of hydrogen in the steel industry and for ammonia production.	Hydrogen use reaches 80% production shares for ammonia and ethylene. The use in the steel industry is moderately increased.
Downstream	More recycling: steel, glass, paper, aluminium	More recycling and strong increases in material efficiency

2.2.2.2 Results: Industrial energy demand and CO_2 emissions

From 2015 until 2018 (model calibration year) final energy demand in the industrial sector has increased by 2.1% (+68 TWh). After 2018, in the Current Policy scenario (CP) industrial final energy demand (FED; Figure 16) for the EU28 is only slightly decreasing as efficiency effects are nearly equalled out by activity effects, from 3250 TWh in 2015 to 3152 TWh in 2050. In addition to energy efficiency improvements using the best available techniques (BAT), the scenario is characterised by fuel switch towards renewable energy and electricity as well as higher recycling rates particular for steel. Since 2015, biomass use more than doubles from 250 TWh to 613 TWh in 2050 and electricity remains the dominant energy carrier increasing by around 10%. Consequently, biomass and ambient heat gain substantial market shares from 2015 to 2050 leading to a decrease in fossil energy demand for fuel oil (-70%), coal (-62%) and other fossils. However, natural gas remains the second most important energy source in this scenario even though demand decreases by nearly one third, from 914 TWh in 2015 to 636 TWh in 2050. Hydrogen is only used to a limited extent in this scenario and reflects the EU Hydrogen Strategy (European Commission, 2020b) in combination with the overall scenario assumptions (e.g. production developments). Hydrogen is used only in the iron and steel industry as well as chemical feedstock (see section 2.2.1.3). Even though, in the iron and steel industry, pilot plants are currently under construction/planning, relevant production is assumed to start after 2025. In 2050 it is assumed that 27.6 Mt hydrogen-based steel (direct reduction using green hydrogen + electric arc furnace; DR RES H2 + EAF) is produced leading to a hydrogen demand of 40 TWh in 2050.

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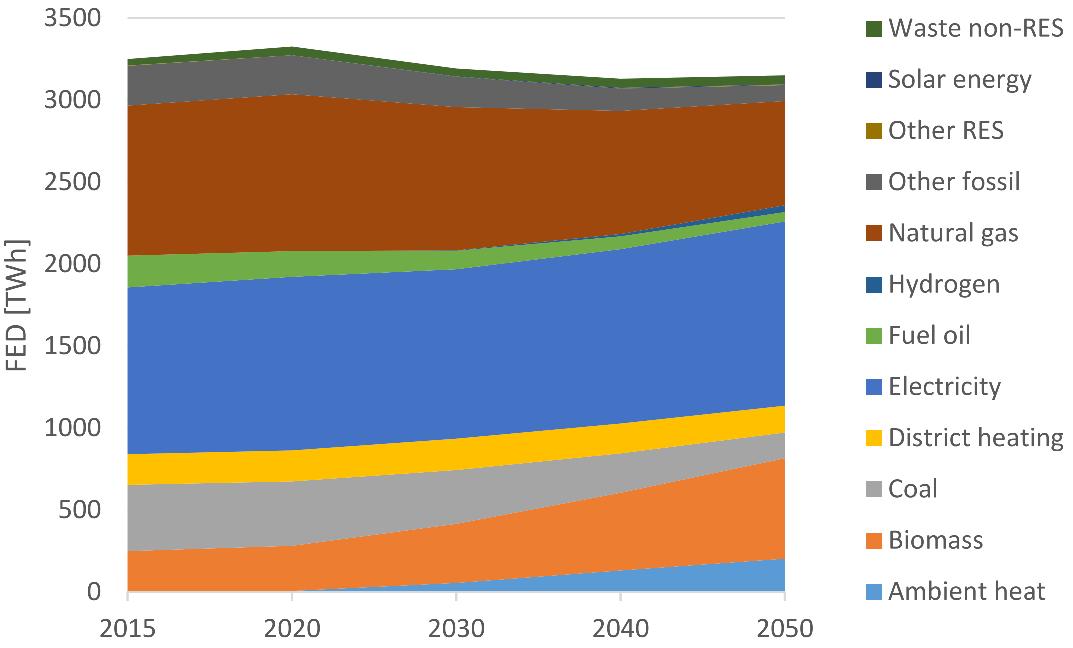
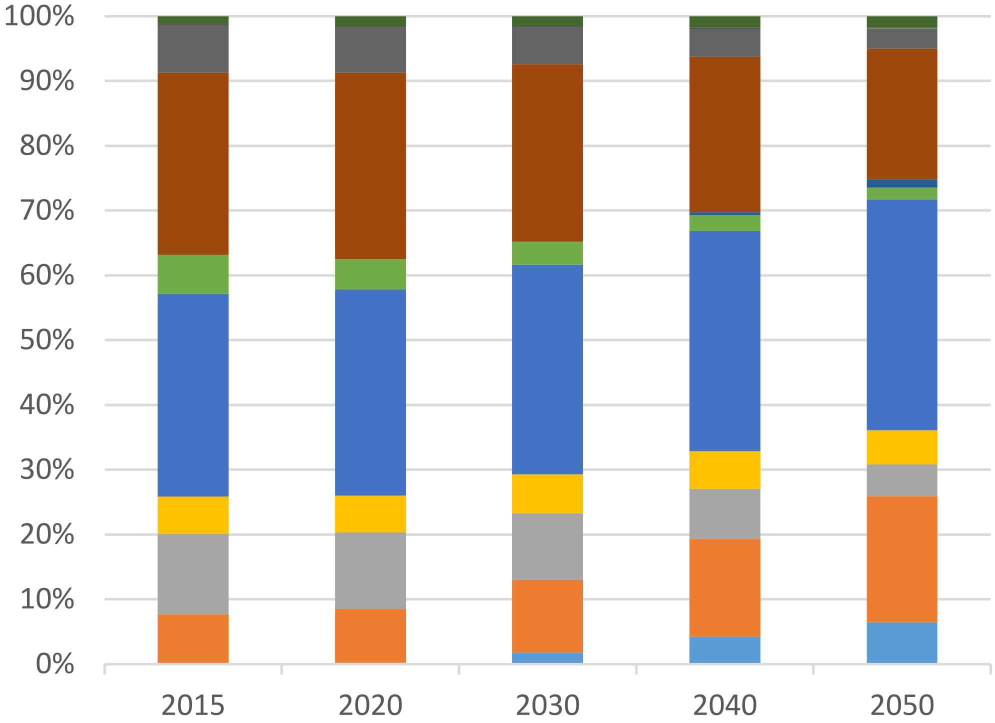


a) in level (TWh)



b) in %

Figure 16: Final heating energy demand by energy carriers in Current Policy scenario in EU28

Source: FORECAST model. (a): Final heating energy demand by energy carriers in Current Policy scenario in EU28 in absolute value (TWh) and (b) on percentage of total.

The Stated Policy scenario needs to use mitigation options of various types to achieve higher emission reductions (see Figure 17). This includes additional energy-efficient and low-carbon production innovations, renewable-based electricity and hydrogen, a comprehensive circular economy and material efficiency improvements. The scenario excludes the use of CCS[12] in industry and reduces the need for biomass to more or less the same level of use as in 2015. In addition, the feed-in of synthetic gas in the natural gas grid is not considered.

Driven by energy and material efficiency improvements, final energy demand decreases by about 10% towards 2050. While natural gas (377 TWh), biomass (288 TWh) and ambient heat (270 TWh) also play an important role, electricity is clearly the major energy carrier in 2050. Where possible, the direct use of electricity is preferred over indirect use. The resulting total electricity demand increases from 1019 TWh in 2015 to about 1583 TWh in 2050. 97 TWh of hydrogen are used in the steel industry which translates into 44 Mt of hydrogen-based steel (DR RES H2 + EAF). Fuel oil and coal are nearly phased out by 2050 in this scenario.

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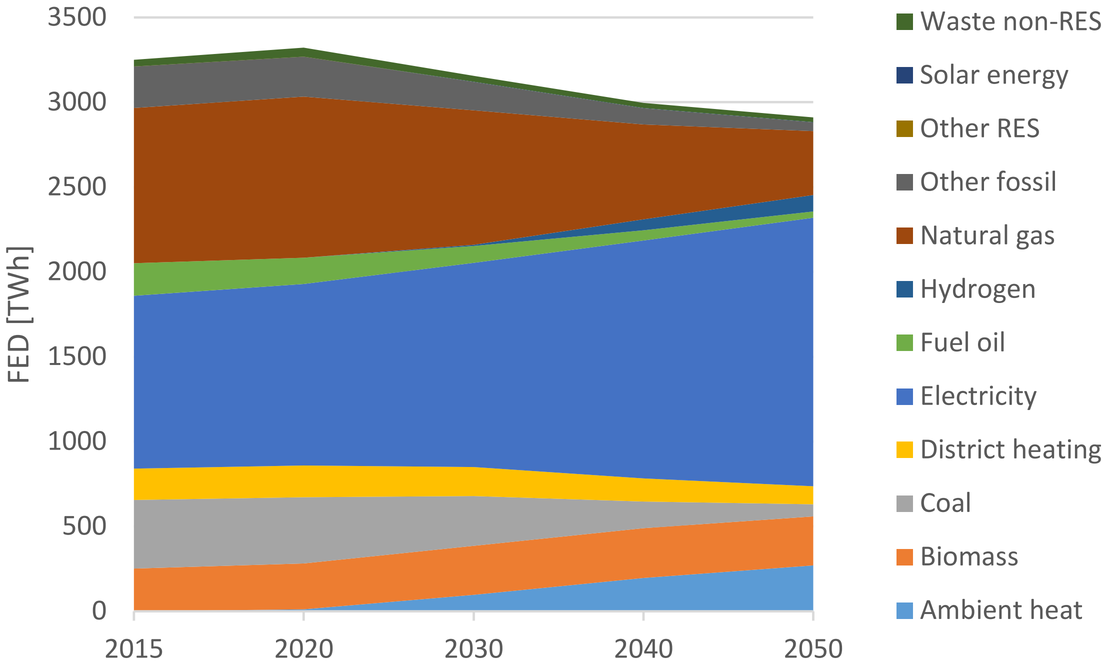
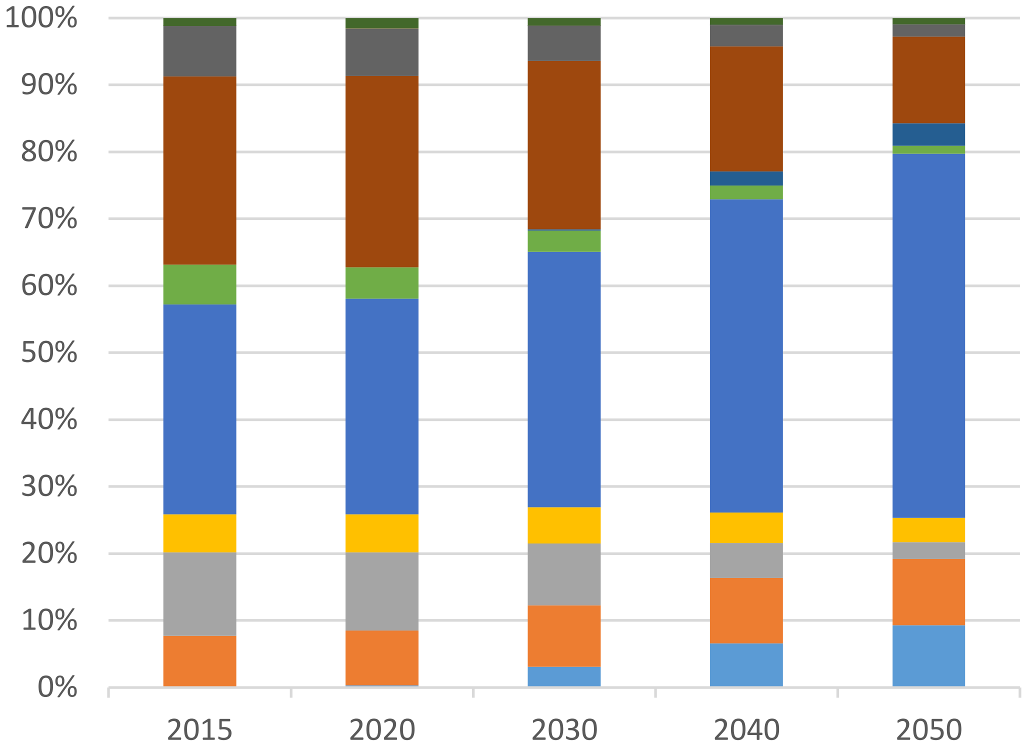
[12] At the current point in time, the use of CCS in the industrial sector is highly uncertain. Countries with strategies to use CCS in the power sector might also use CCS in geographically advantageous located industrial plans, which could allow the use of existing infrastructure and storage facilities. However, public acceptance of this technology is limited and the hydrogen economy currently the dominant debate, which is why CCS was not considered for this scenario. However, the technology will be taken into account in the carbon-neutral scenario(s).



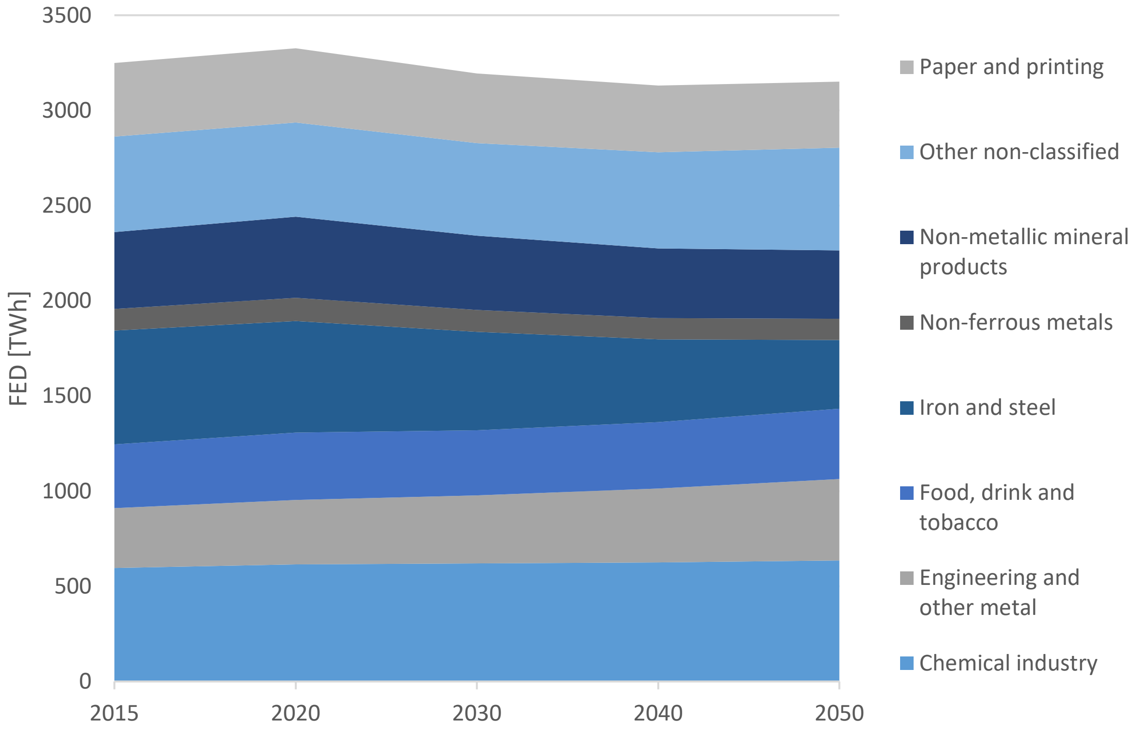
a) in level (TWh)



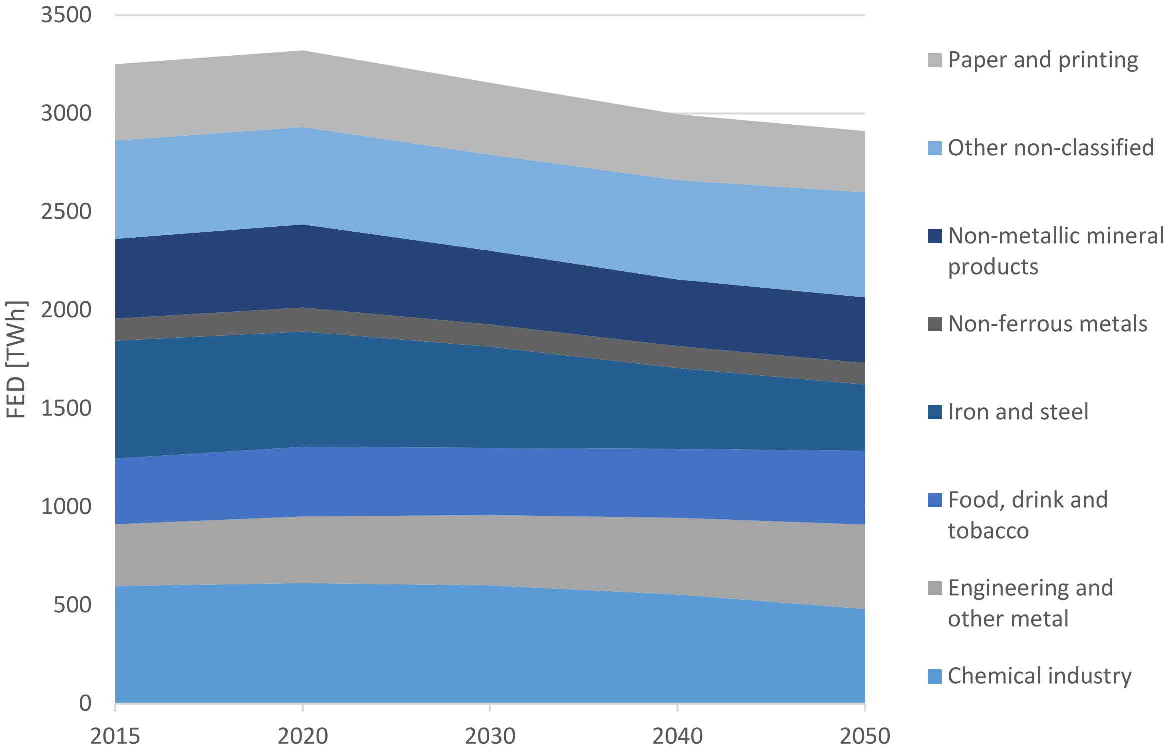
b) in %

Figure 17: Final heating energy demand by energy carriers in Stated Policies scenario in EU28

Source: FORECAST model. (a): Final heating energy demand by energy carriers in Stated Policies scenario in EU28 in absolute value (TWh) and (b) on percentage of total.



a) in Current Policies scenario



b) in Stated Policies scenario

Figure 18: Final heating energy demand of EU28 by sub-sector

Source: FORECAST model. (a): Final heating energy demand of EU28 by sub-sector in the Current Policies scenario in (TWh) (b) in the Stated Policies scenario in (TWh).

In industry, three types of GHG emissions sources can be distinguished:

- Direct energy-related emissions from on-site fossil fuel combustion.
- Direct process-related emissions from chemical reactions within the production process (process emissions).
- Indirect emissions from the consumption of electricity and district heat.

This study analyses the direct energy- and process-related emissions in industry. Indirect emissions are accounted for in the conversion sector and depend on the energy carrier mix on the supply side - consequently, they are outside the system boundary of the industry sector. Figure 19 shows the direct industrial emissions. In total EU28 direct CO_2 emissions decrease from 648 $MtCO_2$ in 2015 to 391 Mt in the Current Policies scenario and 230 Mt in the Stated Policies Scenario. This reflects a reduction of -40 % in the CP scenario and -65% in the SP scenario compared to 2015. Process related emissions account for 163 $MtCO_2$ in 2015 and decrease to 149 Mt in the CP scenario and 98 Mt in the SP scenario. The slow reduction of process-related emissions in the CP scenario is explained by the fact that they are dominated by the production of non-metallic minerals, e.g. clinker/cement or lime, which do not change substantially. In the SP scenario, fundamental changes in process technologies are already taking place (e.g. increased use of hydrogen, the introduction of low carbon cement sorts) which lead to significantly lower process emissions (98 Mt in 2050).

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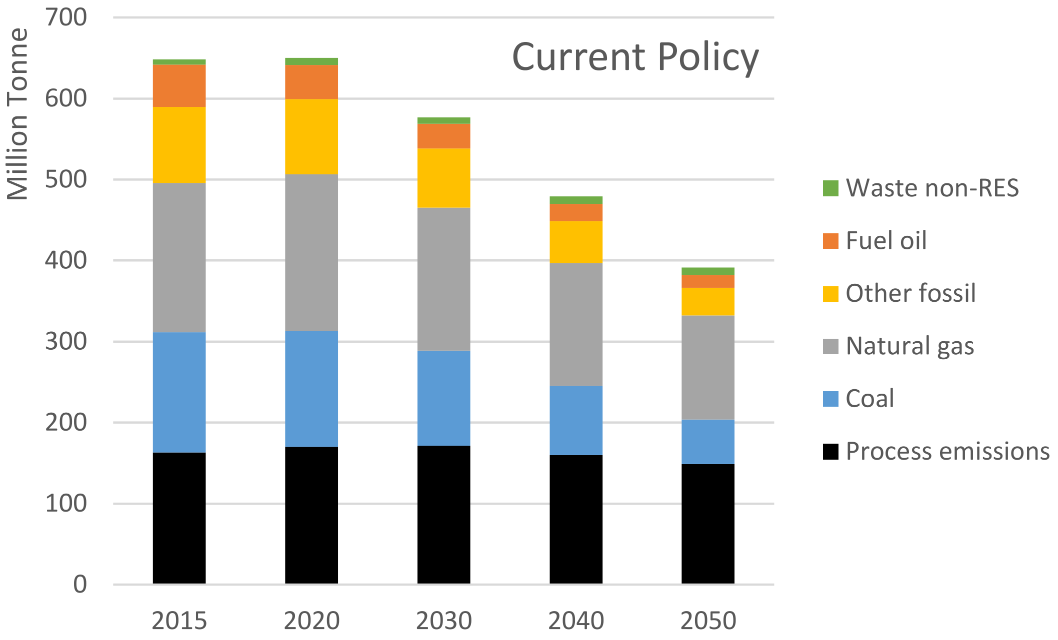
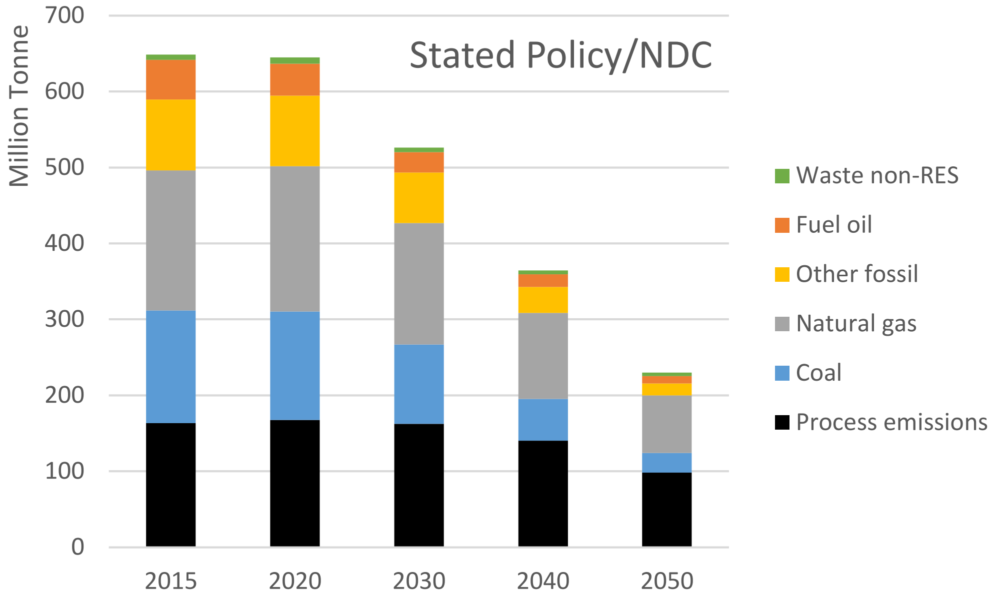


a) in Current Policies scenario



b) in Stated Policies scenario

Figure 19: Industrial (direct) CO2 emissions in EU28

Source: FORECAST model. (a): Industrial direct CO_2 *emissions in EU28 in the Current Policies scenario* ($MtCO_2$) *(b) in the Stated Policies scenario* ($MtCO_2$).

2.2.3 Transport

The modelling of transport demands, the diffusion of alternative drives and the resulting estimation of the final energy consumption and the greenhouse gas emissions of the transport sector are based on a bottom-up calculation of five transport modes:

- Cars (passenger road transport)
- Heavy duty vehicles (freight road transport)
- Rail (passenger and freight transport)
- Air traffic (passenger and freight transport, territorial and international transport)
- Ships (inland shipping and maritime shipping)

The "*Where EU are headed*" scenario, implemented in the ALADIN model, is assumed to be the most probable scenario concerning current political plans and frameworks to achieve 80% GHG mitigation in 2050 (relative to 1990 levels). Therefore, measures and assumptions are included in the calculation of the diffusion of alternative drives and transport demands.

2.2.3.1 Passenger Cars

As electric drives are already common in passenger cars, the market diffusion is calculable by using empirical data to estimate electric vehicle (EV) annual registration numbers. With the registration numbers and the country specific life cycles, the total car stock is calculated for each year. In regard to the average driving performances for each nation, the electric, conventional and synthetic fuel energy demands can be derived. As the market diffusion depends on national framework conditions, a diffusion curve represented by a logistic growth function, for each country is calculated. Therefore, the market diffusion for electric vehicles (EV) in Norway, a pioneer in e-mobility, with a market share of 81,8% EV in 2020 (ACEA, 2020) was analysed from 2009 to 2019 by regression analysis.

The start value for the logistic growth is the country specific market share of EV in 2019. The saturation of the growth function is set to be 90% for every country as it is the best fit with the empirical market share data from Norway and it is most probable that EV will almost completely substitute conventional drive technologies. In the "*Where is the EU headed*" scenario, we assumed that in passenger cars there would not be a relevant availability of fuel cell electric vehicle (FCEV) in future due to high costs of FCs and due to the predominance of (battery electric vehicles (BEV) already on the market. Therefore, we do not expect any relevant hydrogen demands in the "*Where EU are headed*" scenario for passenger cars.

In order to adapt the annual national growth rates to each country, the national fuel-electric energy price ratios and national monetary incentives are taken into account. The impact of the two factors on the market share of Passenger Electric Vehicles (PEV) was calculated by a panel analysis from Münzel et al. (2019). Monetary incentives include all cost savings for PEV compared to conventional cars and assumed constant for 2019 to 2029 and zero from 2030 to 2050 as costs for BEV will decrease in the 2020s by upscaling and learning effects. National bans of combustion engines have not been taken into account, as the country with a stated ban will already have almost 100% EV sales share when the ban will be realised.

The battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) registration numbers are calculated by the national market share of PHEV under PEV. The national market shares of PHEV are set to be constant from 2020-2029, linearly decreased from 2030-2039 and zero from 2040-2050 as PHEV is assumed to be completely substituted by BEV in future as BEV will extend ranges and will have cheaper battery costs. The average electric driving performance was assumed 56 % of total driving performance for PHEV to calculate electric and fuel energy demands. For all drives, a total efficiency increase of 30% from 2018 to 2050 is assumed. The data for car stocks, registrations, and market shares of alternative drives for all countries from 2011 to 2019 were collected from ACEA[13].

Main results

The results for the cars are dominated by the market diffusion of electric vehicles (EV) where in 2050 the market share of EV will be 90% in all European countries.

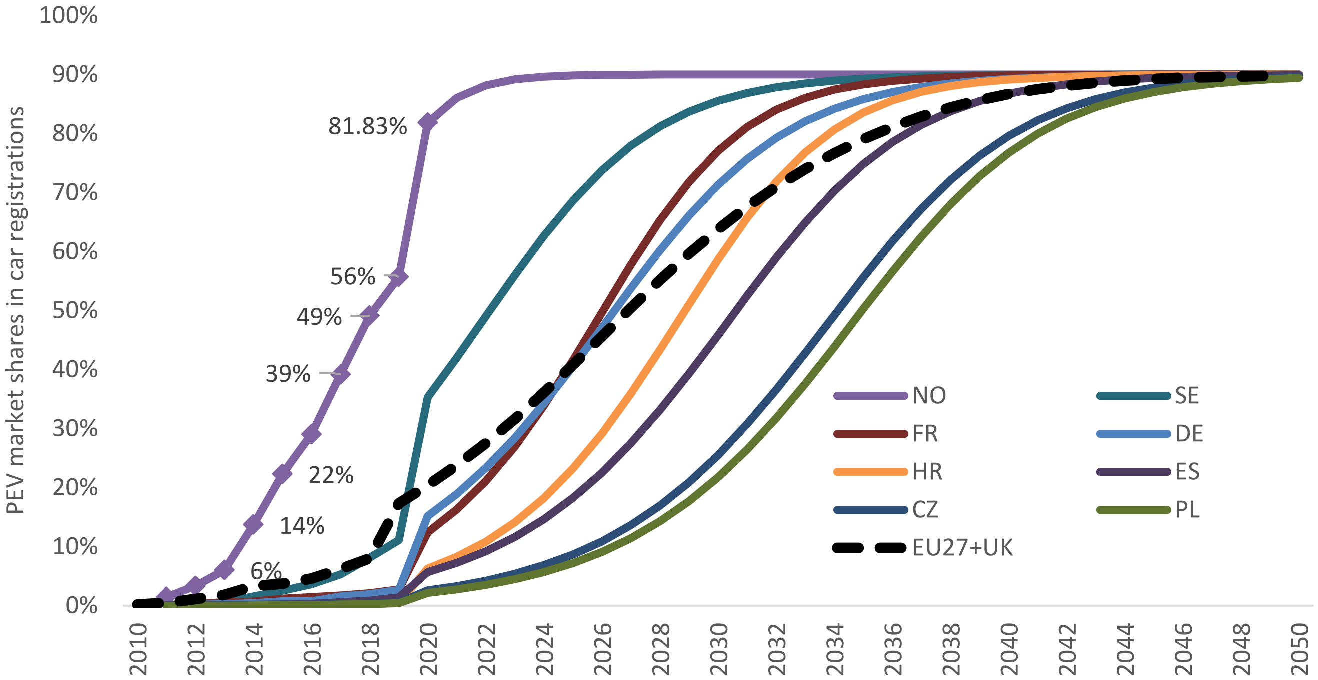


Figure 20: Market shares of PEV in car registrations by a selection of EU27+UK+NO countries

Historical data from 2011 to 2020 retrieved from ACEA (2021) and projections from 2021 to 2050

Northern European countries (Norway, Sweden, Finland and Denmark), Belgium and the Netherlands have the most advanced market diffusion of PEV whereas the eastern European countries adapt slower to alternative drives. Out of the projected car registrations, the passenger car stocks for each country were calculated by its individual useful lifetime. Electric energy demands were derived by the stocks of PEVs and the average energy consumption per car including yearly efficiency increases (see Figure 21).

Synthetic fuels and hydrogen will play a minor role due to the electrification of road transport and will not exceed 70 TWh of synfuels (2,6 Mt of hydrogen equivalent).

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[13] https://www.acea.be/statistics) and adjusted for future projections

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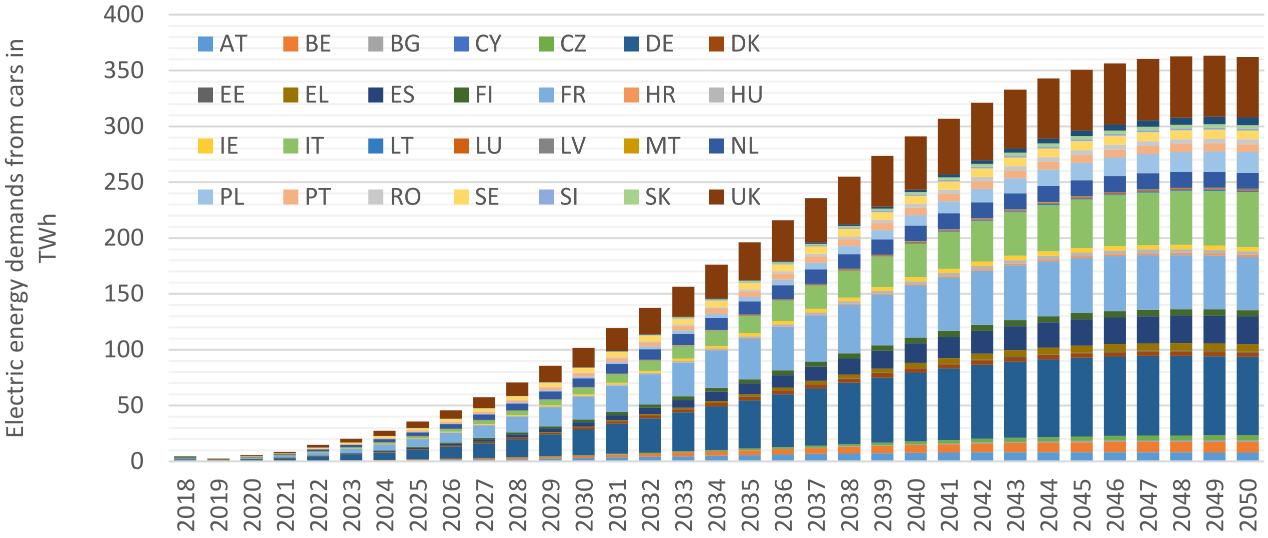

Figure 21: Electric energy demand from PEV cars in TWh by EU28 country

Source: ALADIN model

2.2.3.2 Heavy-duty vehicles

As there is hardly any empirical data on market diffusion of alternative drives for heavy-duty vehicles, another module of the ALADIN ("Alternative Antriebe Diffusion und Infrastruktur") is used to model the market ramp-up of alternative drives. It is an agent-based simulation model that depicts the purchase decision of individuals under given framework conditions. The purchase decision is simulated based on real driving profiles and the resulting requirements. The drive technology that maximises benefits is selected for each driving profile. Then the individual purchase decisions are brought together in a total stock to derive the energy demand with respect to the type, size and driving profile. The model has already been used in various studies, (e.g. in Plötz et al., 2014b and Wietschel et al., 2017)[14]. ALADIN distinguishes between seven drive alternatives: (1) diesel vehicles, (2) gas vehicles, (3) PHEV, (4) BEV, (5) FCEV and catenary vehicles that either equipped (6) with an additional battery or (7) with an additional combustion engine (Diesel). A distinction is also made between three vehicle classes: (1) light vehicles with a gross vehicle weight of less than 3.5 t, (2) vehicles with a gross vehicle weight of 3.5 t to 12 t and (3) heavy vehicles with a gross vehicle weight greater than 12 t. In the first step, based on vehicle usage data from 6,098 vehicles (KiD 2010; Truck-scout24 2016), the technical feasibility in terms of range and electric driving share is checked. This is followed by a a total cost of ownership (TCO) analysis since the total costs of commercial vehicles have the greatest influence on the purchase decision (Kluschke et al., 2019). Limited vehicle availability and political measures are also taken into account for commercial vehicles. In the third step, a market ramp-up scenario is calculated based on the individual vehicle selection that is optimal for the user. Further information on the procedure for commercial vehicles can be found in Wietschel et al. (2017) and Gnann et al. (2017).

The battery capacities were selected so that BEVs have a gross vehicle weight of less than 12 t and have a range of 300 km by 2050. BEVs over 12 t have a range of 400 km. This is sufficient to cover the usual distance between two breaks (4.5 h). PHEV are only available in the smaller vehicle classes up to 12 t. For vehicles over 12t hybrid overhead line trucks with additional diesel engines are assumed to be available. At this point, it is also assumed that overhead line infrastructure is partly available on most frequented European motorways.

ALADIN calculates the energy demands for Germany. For the other European countries, the energy demands from

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[14] Further information on modelling, reference projects and publications can be found at www.aladin-model.eu.

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Germany are adjusted to the territorial transport performances [tkm] of each nation (European transport statistical pocket book 2019). For all European countries, efficiency increases up to 30% for alternative and conventional drives.

Main results

Battery electric vehicles (BEV) will dominate the stock of trucks smaller than 3.5t similar to passenger cars in 2050. And in heavy duty vehicles higher 12t hybrid Diesel catenary trucks will be the most cost-efficient alternative following the assumption that electric overhead lines will be partly constructed on European highways. Hydrogen will play a minor and natural gas a negligible role (see Figure 22).

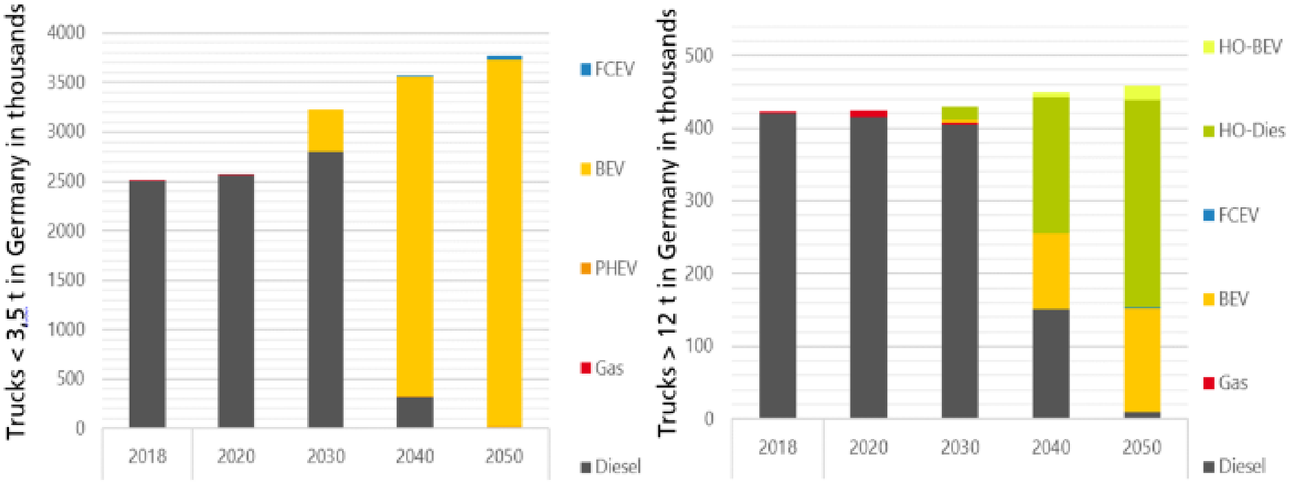

Figure 22: Number of trucks <3.5t (left) and >12t (right) in Germany in thousands, by fuel type from 2018 to 2050

Source: ALADIN model

Aggregating all truck sizes together, the final electric energy demand of road freight transport can be calculated. The EU28 electric energy demand will grow to 220 TWh in 2050 (20 TWh in 2030) whereas the highest growth is between 2030 and 2040 (see Figure 23).

Whereas the direct hydrogen consumption will not exceed 14 TWh (0.5 Mt H_2) as FCEV are less cost efficient due to the higher hydrogen prices and the later onset of hydrogen technology in transport (see Figure 24). The synfuels will mostly be demanded by Diesel catenary hybrid trucks that will dominate heavy-duty road transport in the "*Where are we headed*" scenario. The synfuels will be applied as mandatory admixture quotas to Diesel fuels and will reach a maximum of about 40 TWh (1.5 Mt hydrogen equivalent) in EU28.

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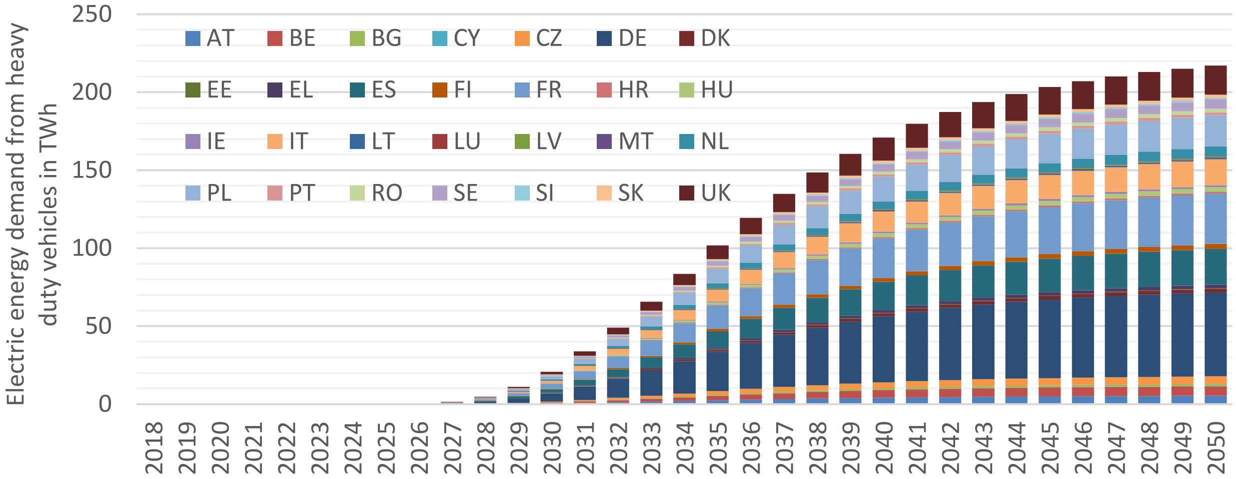

Figure 23: Electric energy demand in TWh from 2018 to 2050, by EU28 country

Source: ALADIN model

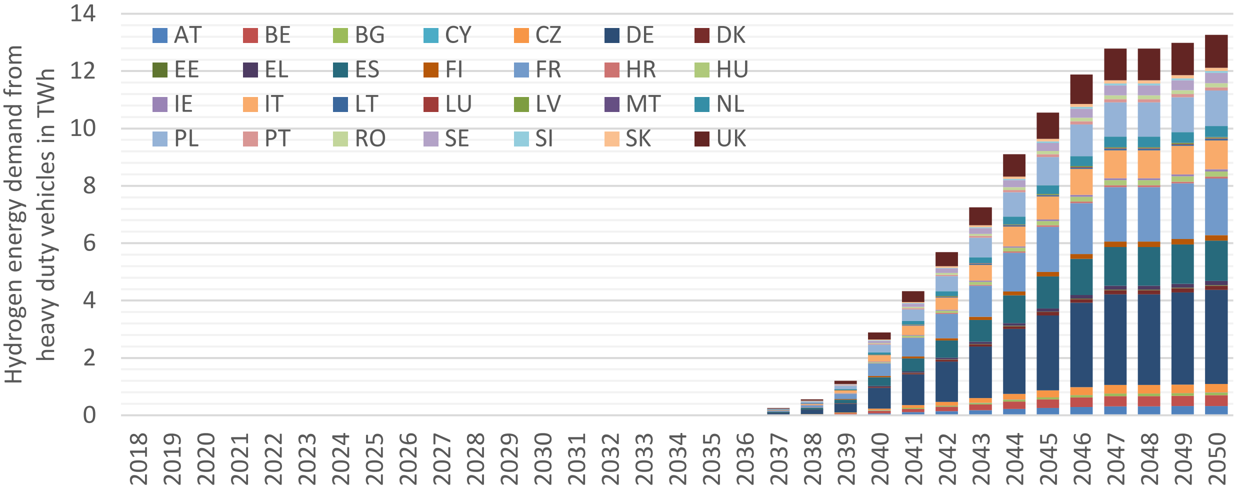

Figure 24: Hydrogen demand from trucks in TWh from 2019 to 2050, by EU28 country

Source: ALADIN model

2.2.3.3 Rail transport

Passenger and freight transport performances for railways were extracted from the European transport statistical pocketbook 2019 for the reference year 2018. Regarding the PRIMES EU28 Reference Scenario (European Commission, 2016), passenger transport performance increases 60% and freight transport performance increases 70% from 2015 to 2050. Therefore, the transport performances were adjusted for each nation. At the same time, efficiency improvement of the train loading by e.g. expanding of tracks and the use of longer trains also augments the load factors by 8% till 2030 and 20% till 2050. This does not completely compensate for the growing demands.

To calculate the electric and diesel energy demands for railways, empirical data (Statistical pocket-book transport, 2019) was used to derive a Lorentz-curve. The curve predicts the percentage of electric transport performance from the percentage of electrified tracks (see Figure 25).

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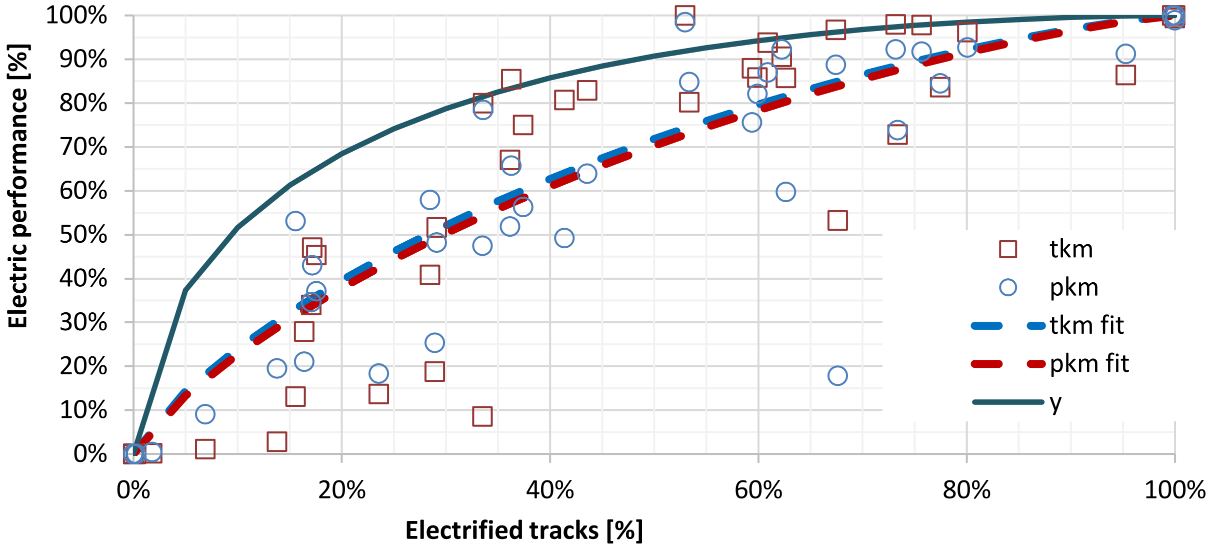

Figure 25: Relationship (blue line) between the percentage of electrified tracks and the percentage of electric drive trains in railway.

The curve was derived by empirical traffic data (red and blue dots and dashed lines).

Main results

In rail transport, an increase in efficiency of 2% p.a. for both drives, electric and diesel drives were assumed till 2050. In the "*Where are we headed*" scenario a moderate growing use of electrified tracks were assumed. So, the overall electricity demand will constantly grow to 62 TWh till 2050 (50 TWh in 2030) by increasing transport performances and a slight electrification of tracks (see Figure 26). Hydrogen and synthetic Diesel demands can be neglected in this scenario.

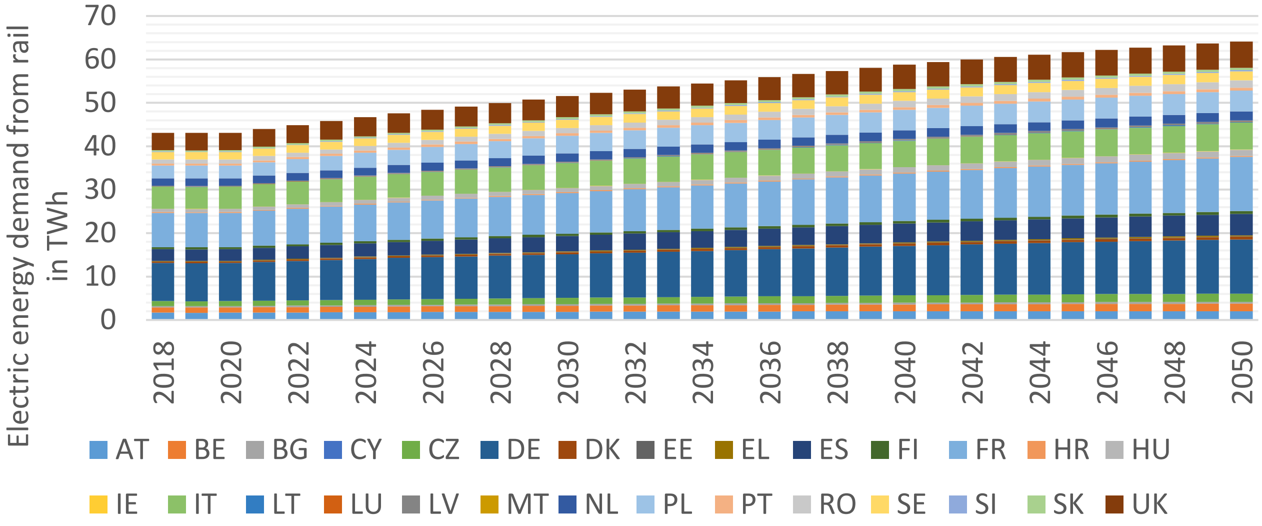

Figure 26: Electric energy demand from rail in TWh from 2019 to 2050, by EU28 country

Source: ALADIN model

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2.2.3.4 Maritime transport

Transport performances for inland shipping were calculated with the numbers from the European transport statistical pocketbook 2019. Increase in efficiency is estimated by 1% p.a. for inland shipping (Timmerberg et al., 2018). National energy demands for ocean shipping is even more difficult to determine, as there are many possible considerations: the owner, operator and flagging of the ship do not have to match and re-fuelling does not have to take place in the home port (Heitmann and Khalilian 2011). This is why the European share of international ocean traffic is calculated using the voluntarily specified amount of CO_2 in the so-called "international bunkers" for ocean shipping from the reporting of the UNFCCC. The three largest emitters in international ocean shipping are container and bulk carriers as well as oil tankers. As there are no territorial calculations, ocean shipping is calculated as an aggregation for all EU28 countries. Due to the large distances and times required at sea, no electrical variants are considered in ocean traffic. Ships are assumed to have efficiency improvements of 2% p.a. due to energy-saving behavioural adjustments, slow steaming, reduced turnaround times in the port, weather routing, and optimized autopilot, etc.

Main results

As electrification in shipping is neglectable the climate targets will be fulfilled by an admixture quota of 30% synthetic Diesel till 2050. This leads to a total demand of 10 TWh (0.4 MtH_2-eq.) synthetic Diesel in inland waterway shipping and 80 TWh (2.9Mt H_2-eq.) in maritime shipping.

2.2.3.5 Aviation

Transport performances for inland flights and international flights were collected from the ICAO annual report and the European transport statistical pocketbook 2019. At the same time, the volume of air traffic in Europe is assumed to constantly grow with 0,5 % starting in 2018. The impact of the COVID-19 pandemic is taken into account by reducing the annual growth to 2050 slightly but is not represented directly for the 2020 and 2021 flight performances. Energy efficiency improvements through improved propulsion efficiency and increased engine efficiency are to be expected in new aircraft, so that energy efficiency improvements of 1% p.a. can be achieved. There will be no relevant alternative drive technologies in aviation in the “Where are we headed” scenario.

Main results

No electrification of aircraft and no relevant number of hydrogen-driven planes are assumed in this scenario due to high operating times and the long time to market of electric or hydrogen technologies in aircraft. But synthetic jet fuels will be admixed with 30% in 2050 leading to a consumption of about 200 TWh synthetic jet fuels (7.4 MtH_2-eq.).

2.2.3.6 Summary of transport results

This section gives an overview of the total EU27+UK energy demands for electrical energy (see Figure 27), the total energy demands for synfuels (see Figure 28) and finally the sum of CO_2 (eq.) emissions by the transport sector (see Figure 29).

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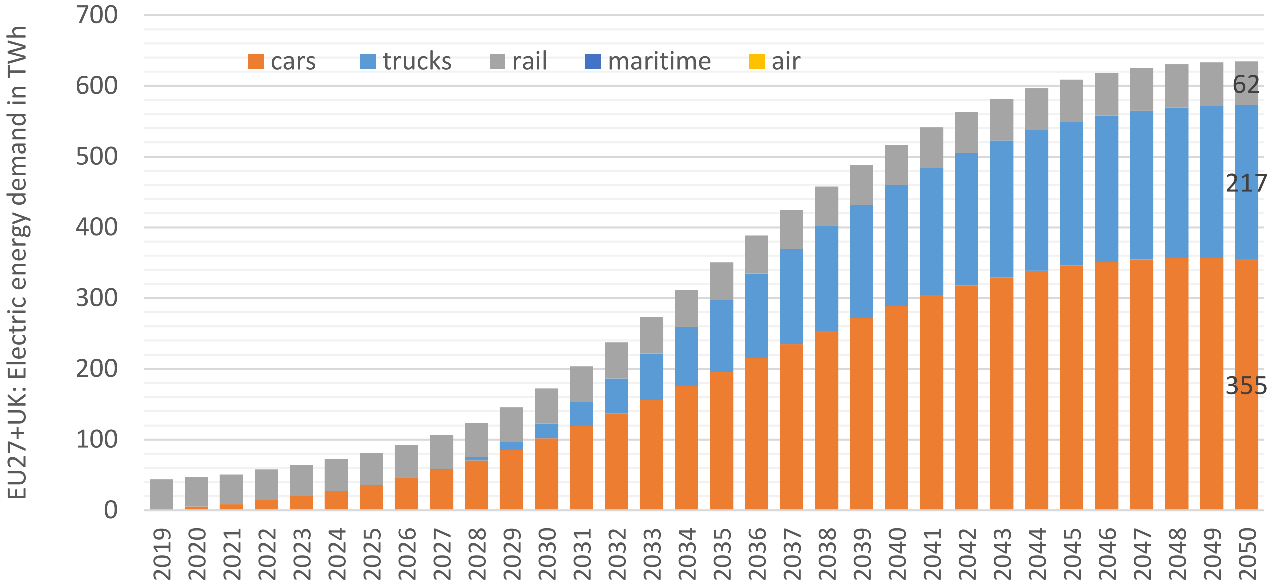

Figure 27: Electric energy demand in TWh for all EU28 countries from 2018 to 2050, grouped by transport mode

Source: ALADIN model

Electricity demands in EU28 rise to 640 TWh in 2050 (170 TWh in 2030) due to the ongoing electrification of road transport. Synfuels will play a major role in the modes where electrification and hydrogen drives cannot substitute conventional driving technology. So mostly air and maritime transport need mandatory admixture quotas of carbon neutral synfuels (30% by 2050) to achieve an 80% CO_2 mitigation.

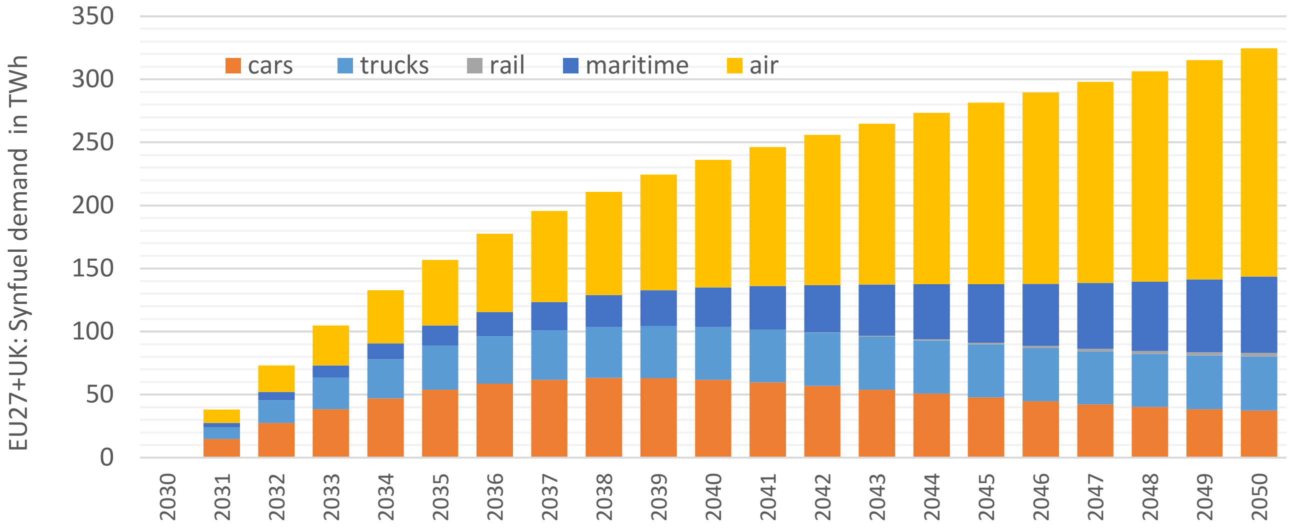

Figure 28: Synfuel energy demand in TWh for all EU28 countries from 2030 to 2050, grouped by transport mode

Source: ALADIN model

In the “Where are we headed” scenario the CO_2 emissions from transport are reduced 77% from 1990 to 2050, but only 5% from 1990 to 2030. To achieve the 2030 mitigation targets, other sectors need to compensate for the delayed shift in transport. Alternatively, more ambitious political measures should accelerate the transformation

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to carbon neutrality within the transport sector. The reason for the slow growth of carbon neutral transport technologies from 2020 to 2030 and the higher growth from 2031 to 2040 is simple: The current vehicle stocks must be step by step substituted by new vehicles with alternative drives and this needs time.

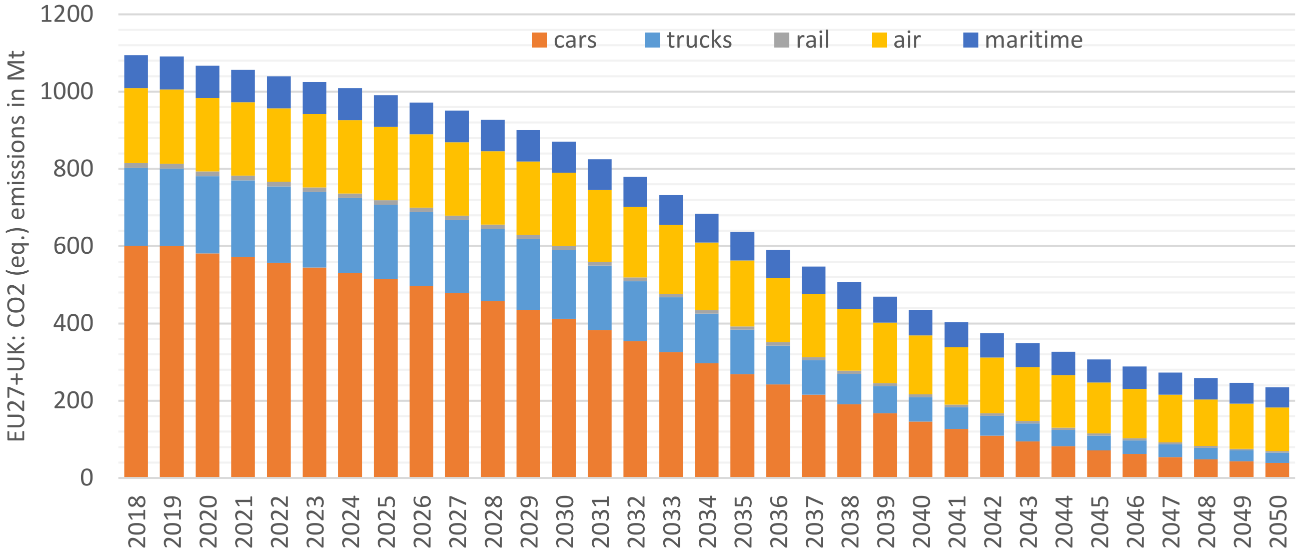

Figure 29: Emissions of CO2 (eq) from transportation in the EU28 countries in Mt, grouped by transport mode

Source: ALADIN model

2.3 Game-changing innovation: insights from “Where is the EU Headed” results

2.3.1 Introduction

Rapid decarbonisation that is needed to achieve the Paris Agreement’s goals requires innovative solutions. Task 5.3.3 sets out to identify transformative innovations, or “game changers”, and test their effects on European decarbonisation pathways and overall climate goals, in light of the need to increase ambition. Innovation in this context is not simply technological, but it can also involve fundamental re-organisations or shifts that require managerial, institutional, social and behavioural innovations including at the EU-regional, EU MS-national, non-EU national levels. There are several existing frameworks that are used for looking at innovation in decarbonisation pathways. For example, the Sectoral Innovation Systems (Malerba, 2002) and the Systems Failure (Woolthuis et al., 2005) frameworks. According to Malerba (2002), sectoral systems undergo change and transformation through the co-evolution of their various elements. In addition to technological innovation, social innovation is crucial in enabling and supporting the rapid transition to a low carbon economy. For example, it is argued (see de Geus and Wittmayer, 2019, for a literature review) that social innovation in energy might 1) accelerate the energy transition, 2) address democratisation and equity, 3) mainstream new practices, and 4) create new actor configurations and relations. They argue that ‘… *social innovations might simultaneously entail technological, economic and policy innovations, and vice versa. As such, different types of innovation can overlap and are not clearly delineated. Business innovations such as crowdfunding or social enterprises can also be regarded as social innovations. (p.7)*’

In this subsection, the insights from the ‘Where the EU is Headed’ modelling scenarios for game-changing sectoral innovation are discussed following the protocol set up in the Paris Reinforce Milestone 7 (Box 2).

For the purposes of this report, eleven models were deployed: seven global with explicit disaggregation of the European region, and four regional covering Europe in detail at the national level (sections 2.1 and 2.2). This sector focuses on electricity, three of those are used as examples for discussing-game changing sectoral technology choices in the EU: regional energy system model EU-TIMES and two regional sectoral models, one for transport (ALADIN) and one for the residential and industry sectors (FORECAST). These models as well as other models used in Section 2.1, along with their classification, coverage and description are presented in Table 2; full documentation of the models can be found in the I^{2}AM PARIS platform. We focus our discussion on the uptake of technologies, as percentage share of total from 2010 to 2050, in the electricity, transport, industry and buildings sector. Below the modelling results for these sectors are presented in the following subsections 2.3.) and that is followed by a discussion.

Box 2 Protocol for studying innovation dynamics in Europe and non-EU countries (MS7)

The partners are invited to pay attention to the following while preparing respective deliverables (D5.3 and D6.5):

(1) The deliverables should have a section on innovation, which is normally technological and/or institutional (i.e. changing the rules of the game) in its nature.
(2) It is also possible to envision innovative deployment or implementation of technologies that may already exist and be also in use at a small scale. However, upscaling an already commonly used technology and reaching economies-of-scale is generally NOT innovation, nor does the implementation of least-cost policies or existing legislation qualify as innovation.
(3) This work should not repeat what has already been done in the published papers and in other deliverables of Paris Reinforce. It should obtain value-added beyond these.
(4) The expected climate mitigation impacts of the observed or desired innovations should be significant, either in quantitative terms or because they create a new pathway that is arguably low carbon or low emissions in the longer term.
(5) The innovations considered have to have some broader appeal. Otherwise, these are certainly not game-changing in any way.
(6) The game-changing innovations should be discussed with stakeholders and additional options will be identified/co-created during these engagements.

The sections on innovations dynamics in D5.3 and D6.5 should

1. Provide the background and rationale as to why the issue is important
2. Identify and explain what and in which ways the identified or desired innovation is innovative and/or game-changing
3. Explain the appropriate geography and why it is significant in climate terms.
4. Demonstrate clearly value-added to other work done in Paris Reinforce.
5. Explain the modelling or analytical approach taken and how this goes beyond previous approaches (i.e. adds value) even if using the same tool(s) or methods.
6. Describe any key linkages with other WPs, tasks, sub-tasks, deliverables and milestones.

Provide results, discussion, and conclusions and scope for further research.

2.3.2 EU electricity generation 2010-2050

The figures below show the electricity generation by energy source either with or without CCS for the "Where are we headed" scenarios as modelled with the EU-TIMES model. Figure30a presents a case for current policies before the European Green New Deal is implemented and Figure 30b for a more ambitious scenario based on NDCs.

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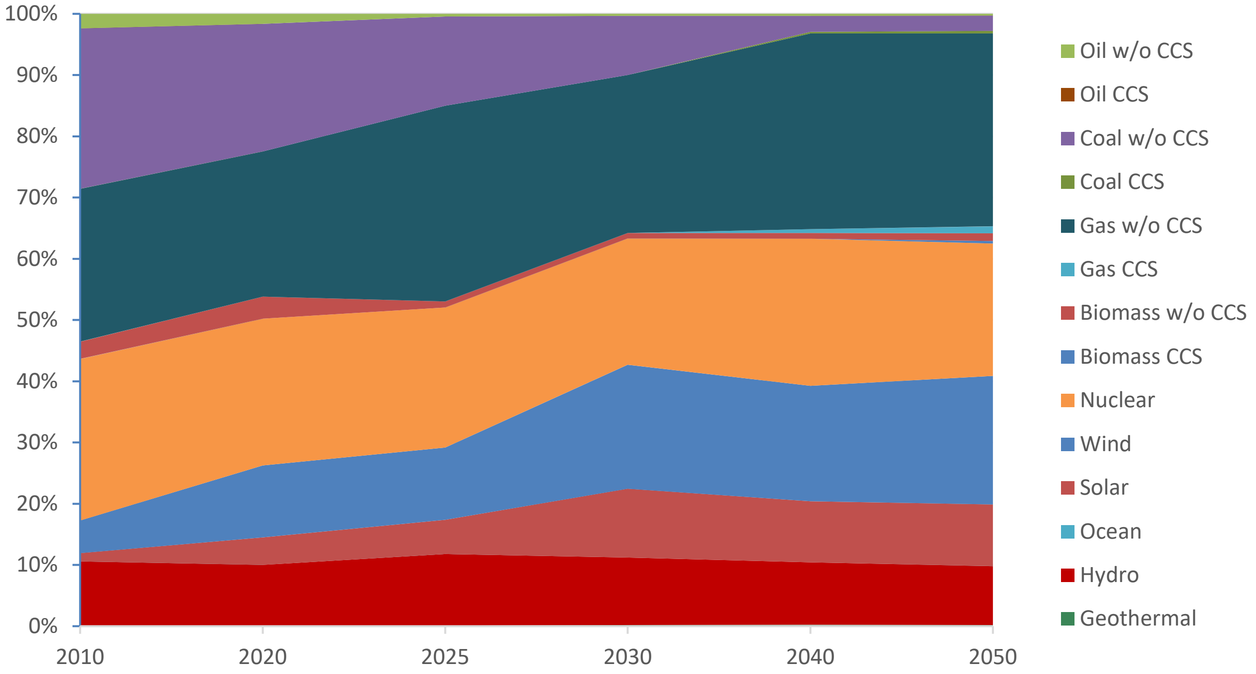
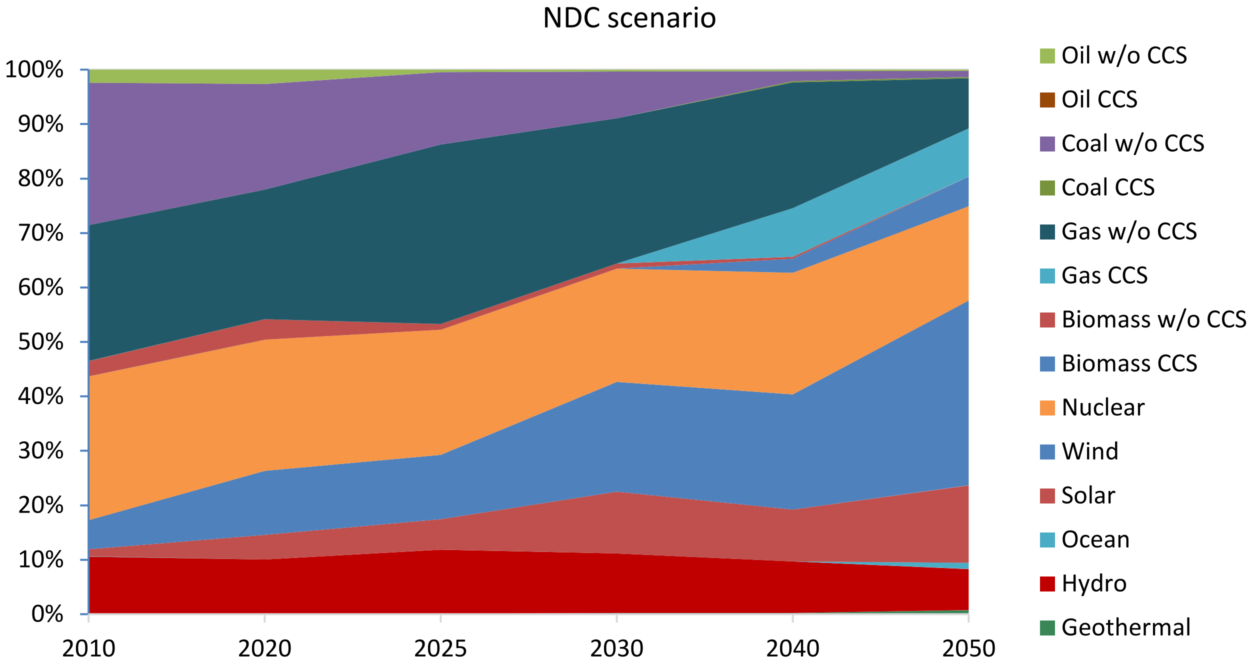


a) in Current Policies scenario



b) in NDC scenario

Figure 30: Electricity generation by source (in % of the total)

Source: EU-TIMES model; a): Electricity generation by source (in % of the total) in the current policies scenario and (b) in the NDC scenario

In case of the current policies scenario, power generation continues to rely on current technologies because after 2030 the push for large uptake of CCS technologies is missing. Gas, nuclear and wind are the main source of power generation covering a share of 33%, 22% and 21% of electricity generated in 2050. Only 1% of gas is used with CCS technologies and only 25% of wind-based electricity is coming from offshore applications. The least used renewable sources are biomass, geothermal and ocean energy, while fossil fuels oil and coal only cover 3% of share in 2050. Coal is mostly replaced by gas, wind and solar energy by 2050. In the case of a current NDC scenario,

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in 2050 we observe a larger deployment of CCS technologies for power generation (Figure 30a). This scenario shows a higher push towards the uptake of climate friendly technologies post 2030 due to more stringent CO_2 reduction targets to be achieved and technological progress in low carbon technologies. By 2050 5% of power generation is produced by biomass with CCS and 9% by gas with CCS. Moreover, 63% of electricity is generated by renewable energy - the main sources are wind with 34% of share, hydro 8% and solar 14%. In the case of wind 14% is coming from wind offshore applications. Nuclear energy reduces but still covers 17% of power generation. Geothermal and ocean penetrate but remain at their niche status. There are several other models used to identify the uptake of currently available electricity generation technologies. The models include different sets of technologies, already existing or in development, that do not span much beyond what is presented in the figures above (see the I^2AM PARIS platform for detail).

2.3.3 EU stocks of cars and trucks 2010-2050

The figures below show the vehicle stocks by driving technologies for the "Where are we headed" scenarios based on the NDC scenario. Figure 31 shows the percentages of passenger car stocks of the total EU27+UK registered cars and Figure 32 shows the percentages of driving technologies in heavy duty vehicle (heavier than 12 t) stocks.

Alternatively, different energy carriers demanded by, for example, heavy road transport can be explored. Total energy demands differ a lot from the actual stocks due to different driving performances and energy efficiency by truck sizes. The technology used is not included in this case, but it does give an indication of different engine types used. However, the total work done by diesel are relatively much lower than the impression given by Figure 33, as they are just percentages and electricity has a much higher energy efficiency from the carrier to the wheel. The model does not identify technologies and innovations that allow for different driving performances.

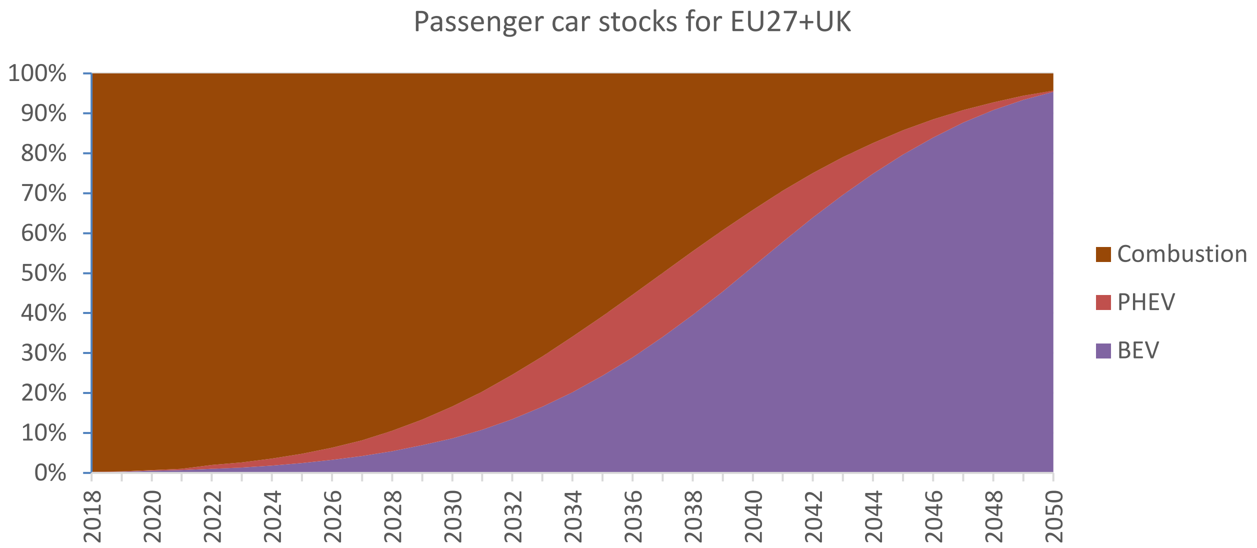

Figure 31: Percentages of driving technologies in passenger car stocks for EU27+UK - WWH_NDC scenario

Source: ALADIN model: Total passenger car stock is 259 M in 2018. FCEV = Fuel cell electric vehicles, BEV = Battery electric vehicles

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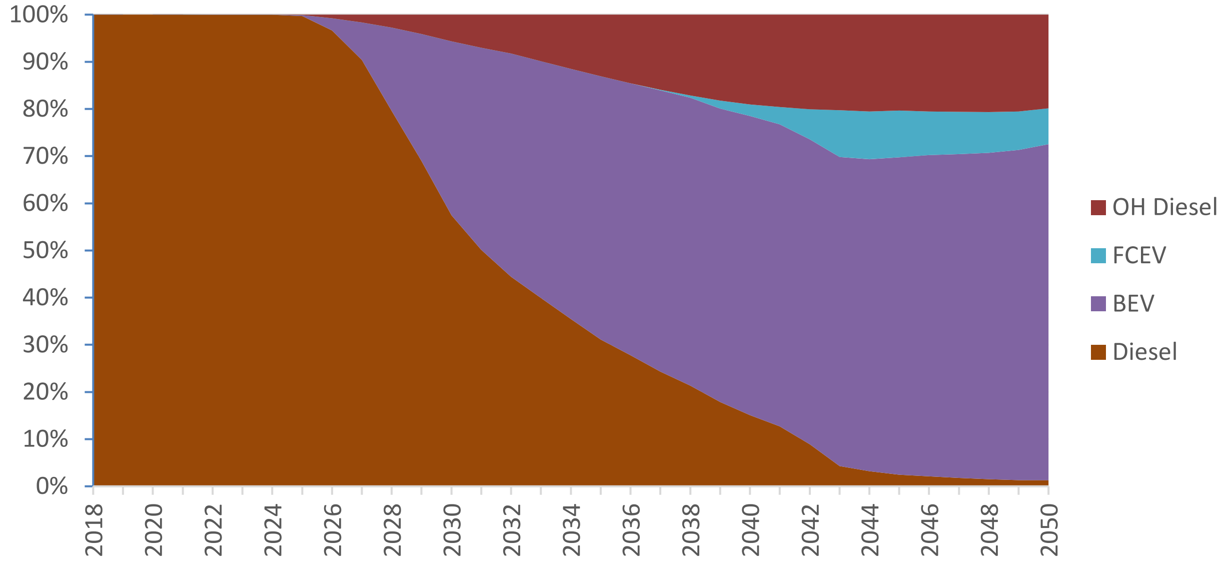

Figure 32: Percentages of driving technologies in heavy duty vehicles (>12 t) stocks for EU27+UK - WWH_NDC scenario

Source: ALADIN model. OH Diesel = Catanary Diesel hybrids, FCEV = Fuel cell electric vehicles, BEV = Battery electric vehicles, Diesel: trucks with conventional Diesel

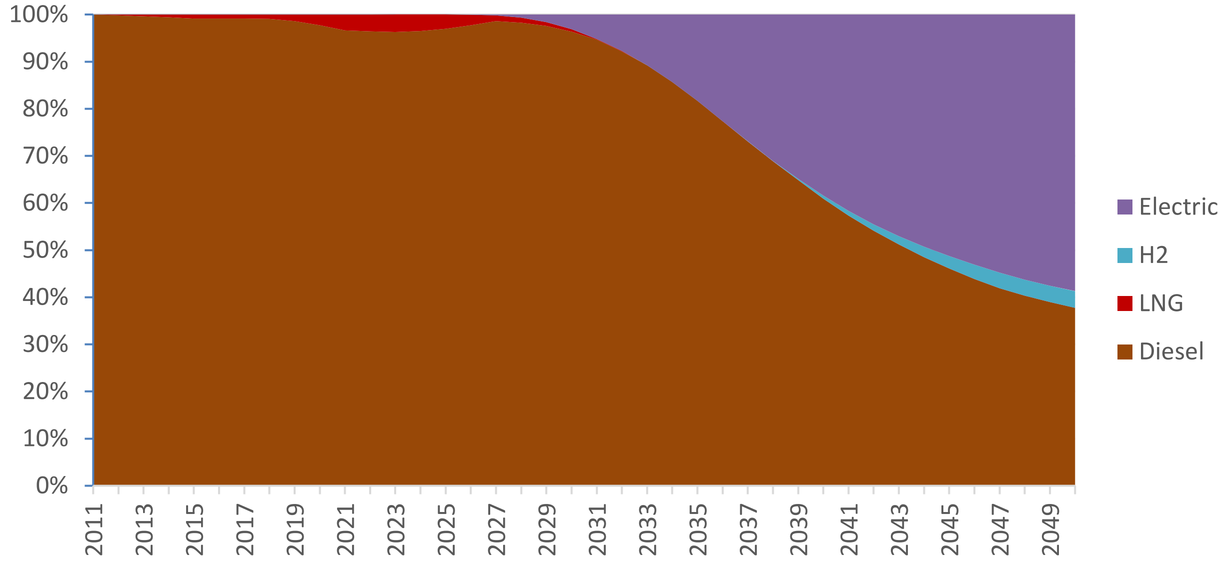

Figure 33: Percentages of different energy carriers in heavy duty vehicles for EU27+UK - WWH_NDC scenario

Source: ALADIN model. Electric = electricity, H2 = Hydrogen, LNG = Liquid Natural Gas.

2.3.4 EU industry and buildings 2010-2050

For buildings and industry, energy demand by different sources is used as a proxy for the uptake of different technologies in the scenarios modelled with the FORECAST model. The European buildings under the current policies scenario (CP) reduce their final energy demand for heating by 20% in 2050 compared to 2015 levels.

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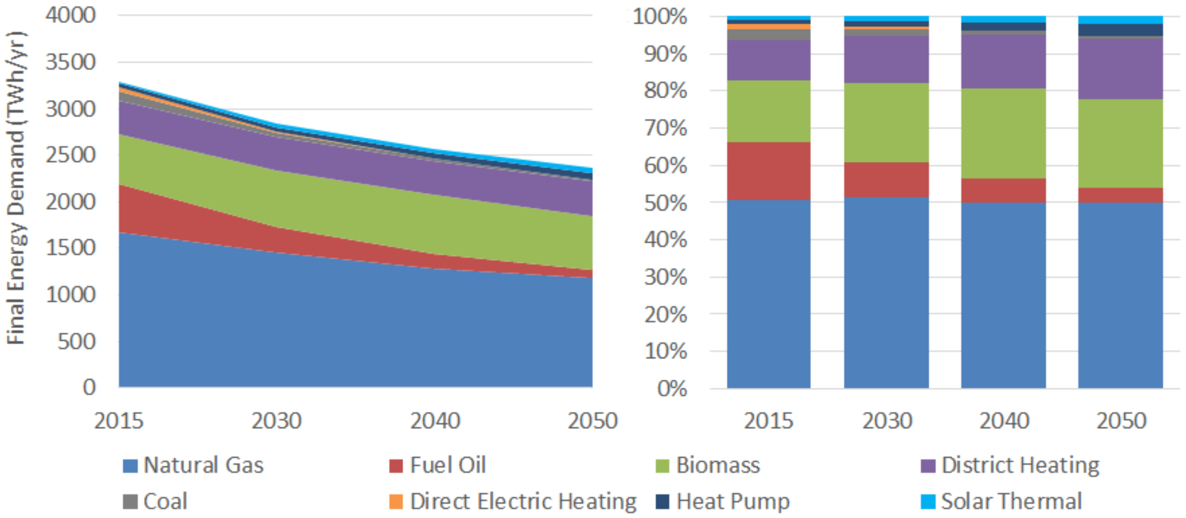

Figure 34: Final heating energy demand by energy carriers in Current Policies scenario in EU28

Source: FORECAST model

Despite the increase in water heating needs there 28% demand reduction in space heating. Under the implementation of the NDC scenario by the member states, the final energy demand for heating would further reduce by around 27% in 2050 compared to 2015 levels. This is driven by the higher compliance rates and the diffusion of higher building standards both in new and refurbished buildings. The switch to renewable fuels of solar thermal and heat pumps are visible in the Current Policies scenario after 2040. The biomass and district heating take-up is evident towards 2050 (Figure 34). However, the share of natural gas remains almost constant in 2050 at the level of 2015. This means that new innovations are needed to reduce natural gas demand, as well as in solar thermal and heat pump technologies. Coal and oil phase-out are achieved by 2050 under the NDC scenario, and the natural gas share has dropped to around 37% in 2050 (Figure 35). Biomass and district heating meet the majority of the heating demand and heat pumps and solar thermal systems are more visible in the energy mix. Natural gas demand is still significant due to the low price of the fuel itself, which makes the operational fuel costs attractive during the lifetime of the technology. Non-ETS CO_2 price can have a role here to decrease the demand for natural gas further and other innovative solutions can have a role here.

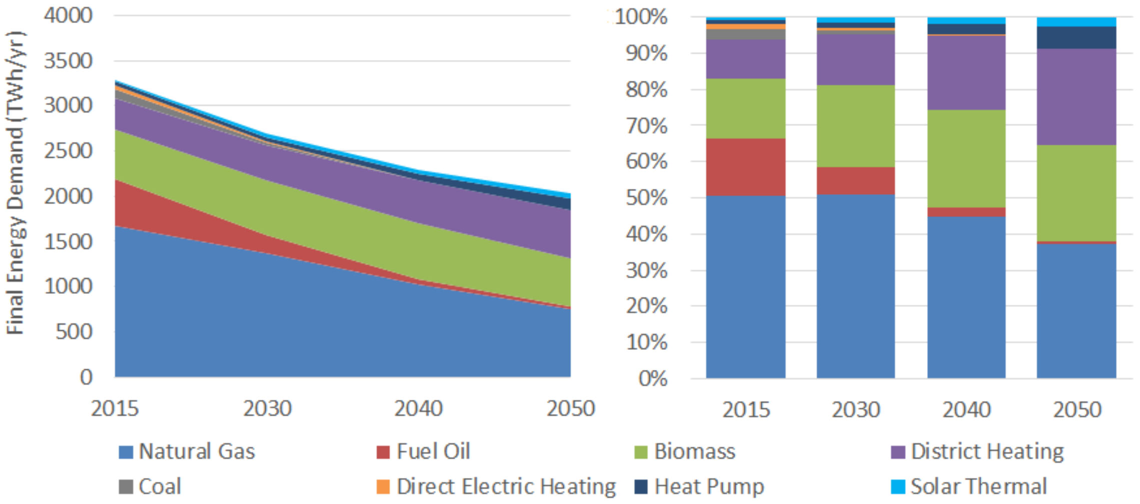

Figure 35: Final heating energy demand by energy carriers in NDC scenario in EU28

Source: FORECAST model

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After 2018, in the Current Policy scenario, final energy demand by industry (Figure 16) for the EU28 is only slightly decreasing as efficiency effects are nearly equalled out by activity effects, from 3250 TWh in 2015 to 3152 TWh in 2050. In addition to energy efficiency improvements using the BAT, the scenario is characterised by fuel switch towards renewable energy and electricity as well as higher recycling rates particular for steel. Since 2015, biomass use more than doubles from 250 TWh to 613 TWh in 2050 and electricity remains the dominant energy carrier increasing by around 10%. Consequently, biomass and ambient heat gain substantial market shares from 2015 to 2050 leading to a decrease in fossil energy demand for fuel oil (-70%), coal (-62%) and other fossil fuels. However, natural gas remains the second most important energy source in this scenario even though demand decreases by nearly one third, from 914 TWh in 2015 to 636 TWh in 2050. Hydrogen is only used to a limited extent in this scenario and reflects the EU Hydrogen Strategy in combination with the overall scenario assumptions (e.g. production developments). Hydrogen is used only in the iron and steel industry as well as chemical feedstock (see section 2.2.1.3). Even though, in the iron and steel industry, pilot plants are currently under construction/planning, relevant production is assumed to start after 2025. In 2050 it is assumed that 27.6 Mt hydrogen-based steel (DR RES H2 + EAF) is produced leading to a hydrogen demand of 40 TWh in 2050.

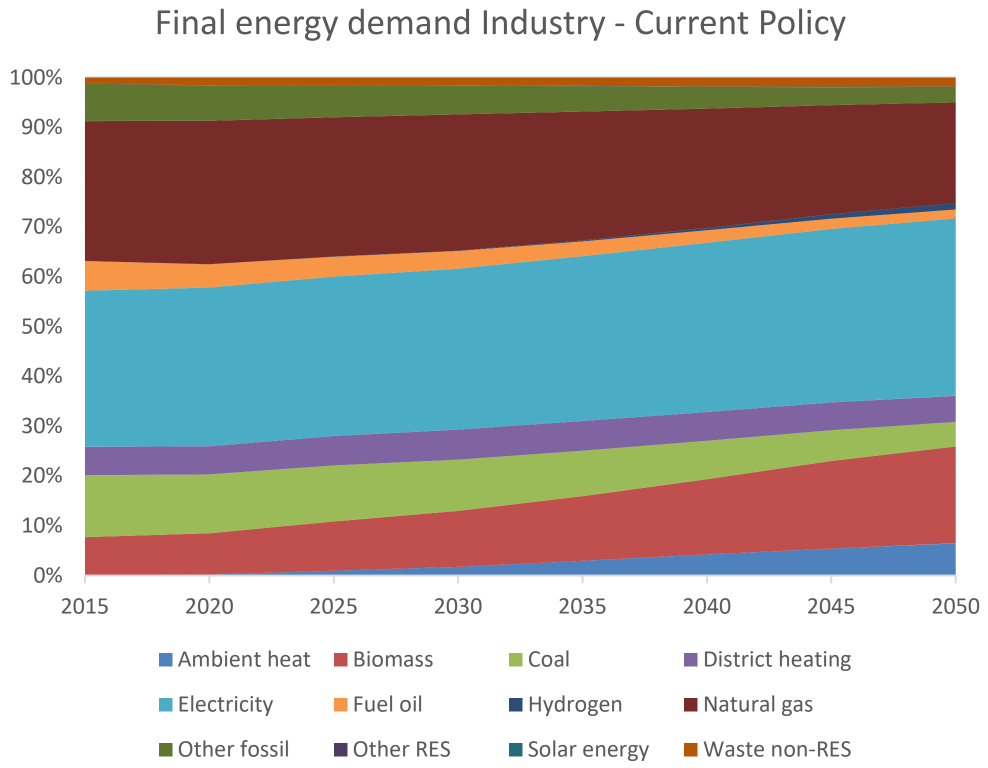

Figure 36: Final energy demand without feedstock by energy carrier in Current Policy scenario in EU28

Source: FORECAST model

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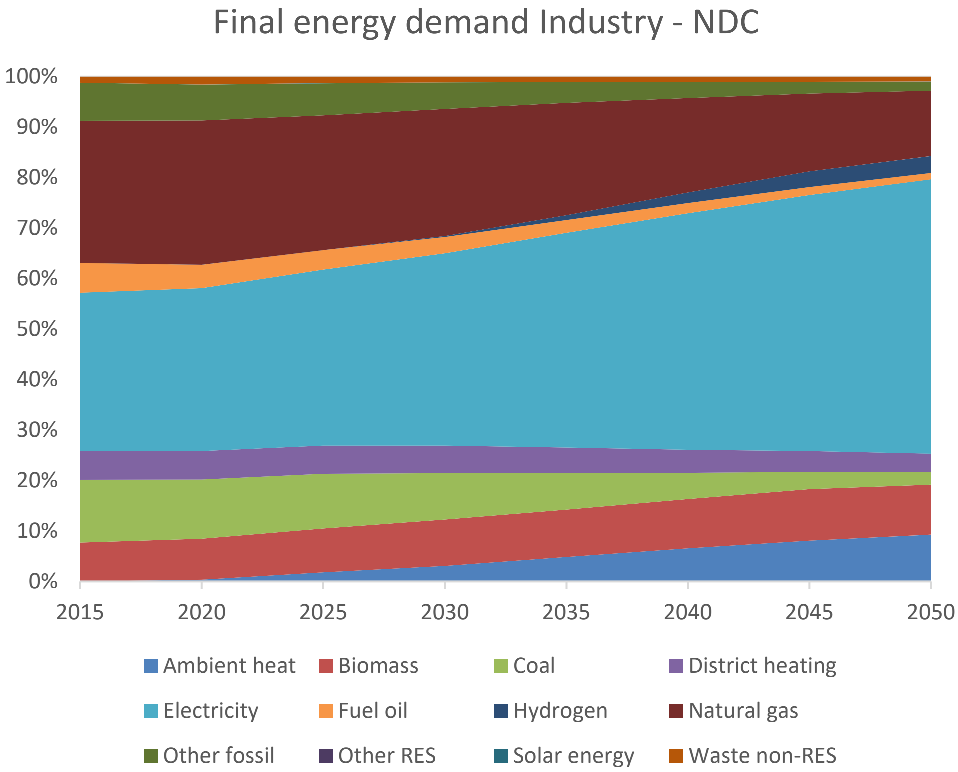

Figure 37: Final energy demand without feedstock by energy carriers in NDC Scenario in EU28

Source: FORECAST model

2.3.5 Discussion, conclusions, and further work

The models in this study present technologies that already exist or are in development. The uptake of these technologies depends to a large extent on the carbon prices (ETS and ESR sectors) implied in the Currently Policies and NDC scenarios or developments of technology costs that are exogenous in most of the Paris Reinforce models. Hence, in order for a technology to be presented in a model, there has to be some understanding of its costs, meaning that new and innovative technologies are not included in the models since there is no mechanism for their uptake under various scenarios.

Even if the cost developments of a technology are known, there are still uncertainties about their feasibility. For example, large-scale use of CCS with or without bioenergy in the electricity and industrial sector is highly uncertain. Countries with strategies to use CCS in the power sector might also use CCS in geographically advantageous located industrial plans, which could allow the use of existing infrastructure and storage facilities. However, the availability of bioenergy and storage facilities are not featured as constraints in the models that were used in this section for exploring changes in technologies. Moreover, public acceptance of this technology is limited (Fuss et al., 2014) and the risks of using large-scale BECCs to biodiversity, food security, and water availability are highlighted (IPCC, 2019). In addition, the hydrogen economy is currently still widely debated.

Napp et al. (2017) found that several important sectors do not require extensive technical R&D to be decarbonised as the technologies and processes to do so are already available. These sectors include: transport (excluding aviation), buildings and electricity generation. That does not mean that other types of innovations could not accelerate the uptake of technologies in these sectors. They also identified 21 technologies (including artificial photosynthesis for biofuels and thermal cycle for energy storage) that are critical for achieving a low-carbon

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economy and still require substantial R&D investment before they will be commercially viable.

The explored scenarios in all four industries also capture reductions in supply or demand including energy efficiency improvements (either via technology improvements or changes in operational strategies) while meeting the scenario targets. However, the models do not specify whether this type of changes require managerial, institutional, social and behavioural innovations.

The Current Policies and NDC scenarios do not identify any game-changing innovations as defined in the study protocol (Box 2). As next steps, it is worth having a look at the MS level and discussing the potential innovations needed to accelerate technology uptake or new alternative technologies that could be developed and deployed in the EU member states. To begin with, a stakeholder survey is planned for getting insights on potential developments and innovations beyond what the models can currently indicate.

3 Paris Agreement-Compliant scenarios: first elements

We present in this section the first elementσ of the EU PARIS Agreement Compliant (PAC) scenario. We start a literature review of the existing quantification of potential AFOLU sector emissions projects and its potential contribution to PAC scenarios. We continue with a description of a methodology developed in PARIS REINFORCE to assess the impact of the COVID-19 pandemic on the EU energy system according to different scenarios about the EU economic recovery, the EU climate action and some potential long-term behavioural changes.

3.1 How can the AFOLU sector contribute to the EU Green Deal and EU Long-Term Strategy for climate action: a review

Agriculture, and Land Use, Land Use Change and Forestry (LULUCF) are reporting sectors defined by IPCC in the context of emissions accounting (IPCC, 2006). The AFOLU sector includes LULUCF and Agriculture, where the 'Agriculture' sector, in accordance with IPCC terminology, includes non-CO_2 emissions from enteric fermentation, manure management, rice cultivation, prescribed burning of savannas and grassland, and from soils. Emissions related to forest and other land uses are covered under LULUCF. The land sector represents a key component to achieve the mid-century goal, especially because plays an important role in providing negative emissions, which are needed to offset the most difficult to abate emissions from industry and non-CO_2 residual emissions from the agriculture sector.

LULUCF presently is a net sink at a global level: it absorbs more CO_2, by storing it in biomass or soil carbon, than it releases to the atmosphere, although still representing the second source of emissions after fossil fuels, mainly due to deforestation. Forest areas are subject to variations, both in terms of surface and of GHG emissions and removals. Deforestation, wood harvest for both material and energy purposes, forest ageing and natural hazards drive most of the variations of the forest removals. Effects of LULUCF activities need quite long timescales and its contribution in the shorter term is relatively small: while deforestation can have an immediate impact, afforestation or fundamental adjustments to forest structure (species, age class distributions) to generate more sink will take decades. Furthermore the stored carbon can be re-emitted into the athmosphere due to distrubances such as fires. These characteristics have hampered a wide diffusion of forest carbon credits within compliance carbon markets.

Agriculture emits about half of the total non-CO_2 emissions (IPCC, 2019): they have decreased since 1990, however, with currently available and foreseen technology and management practices, agriculture emissions cannot be fully eliminated (European Commission, 2020d). Therefore, this sector is expected to make up most of the remaining sources of EU GHG emissions after 2050 in case of deep decarbonisation.

This section presents the contribution of the AFOLU sector to the EU 2030 and 2050 climate target. The projections described in the following sections come from four sources: the EU Reference Scenario 2020 (European Commission, 2021c), the Impact Assessment of the 2030 Climate Target Plan by the European Commission (European Commission, 2020d); the Communication from the Commission "*A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*" (European Commission, 2018a); finally the "where are we headed" scenarios produced by the PARIS REINFORCE models and available on the I^{2}AM PARIS[15] platform. The section is divided into five sub-sections, one for each data source, while the last one presents zoom-in of the land sector in the EU member states' long-term strategies.

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[15] https://paris-reinforce.epu.ntua.gr/main

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3.1.1 The AFOLU sector in the EU policy framework

LULUCF is a key element of reaching the European Green Deal objectives because it is the only sector that can actively remove CO_2 from the atmosphere, thus potentially compensate for residual GHG emissions, in the pathway towards EU climate neutrality by 2050. At the same time, agriculture, forestry and other land uses are essential in providing food and materials to support a circular economy next to providing other ecosystem services such as biodiversity. LULUCF and agriculture, therefore, play a relevant role across multiple EU policies (Figure 38).

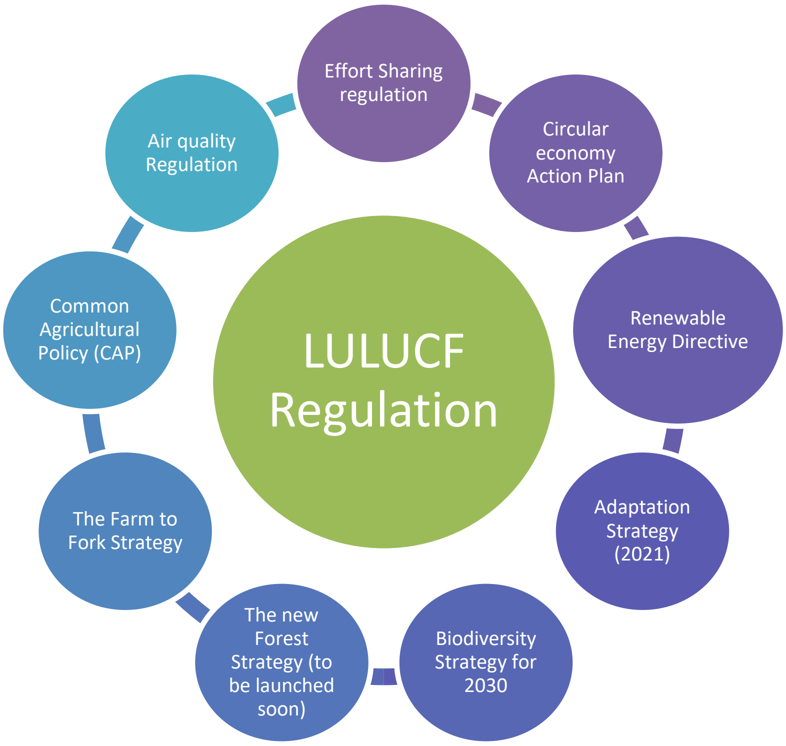

Figure 38: The AFOLU sector in the Eiuropean Green Deal

The EU "*Long-term vision for a prosperous, modern, competitive and climate neutral economy*" sets a 2050 climate neutrality target that relies on the compensation of residual emissions by absorption of land-use sector that is required to nearly double their net sink to achieve removals of 425 $MtCO_2$-eq by 2050. In line with the carbon neutrality target, the EU has recently updated its emission targets within the EU Green Deal (European Commission, 2019b) proposing a net emission reduction target of 55% by 2030 against 1990 levels. As a result, core elements of the 2030 framework that deals with the AFOLU sector, namely LULUCF regulation[16], the Effort Sharing Regulation[17] and the Renewable Energy Directive (REDII)[18], needed to be revised. The LULUCF regulation (841/2018) establishes a new pillar in the 2030 EU climate policy, with dedicated rules for LULUCF accounting of emissions and removals and a commitment that the LULUCF sector remains emissions 'neutral' in the period 2021-2030 (the so-called 'no debit rule'). The REDII sets renewable energy targets while strengthening the EU sustainability criteria for bioenergy and introducing new risk-based sustainability criteria for forest biomass, with the aim to ensure compliance with sustainable forest management laws and principles and that the carbon impacts of bioenergy are properly accounted for under the LULUCF sector. In mid July 2021, the European Commission

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[16] Regulation (EU) 2018/841 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry in the 2030 climate and energy framework, and amending Regulation (EU) No 525/2013 and Decision No 529/2013/EU

[17] Regulation (EU) 2018/842 on binding annual greenhouse gas emission reductions by Member States from 2021 to 2030 contributing to climate action to meet commitments under the Paris Agreement and amending Regulation (EU) No 525/2013

[18] Directive (EU) 2018/2001

has put forward the “Fit for 55” legislative proposals to make its policies fit for delivering the recently updated 2030 GHG emissions net reduction target. The “Fit for 55” package consist of a set of inter-connected proposals, covering a wide range of policy areas including climate, energy, transport and taxation; they all drive towards the same goal of ensuring a fair, competitive and green transition by 2030 and beyond. The revision concerned also theLULUCF regulation, containing, *inter alia*, a proposal to move towards a more stringent contribution from the LULUCF sector and, from 2031 onwards, to combine the agriculture non-CO_2 GHG emissions (agriculture sector) with LULUCF sector, thereby creating a newly regulated land sector, covering emissions and removals from Agriculture, Forestry and other Land Use (AFOLU) with a neutrality target by the 2030. The legislative proposals is still under consideration by Member States and the European Parliament for further consideration under the ordinary legislative procedure. The proposal confirm the no-debit rule for the 2025, while establishing a 2030 Union target for net GHG removals of -310 $MtCO_2e$. In other words, the LULUCF sector, that it is registering a general decline of the sink, will need to increase its removals of more than 25 % compared to 2019 levels and of more than 70% to offset all agriculture emissions by 2035 (if we assume no decline of such emissions).

It is already clear that in order to achieve the ambitious long term EU objectives, farmers and foresters will be called to play a more active role in increasing the carbon uptake and reducing emissions. To promote a more direct incentive system, the circular economy Action Plan (European Commission, 2020e) foresees a new regulatory framework for the certification of carbon removals by 2023, aimed at encouraging EU farmers to store carbon in soils and vegetation, and reduce emissions linked to agriculture practices. This system is also mentioned by the Farm to Fork Strategy (that aims at building a sustainable food system, European Commission, 2020f) and by the recent EU Adaptation Strategy (European Commission, 2021a) as a tool for achieving adaptation objectives in the agriculture and forestry sector, alongside mitigation. In fact, the adaptation strategy is calling for a more integrated and systemic approach to adaptation, where land management has relevance for biodiversity, water, soil and all natural resources. Nature based solutions on a larger scale are seen as options for increasing climate resilience while also contributing to the other Green Deal objectives. Ultimately, the main tool for the implementation of agriculture and forestry policy at the EU level is represented by the Common Agricultural Policy (CAP). The new CAP represents the main policy tool at EU level to support sustainable agriculture and rural development and promotes, among others, climate mitigation actions, and enhancing climate resilience through increased soil carbon content and water holding and efficient management of nutrient supply. However, how the carbon farming system will be integrated into the CAP financing instruments still remains to be seen.

All these policies aim also to increase the vitality and functioning of terrestrial ecosystems, resulting in decreasing their climate vulnerability. However, synergies and trade-offs need to be considered in relation to competing uses of land (e.g. biomass vs food production, protection purposes vs production, etc.). Furthermore, the AFOLU sector is highly exposed and very vulnerable to climate change. Therefore, in the face of a changing climate, long-term sustainable resource management is a key challenge to secure stability and adaptability of the carbon pools, and to guarantee effective carbon sequestration.

3.1.2 The 2020 Impact Assessment of the European Commission

All data reported in this sub-section refer to the Impact Assessment of the European Commission (European Commission, 2020d), which shows the contribution of all sectors of the economy and society to the achievement of carbon neutrality by 2050, plus it outlines the needed policy actions. The Impact Assessment presents CO_2-eq emission projections according to various scenarios for EU27.

3.1.2.1 LULUCF contribution

The Impact Assessment uses LULUCF emissions and removals projections developed by the Global Biosphere

Management Model (GLOBIOM-G4M)[19] model (Havlík et al., 2018), which provides insights for policy analysis on land use competition between the major land-based production sectors, namely the agricultural, bioenergy and forestry. The GLOBIOM-G4M is specifically used for the forestry sector emissions and removals and for the LULUCF to assess the options (afforestation, deforestation, forest management, and cropland and grassland management) and costs of enhancing the LULUCF sink for each EU Member State. The main data sources for G4M are CORINE (European Union, 2018b), Forest Europe (MCPFE, 2015), countries' submissions to UNFCCC and KP[20], FAO Forest Resource Assessments[21], and national forest inventory reports. Afforestation and deforestation trends in G4M are calibrated to historical data for the period 2000-2013.

The assessment of the European LULUCF emission and removal is performed considering four different future scenarios. Two out of four scenarios assume that the sink can be reduced mainly by increased harvesting and natural hazards: the "FRL" and the "No debit" scenario. The other two scenarios are more optimistic about the enlargement of the sink: the "MIX" and the "LULUCF+" scenario (Table 1).

- The ***"BSL" baseline*** scenario assumes a deterioration of the EU emissions and removals from forests, due to management (increasing harvesting rates) and natural disturbances like forest fires; it is in line with increasing harvesting foreseen under the Forest Reference Levels.
- The ***"FRL" scenario*** refers to the recently agreed Forest Reference Levels and integrates them with the other LULUCF land categories projected by the GLOBIOM model. The latter optimistically reports that deforestation, afforestation and other land use change will improve and, as a result, the total net LULUCF removals will reach - 260 $MtCO_2$-eq in 2030.
- The ***"No Debit" scenario*** projects a natural sink of -225 $MtCO_2$-eq by 2030. The LULUCF Regulation, adopted in May 2018, sets a binding commitment for each Member State to ensure that accounted emissions from land use are entirely compensated by an equivalent accounted removal of CO_2 from the atmosphere through action in the sector. This is known as the "no debit" rule: it establishes, for example, that emissions due to forest loss have to be compensated by an equivalent afforestation effort, or by improving sustainable management of existing forests beyond a projected benchmark. The "no-debit" rule is introduced by the Regulation on the integration of LULUCF into the EU's 2030 climate and energy framework. The LULUCF Regulation represents the third pillar of the EU's 2030 climate and energy framework, along with the EU Emissions Trading System and the Effort Sharing Regulation.
- The ***"MIX" scenario*** projects that the recent decrease observed in LULUCF removals is not representative of the long-term trend and in 2030 the natural sink would be -295 $MtCO_2$-eq (like in 2015).
- In the **"LULUCF+" scenario** the LULUCF sink is enhanced to approximately -340 $MtCO_2$-eq by 2030, which is close to the 30-year maximum sink observed in 2006. In this regard, actions can include optimization of forest management, afforestation projects and improving soil management including through rewetting and restoration. Furthermore, by 2050 in the scenario, cropland is no longer a net LULUCF emitter and the forest land is removing substantially more CO_2 from the atmosphere. The entire LULUCF sector could then balance about 425 $MtCO_2$-eq.

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[19] https://iiasa.github.io/GLOBIOM/
[20] https://unfccc.int/ghg-inventories-annex-i-parties/2020
[21] http://www.fao.org/forest-resources-assessment/en/

Table 10: LULUCF net emissions/ removals for different scenarios for EU27

	2030					2050
$MtCO_2$-eq.	BSL	FRL	No debit	MIX	LULUCF+	LULUCF+
LULUCF	-224	-260	-225	-295	-340	-425

Source: European Commission 2020d

3.1.2.2 The Agricultural contribution

Regarding the non-CO_2 emissions contribution of the agricultural sector, the Impact Assessment of the European Commission (European Commission, 2020d) provides scenarios produced by CAPRI[22] and GAINS[23] models. CAPRI is a global multi-country agricultural sector model, though it has a greater detail for Europe than for other world regions. The CAPRI model provides the agricultural outlook, in particular on livestock and fertilizers use, further it provides the impacts on the agricultural sector from changed biofuel demand. The main data source for CAPRI is Eurostat. The GAINS (Greenhouse gas and Air Pollution Information and Simulation) model is an integrated assessment model of air pollutant and greenhouse gas emissions and their interactions. Model uses include the projection of non-CO_2 GHG emissions and air pollutant emissions for EU Reference scenario and policy scenarios, calibrated to UNFCCC emission data as a historical data source. For agricultural sector activity data, GAINS adopts historical data from Eurostat and aligns these with future projections from the CAPRI model.

Agricultural emissions are especially represented by CH_4 emissions from enteric fermentation and N_2O emissions linked to fertiliser and manure application. Whereas non-CO_2 GHG in energy, waste and industry are projected to significantly decrease already in the baseline, this is not the case with agriculture, where the decrease is projected to be more limited. It should be noted that the baseline does not incorporate any specific policies that might be undertaken under the future Member States' CAP strategic plans or other new policy initiatives under the European Green Deal. At baseline, with current policies in place (projected population stabilize and no changes is assumed in EU diets), the EU's agriculture emissions are projected to slightly decline until 2030 and then stabilize just over 400 $MtCO_2$-eq in 2050. Applying existing technical mitigation measures to the baseline would reduce emissions by around one third to below 300 $MtCO_2$-eq. Approximately 60% of this reduction would be achieved via abating nitrous oxide emissions and 40% via methane emissions.

Table 11: Baseline agricultural non-CO2 GHG emissions for EU27

$MtCO_2$-eq.	2025	2030	2050
Agricultural non-CO_2 emissions	380	375	400

Source: European Commission 2020d

3.1.2.3 The AFOLU contribution

The AFOLU category gathers together Agriculture, Forestry and Land Use. Therefore, it is the sum of the non-CO_2 agriculture emissions and the LULUCF sink. The Impact Assessment of the European Commission defines some scenarios that are specific to LULUCF, therefore, it is possible to produce an estimate of the total emissions from AFOLU only for the baseline scenario, which is common for both LULUCF and agriculture. The total emissions modelled from AFOLU in 2030 are 151 $MtCO_2$-eq.

3.1.3 EU long-term strategy (2018)

In 2018, the European Commission published the assessment report "*A Clean Planet for all - A European strategic*

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[22] https://www.capri-model.org/dokuwiki/doku.php

[23] https://iiasa.ac.at/web/home/research/researchPrograms/air/GAINS.html

long-term vision for a prosperous, modern, competitive and climate neutral economy" in support of the development of the Strategy for long-term European greenhouse gas emissions reduction for EU28 (European Commission, 2018a). It presents the vision of the European Commission to achieve net-zero GHG emissions by 2050; all data reported in this sub-section refer to that report.

The model suite used for the scenarios presented in the assessment report were already adopted for the 2020 and 2030 climate and energy policy framework, as well as for the 2011 Commission's decarbonisation Roadmaps. It has allowed to enhance the scale of detail of both energy system and GHG emissions and removals, and the characteristics of representation of technologies. The assessment report adopted the same model suite as that presented in the previous paragraph: through the PRIMES, GAINS, GLOBIOM and CAPRI models eight economy-wide scenarios are explored[24]. Details on methodology and modelling are presented in §7.2 of the assessment report (European Commission, 2018a).

The scenarios are built on the baseline, i.e. they show different potential levels of GHG reductions achievable if the current policy framework (presented in the baseline) is further intensified post-2030. The aim of the baseline is to illustrate the impact that current climate and energy policies and goals would have on long-term energy and GHG evolution. It assumes no intensification of policies post-2030 and no target for GHG emissions reduction from 2030 to 2050. The baseline, which does not reflect specific Member State policies, is based on the trajectory that is entailed by the 2030 European strategy targets: reducing greenhouse gas emissions by at least 40%, increasing the share of renewable energy to at least 27%, and achieving an energy efficiency improvement of at least 27%. Recently, the European Commission proposes to raise these targets, reducing greenhouse gas emissions to at least 55% below 1990 levels by 2030.

The set of scenarios built on the baseline are not specific for the AFOLU sector (like those presented in the 2020 Impact Assessment); they can be grouped into three categories, based on different levels of emissions reduction.

- ***Scenario category 1***: these scenarios suppose emissions reduction contributing to the Paris Agreement goal of well below 2°C. Five different scenarios fall under this category; all of them envisage greater energy and transport system efficiency, as well as developments of renewable energy, which goes well beyond the assumptions of the baseline scenario. The Electrification (ELEC), hydrogen (H2) and e-fuels (P2X) scenarios (sub-category 1-A) are based on the adoption of innovative energy carriers and examine the effect of switching from the direct use of fossil fuels to zero/carbon-neutral carbon carriers. The sub-category 1-B describes the impact of: energy efficiency measures (EE) and the transition to a more circular economy (CIRC).
    - The ***Electrification scenario (ELEC)*** highlights the electrification of the energy demand and thus higher electricity supply;
    - The ***hydrogen scenario (H2)*** highlights a deployment of e-hydrogen in the energy demand sectors and thus hydrogen production on the supply side;
    - The ***E-fuels (P2X)* scenario** highlights a larger demand and production of e-fuels (e-gas and e-liquids) in the energy sectors;
    - The ***Energy Efficiency scenario (EE)*** highlights a major energy efficiency in buildings, industry and transport;
    - The ***Circular Economy scenario (CIRC)*** envisages an increased resource and material efficiency, with higher recycling rates, material substitution and circular measures. It assumes

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[24] Details on methodology and modelling are presented in §7.2 of the assessment report (European Commission, 2018a).

standardization of recyclable material and improved systems for waste collection.

- ***Scenario category 2***: the sole scenario presented in this category combines the actions and technologies described in the five scenarios of category 1 into a single sixth scenario, named ***Combination (COMBO)***, which shows the potentiality of combining actions and technological solutions with small reliance on negative emissions technologies and without changes to consumer preferences. It goes beyond the well below 2°C goal.
- ***Scenario category 3***: these scenarios assume the largest emissions reduction, reaching net zero GHG emissions by 2050 and therefore the ambitious goal of 1.5°C temperature increase. The LULUCF sector plays a key role compensating for the remaining emissions that cannot be abated by 2050.
    - The ***1.5°C Technical (1.5TECH)*** scenario is based on the COMBO scenario, with more BECCS (Bio-energy with carbon capture and storage) and CCS (Carbon capture and storage). It aims to further increase the contribution of all the technology options and relies more heavily on the deployment of biomass associated with significant amounts of carbon capture and storage in order to reach net zero emissions in 2050.
    - The ***1.5°C Sustainable Lifestyles (1.5LIFE)*** is based on COMBO and CIRC with lifestyle changes. So, it relies less on the technology options of 1.5TECH but assumes a drive by European business and consumption patterns towards a more circular economy. It also includes dietary changes (which is key for agriculture emissions) and enhancement natural sink[25].

3.1.3.1 The LULUCF contribution

The 2050 baseline scenario (also referred to as BSL) sees a LULUCF sink that decreases to 236 MtCO$_2$ due to the ageing of the forest and an increasing mobilisation of forest biomass, mainly for material use (industrial roundwood, sawnwood, wood panels, paper, paperboard). The BSL scenario contributes to illustrate the impact that current climate and energy policies and goals would have on long-term GHG evolution. Furthermore, the report describes the potential role of LULUCF to achieve net zero GHG emissions in 2050, considering a set of scenarios, without carbon pricing (Table 12).

Table 12: European LULUCF net emissions/removals in 2050 without carbon price for EU28

	BLS	Category 1					Category 2	Category 3		
MtCO$_2$-eq.		**ELEC**	**H2**	**P2X**	**EE**	**CIRC**	**COMBO**	**1.5TECH**	**1.5LIFE**	**1.5LIFELB**
LULUCF	-236	-238	-244	-263	-241	-292	-248	-247	-329	-340

Source: European Commission 2018a

3.1.3.2 New flexibility to access credits from the land use sector

To stimulate additional action in the land use sector, Member States can use up to 262 million tCO$_2$ over the entire period 2021-2030 to comply with their national targets. All Member States are eligible to make use of this flexibility if needed for achieving their target, while access is higher for Member States with a larger share of emissions from agriculture. This recognizes that there is a lower mitigation potential for emissions from the agriculture sector.

Emissions from the LULUCF sector are not included in the EU Emissions Trading System (EU ETS), which is an internal EU carbon market; in fact, they are covered by the European "Land use, land use change and forestry Regulation". However, the "Clean planet for all" study hypothesised that the LULUCF sink could be enhanced in

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[25] For a detailed description of the scenarios, please refer to §4 of the assessment report (European Commission, 2018a).

2050 through economic incentives targeting various mitigation options. Therefore, it modelled the potential for enhancing the LULUCF sink under different carbon prices. A carbon price of 150€ in 2050 could increase the forest sink by almost 120 $MtCO_2$ and the total LULUCF sink by more than 160 $MtCO_2$ compared to a situation without carbon price applied to the LULUCF sector. At a carbon price of 70€, the total LULUCF sink could already be above 130 $MtCO_2$ (Table 13). These amounts are relatively large compared to emissions by 2050 but small compared to emissions in 1990, this is less than 3% of emissions, underlining the priority to reduce emissions first.

Table 13: Potential for carbon sequestration and LULUCF sink enhancement at different carbon prices in 2050 for EU28

	Carbon price	
$MtCO_2$	70€/tCO_2	150€/tCO_2
Additional LULUCF sink (w.r.t. no carbon price)	130	160

Source: European Commission 2018a

3.1.3.3 The agricultural contribution

Strong reduction potential for non-CO_2 emissions from agriculture exists in 2050. In addition to the BSL scenario, different levels of emission reduction can be achieved under various scenarios (European Commission, 2018a), see Table 14. For the description of the scenarios please refer to the previous section.

Table 14: EU28 non-CO_2 GHG emissions in agriculture in 2050 in different scenarios

$MtCO_2eq.$	BSL	CIRC	COMBO	1.5TECH	1.5LIFE
CH_4 emisions	207	165	165	165	139
N_2O emissions	197	111	111	111	91
Total Non-CO_2 emissions	404	277	277	277	230

Source: European Commission 2018a

3.1.3.4 The AFOLU contribution

The AFOLU category gathers together Agriculture, Forestry and Land Use. Therefore, it is the sum of the non-CO_2 agriculture emissions and the LULUCF sink. The assessment report defines some scenarios that are common both for LULUCF and agriculture. The estimate of the total emissions from AFOLU is reported in Table 15.

Table 15: EU28 AFOLU emissions and removals in 2050

$MtCO_2$-eq.	BSL	CIRC	COMBO	1.5TECH	1.5LIFE
Agriculture	404	277	277	277	230
LULUCF	-236	-292	-248	-247	-329
AFOLU	168	-15	-29	30	-99

Source: European Commission 2018a

3.1.4 The EU Reference Scenario 2020

In July 2021, a new version of the EU Reference Scenario was issued, it updates the previous version published in 2016 (European Commission, 2021c) The aim of the Reference Scenario is to reveal the distance to be covered to reach climate neutrality, considering the current policy framework as starting point. The recently issued publication presents a model-based simulation, for EU27 Member States, up to 2050 that take into consideration the current policy context and the most recent statistical data on energy system (Energy Balances), transport and GHG emissions (GHG inventories). The GAINS model is used for non-CO_2 GHG emission projections, the GLOBIOM-G4M models for projections of LULUCF emissions and removals and the CAPRI model is used for agricultural activity projections. The modelling is based on extrapolation from historical data (until 2019) and preliminary data from 2020 (e.g., monthly statistics of electricity consumption). Moreover, the effects of COVID-19 on agriculture is also factored in: the CAPRI projection for the Reference Scenario builds on the 2020 EU Agricultural Outlook, which incorporates the impact of the COVID-19.

The Reference Scenario for LULUCF and agriculture mainly builds on policies at EU level; while some Member State level policies are considered, such as the National Energy and Climate Plans (NECPs) (particularly coal phase-out and nuclear related policies). It is assumed that their implementation intensifies until 2030 and continues afterwards, assuming no additional measures apply between 2030 and 2050. EU level policies cover directives and regulations included in the "Clean Energy for All Europeans" package. The simulation results from LULUCF, agriculture and AFOLU are reported in Table 16.

Table 16: EU27 GHG emissions and removals according to the EU Reference Scenario for EU27

$MtCO_2$-eq	2025	2030	2035	2040	2045	2050
LULUCF	-260	-258	-262	-250	-265	-271
Agriculture	381	377	373	370	367	364
AFOLU	121	119	111	120	102	94

Source: European Commission, 2021c

In comparison with the target eshrined in the LULUCF regulation proposal submitted by the Commision on July, there is a consistent gap between the AFOLU target that should be carbon neutral by 2035 (while the the reference scenario foresee a net emission of 111 MtCO2-eq, not able to reach its neutrality even by 2050).

3.1.5 The "Where are We Headed" scenarios

The PARIS REINFORCE project has produced a set of scenarios, called "*Where are We Headed*", (see section 2), and even if they are forecasting scenarios, and so do not necessarily deliver deep decarbonisation, they could be useful to provide an assessment of LULUCF and Agricultural emissions in the EU. The only model delivering these emissions is the GCAM model (Edmonds et al., 1994, see section 2.1.2). GCAM provides four different scenarios are modelled for EU28, describing GHG emissions from the AFOLU sector (Table 17). Scenarios are described as follows:

- ***PR_CurPol_CP***: Current policies implemented until 2030 and extending the equivalent carbon price in each region, growing at the rate of GDP per capita from 2030 onwards.
- ***PR_CurPol_CP0***: Unconditional Nationally Determined Contributions implemented on top of current policies until 2030 and extending the equivalent carbon price in each region, growing at the rate of GDP per capita from 2030 onwards.
- ***PR_CurPol_EI***: Current policies implemented until 2030 and keeping emissions intensity of GDP reduction rate same as 2020-2030 period after 2030.
- ***PR_NDC_EI***: Unconditional Nationally Determined Contributions implemented on top of current policies until 2030 and keeping emissions intensity of GDP reduction rate same as 2020-2030 period after 2030.

The equivalent carbon price cited in the scenarios (PR_CurPol_CP and PR_CurPol_CP0) is the carbon price that, on its own (absent other policies), achieves the corresponding level of emissions reductions in 2030. Furthermore, for the last two scenarios, if current policies in a given region led to stronger emissions reductions than NDCs, the NDC scenario is equal to the current policies scenario.

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Table 17: Emissions from AFOLU for EU28 from GCAM for the Where are We Headed scenarios

Year	Scenarios															
	PR_CurPol_CP				PR_CurPol_EI				PR_NDC_CP				PR_NDC_EI			
	CO_2 (Mt)	CH_4 (Mt)	N_2O (kt)	CO_2eq. (Mt)	CO_2 (Mt)	CH_4 (Mt)	N_2O(kt) (kt)	CO_2eq. (Mt)	CO_2 (Mt)	CH_4 (Mt)	N_2O (kt)	CO_2eq. (Mt)	CO_2 (Mt)	CH_4 (Mt)	N_2O (kt)	CO_2eq. (Mt)
2030	-123.64	10.60	779.20	379.6	-123.68	10.60	779.25	379.6	-103.58	11.85	815.26	444.3	-103.58	11.85	815.26	444.3
2050	-62.60	11.07	804.65	460.6	-68.41	11.35	818.63	466.3	-57.36	12.92	853.77	530.6	-76.93	16.01	930.68	618.0

Results have been extracted from the I²AM Paris Platform (https://i2am-paris.eu/pr_wwh/scientific_module) in May 2021.

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

3.1.6 Overview of the land sector in the EU member states' long-term strategies

Alongside Nationally Determined Contributions (NDCs), the Article 4, paragraph 1, of the Paris Agreement requires Parties to formulate and communicate 'mid-century long-term low GHG emission development strategies' by 1st January 2020. The European Union and its Member States are fully committed to the Paris Agreement and aim to be climate-neutral by 2050. The EU submitted its long-term strategy (LTS) to the United Nations Framework Convention on Climate Change (UNFCCC) in March 2020. So, every Member State is required to develop a national long-term strategy on how they plan to meet their commitments under the Paris Agreement and EU objectives. The data reported in this section refer to the eighteen Member States that submitted their long-term strategies. Alongside their LTS, we also report the GHG projections for the AFOLU sectors as presented by member states under the Monitoring Mechanism Regulation (EC; No 525/2013), requiring Member States to report national projections of anthropogenic GHG emissions every two years (Source: the European Environment Agency website[26]).

3.1.6.1 Austria

Austria is committed to becoming climate neutral by no later than 2050, without using nuclear power. This means that the unavoidable greenhouse gas emissions (for example from agriculture and production processes) will be compensated by carbon storage in natural or technical sinks.

- *LULUCF*: Wide range of requirements are placed on Austria's forests, which are implemented through the framework of a sustainable management strategy. This should ensure that the raw materials for the bio-economy and the transition to renewable energy are provided and that the ecosystems are adapted to the climate crisis with the goal of improving the stability and productivity of Austria's forest stock. The increasing frequency of extreme weather events (such as heavy rainfall and heat waves) is exacerbating the problem of increased land use. Land consumption should be reduced through sensible spatial planning. Annual land use is to be drastically reduced and currently sealed areas are to be restored to a natural state. Spatial planning in rural areas shall prevent further urban sprawl and fragmentation of areas. The results show that the target visions are of high relevance for achieving the goal of climate neutrality in 2050 (Table 18).
- *AFOLU*: The containment of greenhouse gas emissions to a declining emission level will be achieved as outlined in the transition scenario (that depicts the greatest possible emission reductions by 2050 based on domestically available resources and technologies and taking lifestyle changes into account). This is based on assumptions about further efficiency increases in the use of nitrogen, the increased keeping of dual-purpose cattle, optimised use of manure, and changes in dietary habits that have an impact on livestock farming. Very ambitious measures will be taken to prevent nitrogen losses. Dual-purpose cattle (milk and meat) and increased pasture grazing will be promoted. Organic farming will be expanded further. Agricultural production is adapted optimally to the local and environmental conditions and a circular economy has been established. Optimal use of manure (e.g. through liquid manure markets) and substantial reduction of mineral fertiliser use. Furthermore, the transition scenario assumes that the population changes its dietary habits, increasing the consumption of high-quality plant foods and reducing that of meat. Alternative protein sources with substantially lower CO_2 intensity (such as algae) will be used for animal feed and other applications. Food waste will be reduced substantially

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[26] https://www.eea.europa.eu/data-and-maps/data/greenhouse-gas-emission-projections-for-7

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Table 18: Austria GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO₂-eq	2030	2035	2040
Agriculture	7,625.6	7,721.3	7,817.8
LULUCF	-2,670.7	-3,130.7	-1,217.6
Total CO_2 emissions without LULUCF	73,962.0	72,299.3	71,019.0

Source: the European Environment Agency

3.1.6.2 Belgium

The long-term strategy of Wallonia aims to achieve carbon neutrality by 2050, by a reduction of greenhouse gas emissions by 95% compared to 1990, supplemented by measures regarding carbon capture and use, and negative emissions; the long-term strategy of Flanders aims to reduce greenhouse gas emissions from the so-called non-ETS sectors (*i.e.* emissions mainly resulting from energy, agricultural, transport and waste sectors) by 85% by 2050 compared to 2005, with the ambition to move towards full climate neutrality. As regards the sectors covered by the EU-ETS, the Flemish Region subscribes to the context set out by the EU for these sectors with a decreasing emissions quota. The long-term strategy of the Brussels-Capital Region sets the objective of moving closer to the European target of carbon neutrality by 2050, in the urbanised context of Brussels (Table 19).

- *LULUCF*: Efforts are envisaged to maintain or enhance carbon sequestration in soils and biomass. These include expanding green spaces (forests, natural areas, parks, etc.), sustainable forest and nature management and the encouragement of agricultural practices that favour carbon sequestration on agricultural land. Each strategy also covers potential synergies with climate change adaptation. For example, carbon rich agricultural soils are more resistant to periods of drought or flooding, expanding green spaces is a protective measure against expected heatwaves (especially in urban areas) and the sound management of forests can increase their resilience to climate change.
- *AFOLU*: The Walloon and Flemish strategies stress that the agricultural sector can make an important contribution as a producer of biomass and biofuels (not only through the direct production of energy crops but also by exploiting secondary flows such as the fermentation of animal manure to extract biomethane) and through carbon sequestration on agricultural land.

Table 19: Belgium GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO₂-eq	2030	2035	2040
Agriculture	9,238.9	9,084.3	NA
LULUCF	-1,219.5	-1,492.7	NA
Total CO_2 emissions without LULUCF	127,546.9	135,475.4	NA

Source: European Environment Agency

3.1.6.3 Czech Republic

The main objective of the Czech Policy is to determine an appropriate mix of cost-effective policies and measures in key sectors that will lead to achieving the greenhouse gas reduction targets. The long-term indicative emission reduction targets aim to achieve 70 $MtCO_2$-eq. of emissions in 2040, and 39 $MtCO_2$-eq. of emissions in 2050 (Table 20).

- *Agriculture*: Emissions reduction is addressed by the Action Plan for Biomass in the Czech Republic for the period 2012–2020, which envisages the possibility to achieve by 2020 annual production of energy from

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agricultural land and by-products of agricultural production and the processing of agricultural products ranging from 133.9 to 186.8 petajoules (PJ). Carbon fixation in the soil helps to meet the mandatory standards of Good Agricultural and Environmental Conditions (GAEC) and to observe Statutory Management Requirements (SMRs). Another tool is the local support for afforestation of agricultural land provided by the Rural Development Program.

Table 20: Czech Republic GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO$_2$-eq	**2030**	**2035**	**2040**
Agriculture	9,052.6	9,147.7	9,174.7
LULUCF	-1,626.3	-1,728.0	-1,810.4
Total CO$_2$ emissions without LULUCF	109,846.3	99,572.6	93,395.9

Source: European Environment Agency

3.1.6.4 Denmark

Three overall targets of Denmark are (*i*) pursuing efforts to limit the global temperature increase to 1.5 degrees, (*ii*) increasing the adaptability and foster resilience to the impacts of climate change, affecting the poorest most severely and (*iii*); shifting finance flows to support the transition to low emissions and resilience to climate change (Tables 21-22).

- *LULUCF*: the sector can contribute to carbon sequestration when carbon is stored both in soils and plants. Net emissions from forests and other land use are expected to amount to 5.3 MtCO$_2$-eq by 2030, equivalent to 33% of total agricultural and forestry sector emissions. Compared with other measures, restoration of carbon-rich peatlands is a cost-efficient measure for achieving greenhouse gas reductions in the agricultural sector. There is an estimated current technical potential for setting aside 50,000 hectares of agricultural soils. This means that setting aside the remaining 35,000 hectares would result in a total one-off cost of at least DKK 4.5 billion in basic compensation. A set-aside of this magnitude is estimated to contribute 0.5 MtCO$_2$-eq per year to greenhouse gas emission reductions.
- *AFOLU*: the 2020 Finance Act agreement allocates DKK 2 billion towards 2029 for the restoration of carbon rich agricultural soils. The expected climate effect is 270 ktCO$_2$-eq per year by 2030. The fund's activities are expected to realise GHG capture of 50 ktCO$_2$-eq per year by 2030. Implementation will result in some 2 000 ha of private afforestation. Afforestation of an additional approximately 1 000 ha is assessed to increase GHG absorption by 5 ktCO$_2$-eq per year by 2030. It has been decided to introduce stricter exploitation requirements on manure and reduce the nitrogen standards for crops cultivated on carbon-rich soils. In addition, a ban is introduced on spraying, fertilisation and conversion of section 3 areas. Together, the initiatives are expected to provide an annual climate effect of 90 ktCO$_2$-eq by 2030.

Table 21: Denmark GHG emissions projections according to its long-term strategy

MtCO$_2$-eq.	**2030**
Agriculture	10.7
LULUCF	5.3
Total CO$_2$ emissions without LULUCF	NA

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Source: European Environment Agency

Table 22: Denmark GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	10,808.3	10,808.3	10,808.3
LULUCF	5,285.6	5,285.6	5,285.6
Total CO_2 emissions without LULUCF	37,805.3	37,805.3	37,805.3

Source: European Environment Agency

3.1.6.5 Estonia

According to the long-term strategy submitted by the country to the EU, the target is to reduce the emission of greenhouse gases by 2050 by 80% in comparison with the emission levels of 1990. As the country moves towards this target, emissions will be reduced by about 70% by 2030 and by 72% by 2040 in comparison with the 1990 emission levels (Table 23).

- *Agriculture*: agriculture is planned to contribute to such a target. The soil's carbon stock will be increased and maintained, and land areas of significant carbon stock will be developed and maintained. Efficient and ecological use of agricultural land will be encouraged while the falling out of agricultural use of such land will be avoided. The focus will be on eco-friendlier manure management for limiting ammonia emissions. The production of bioenergy will be steadily enhanced and such energy will be mainly used instead of non-renewable fuels with more energy intensive manufacturing processes. Greater efficiency and the upcycling of resources will be facilitated in the production of bioenergy. Estonia will also promote fields of research, development and innovation that increase the sustainability of agriculture.
- *LULUCF*: Forest growth and the carbon sequestration ability will be increased through productive and sustainable forest management, and the carbon stock of forests will be maintained in the longer perspective. The productivity of managed forest land will be mainly increased through improvement cutting, timely cutting of forest stands and fast renewal of forests with tree species appropriate for the habitat type. Flexible rotation ages considering the growth potential of forest stands will be implemented in managed forests, and the principles of sustainable forestry and the maintenance of biodiversity will be taken into account. Timber use will be consistently enhanced and the carbon stock in timber products and buildings will be increased, thus replacing the use of non-renewable natural resources. Preservation of the current area under forest land will be facilitated, and in other categories of land use, techniques of increasing carbon sequestration and reducing emissions will be preferred. Trends in the land use sector will be monitored and considered in planning. The carbon stock in the peat layer of mires will be preserved or increased.

Table 23: Estonia GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	1,572.1	1,619.7	1,624.8
LULUCF	-208.2	153.5	776.9
Total CO_2 emissions without LULUCF	12,539.2	12,564.1	11,866.3

The PARIS REINFORCE project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 820846.

Source: European Environment Agency

3.1.6.6 Finland

Finland is required to reduce its greenhouse gas emissions in sectors outside the EU ETS by a minimum of 39% from 2005 levels by 2030. The current goal laid down in the Climate Change Act for 2050 is to reduce greenhouse gas emissions by at least 80% compared to 1990 levels.

Finland developed three scenarios. Under all of the three scenarios, the LULUCF sector produced a net sink. The *WEM scenario (With Existing Measures)* places the LULUCF sector's net sink in 2050 at 26 $MtCO_2$-eq. Under the *Continuous Growth scenario*, the LULUCF sector's net sink will first remain at the current level and then take a swift upswing in 2030, standing as high as 40 $MtCO_2$-eq in 2050. The favourable development in terms of the sink will especially result from lower levels of roundwood removals when compared with the WEM scenario. The *Savings scenario* produced the smallest sink for the LULUCF sector, putting its net sink below 20$MtCO_2$-eq in 2050. The LULUCF sector's small sink under the Savings scenario was especially attributable to the assumption of change in forest industry production structures and the resulting annual roundwood removals in excess of 90 million cubic metres after 2035 (Tables 24-25)

Table 24: Finland GHG emissions projections according to its long-term strategy, considering three scenarios: WEM, With Existing Measures; CGS, Continuously Growth Scenario; SAS Savings Scenario

	2030				**2035**				**2040**				**2050**		
$MtCO_2$-eq	**WEM**	**CGS**	**SAS**		**WEM**	**CGS**	**SAS**		**WEM**	**CGS**	**SAS**		**WEM**	**CGS**	**SAS**
Agriculture	NA	NA	NA		NA	NA	NA		NA	NA	NA		6.45	3.84	4.36
LULUCF	-16.5	-18.5	-11.7		-18.0	-22.5	-12.0		-19.5	-27.5	-11.7		-26.0	-40.0	-16.5

Source: European Environment Agency

Table 25: Finland GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	**2030**	**2035**	**2040**
Agriculture	6,339.3	6,440.8	6,456.2
LULUCF	-2,9897.8	-34,382.0	-39,371.6
Total CO_2 emissions without LULUCF	44,380.5	42,774.2	42,398.5

Source: European Environment Agency

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3.1.6.7 France

France aims to limit global warming "*well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C*", and to achieve a global balance between greenhouse gas emissions and absorption - "carbon neutrality" - in the second half of the 21st century. Recognizes the principles of "*equity and common but differentiated responsibilities and respective capabilities in the light of different national circumstances*" (Tables 26-27).

In order to preserve and increase the sink of the land sector, the levers that can be mobilised are: the fight against land take, especially land with the highest carbon stocks (e.g. wetlands), agricultural practices that are conducive to strengthening the carbon stock of agricultural soils (especially in arable areas where stocks are the lowest today, such as intermediate crops or agroforestry), improving forest management and boosting bio-based chains. From a climate point of view, forestry management should aim to both adapt forests to climate change and optimize climate change mitigation by taking the best account possible of the short-, medium- and long-term effects. The long-term objective is therefore to increase the importance of the sink associated with wood products and to rely less heavily on the forest sink but in a safer way, as forests are better managed and less vulnerable to climate change.

Table 26: France GHG emissions projections according to its long-term strategy

MtCO$_2$-eq	**2030**	**2035**	**2040**	**2050**
Agriculture	73	NA	NA	48
Forest	-48	-50	-51.5	-53

Source: https://unfccc.int/process/the-paris-agreement/long-term-strategies, accessed in April 2021

Table 27: France GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO$_2$-eq	**2030**	**2035**	**2040**
Agriculture	73,348.3	72,609.8	NA
LULUCF	-29,038.7	-25,184.4	NA
Total CO$_2$ emissions without LULUCF	416,451.5	406,206.1	NA

Source: European Environment Agency

3.1.6.8 Germany

The German government is orienting its first Climate Action Plan in the medium term to the target of reducing greenhouse gas emissions in Germany by at least 55%compared with 1990 no later than 2030. According to the First Progress Report on the Energiewende (2014) and the Fourth Monitoring Report on the Energiewende (2015), greenhouse gas emissions are to be reduced by at least 70% no later than 2040 (Tables 28-29).

- *LULUCF*: In the context of the Joint Task for the Improvement of Agricultural Structures and Coastal Protection, German government funds are being used to support forest conversion measures that will also take climate change into account. The measures are aimed at forest adaptation based on growing a climate-tolerant and climate adapted mix of tree species. Both sets of measures have proven themselves and are being further developed. Additional government measures include the following: conservation and sustainable management of forests, conservation of permanent grassland, protection of peatlands, reducing land take.
- *AFOLU*: The current amendment of the Joint Task for the Improvement of Agricultural Structures and Coastal Protection Act will include enhanced measures to promote environmentally sound land and forest

management that is appropriate for the market and location, including contractual nature and landscape conservation. They contribute to climate change mitigation in the form of direct climate measures as well as indirectly through environmental protection and nature conservation measures, and also contribute to landscape management.

Table 28: Germany GHG emissions projections according to its long-term strategy

MtCO₂-eq	2030	2035	2040	2050
Agriculture	-58	NA	NA	NA
LULUCF	NA	NA	NA	NA

Source: https://unfccc.int/process/the-paris-agreement/long-term-strategies, accessed in April 2021

Table 29: Germany GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO₂-eq	2030	2035	2040
Agriculture	61,489.4	61,489.4	NA
LULUCF	18,989.8	18,784.4	NA
Total CO_2 emissions without LULUCF	730,031.5	697,552.3	NA

Source: European Environment Agency

3.1.6.9 Greece

The Greek long-term strategy on the website of the European Commission is not available in English. Therefore, this is section presents only the projections due under the EU Greenhouse Gas Monitoring Mechanism Regulation (MMR), available on the European Environment Agency website (Table 30).

Table 30: Greece GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO₂-eq	2030	2035	2040
Agriculture	9,141.9	9,732.0	10,200.6
LULUCF	-644.8	-195.2	-479.1
Total CO_2 emissions without LULUCF	78,134.5	73,079.7	70,840.2

Source: European Environment Agency

3.1.6.10 Hungary

Hungary submitted a draft of the long-term strategy, which is not available in English, on the website of the European Commission. Therefore, this is section presents only the projections due under the EU Greenhouse Gas Monitoring Mechanism Regulation (MMR), available on the European Environment Agency website (Table 31).

Table 31: Hungary GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO₂-eq	2030	2035	2040
Agriculture	7,754.9	8,029.4	8,029.4
LULUCF	-531.5	-531.5	-531.5
Total CO_2 emissions without LULUCF	62,831.8	62,634.0	62,853.9

Source: European Environment Agency

3.1.6.11 Italy

The main contributions to the decarbonisation of the Italian LULUCF sector (Tables 32-33) include:

- using crops that can foster more extensive vegetative cover in the agricultural year,
- introducing of a higher share of crops from the forage, (*iii*) planting or preserving the hedges, the spots and the buffer strips of shrubs,
- increasing of the conversion of arable land, meadows,
- encouraging the non-working of the soil (no tillage) by planting on the hard,
- implementing rotation schemes long; grow on the terraces,
- managing and recovering the marginal lands with the introduction of new crops,
- favouring organic mulching and improving the activity of both macrofauna and microflora, especially fungal, to increase the porosity of the soil ensuring excellent aeration, water infiltration, heat transfer and root growth,
- monitoring agronomic and environmental indicators,
- encouraging support, training and awareness in schools and professionals of sustainable soil management practices,
- constructing infrastructures for fire prevention and implementing alert systems.

Table 32: Italy GHG emissions projections according to its long-term strategy, considering two scenarios: REF, Reference Scenario; DEC, Decarbonisation Scenario

	2030		2035		2040		2050	
$MtCO_2$-eq	REF	DEC	REF	DEC	REF	DEC	REF	DEC
Agriculture	29	28.6	28	26.8	28.5	26	27.5	23
LULUCF	-14	-30	-15	-32	-14	-29.5	-22	-44

Source: https://unfccc.int/process/the-paris-agreement/long-term-strategies, accessed in April 2021

Table 33: Italy GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	30,042.4	29,633.1	NA
LULUCF	-23,428.7	-26,228.0	NA
Total CO_2 emissions without LULUCF	383,227.3	371,426.1	NA

Source: European Environment Agency

3.1.6.12 Latvia

The overarching objective of the Strategy is to reach climate neutrality of Latvia in 2050. As the final objective of the implementation of LCD (Low Carbon Development) is achieving climate neutrality of Latvia, it is essential not only to reduce GHG emissions but also to increase CO_2 removals (Tables 34-35).

- *LULUCF*: Starting from 2010 an increase of GHG emissions in the LULUCF sector has been observed, moreover, it is being projected henceforth (until 2050) that GHG emissions in the LULUCF sector will exceed removals. The largest changes in GHG emissions and CO_2 removals are in the category "Forest land". The main cause for the decline in CO_2 removals and increase in GHG emissions in the LULUCF sector is the increase in the proportion of stands that have attained or surpassed the falling age which has promoted the increase in the amount of exploitation of the forest and increase in emissions related to the natural mortality of trees. Without endangering the biological diversity, new varieties which are more resistant towards climate change and ensure optimum CO_2 removals are being bred and used. Biofuels of the newest generation which reduce the risks that the crops to be used in food and the soil fit for growing food is being used for the acquisition of bioenergy have been developed.

- *AFOLU:* Significant factors in the land and land use, land-use change and forestry sector in relation to GHG emissions and CO_2 removals are the use of mineral fertilisers, a high proportion of organic soil in the territory of Latvia, as well as forestry coverage.

Table 34: Latvia GHG emissions projections according to its long-term strategy

$MtCO_2$-eq	2030	2035	2040	2050
Agriculture	NA	NA	NA	NA
LULUCF	4.8	4.3	4.0	3.8

Source: https://unfccc.int/process/the-paris-agreement/long-term-strategies, accessed in April 2021

Table 35: Latvia GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	3,102.1	3,115.5	3,128.2
LULUCF	4,636.2	4,425.4	4,152.7
Total CO_2 emissions without LULUCF	10,425.3	9,257.8	8,276.7

Source: European Environment Agency

3.1.6.13 Lithuania

The Lithuanian long-term strategy on the website of the European Commission is not available in English. Therefore, this is section presents only the projections due under the EU Greenhouse Gas Monitoring Mechanism Regulation (MMR), available on the European Environment Agency website (Table 36).

Table 36: Lithuania GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	4,303.8	4,345.8	4,378.8
LULUCF	-3,329.1	-3,042.3	-2,771.8
Total CO_2 emissions without LULUCF	19,634.1	19,292.2	19,058.6

Source: European Environment Agency

3.1.6.14 Netherlands

The Climate Act stipulates that the Netherlands must reduce its greenhouse gas emissions by 95% by 2050 compared to 1990. As an interim target, the Climate Act specifies that the Netherlands must strive to cut its emission level by 49% by 2030 compared to 1990 (Table 37).

- *AFOLU*: With regard to agriculture, the focus will mainly be on the development of solutions that could contribute to the further transition towards nature-inclusive and circular agriculture. As for livestock farming, efforts will concentrate on making stables emission-free, making changes to animal feed and improving the processing of manure. In the greenhouse horticulture sector, work will continue on achieving energy savings, generating sustainable energy and using heating provided by third parties and CO_2 for fertilisation. Efforts will also be made to change the behavioural patterns of food consumers in order to reduce food wastage and increase the uptake of more sustainable, plant-based foods. Smart solutions are also being sought regarding land use, including pilot projects to raise the water level in peat meadow areas. In addition, various measures will be introduced that will contribute to increased carbon capture over time. This will expand the natural area, restore landscape structures, limit deforestation, lead

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to the planting of new trees and increase carbon capture in agricultural soils through smart and sustainable use.

Table 37: The Netherlands GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO$_2$-eq	2030	2035	2040
Agriculture	18,728.7	18,723.7	NA
LULUCF	6,811.3	6,742.0	NA
Total CO$_2$ emissions without LULUCF	157,885.4	150,988.8	NA

Source: European Environment Agency

3.1.6.15 Portugal

The objective of Portugal is to reduce emissions and increase negative emissions from forests and other land uses; it is fundamental on the one hand to reduce burned areas and on the other hand to manage the use given to these areas after the fire, improving forest management and promote the increases in average productivity, the rate of new afforestation (expansion of the forest area from other land uses) and the expansion rate of other land uses. Portugal national emissions related to agriculture account for 10% of the total. Other emissions, broken down by sector, are distributed as follows: 25% in energy production, 25% in transport, 23% in industry, 8% in other energy uses and 8% in waste. Carbon sinks are the result of some land uses, notably in agriculture, pastures, forests and scrubland, and, during this period, they absorbed from the atmosphere about -8.5 MtCO$_2$ (from -13 to +7 MtCO$_2$), or about -12% of the emissions from the other sectors. The net total of emissions and carbon sinks is therefore currently 60 MtCO$_2$, and this is the order of magnitude that will have to be reduced by 2050 in order to achieve carbon neutrality (Tables 38-39).

It will be necessary to ensure a large reduction in burned areas, from an average of about 164,000 ha/year between 1998 and 2017 to 70,000 ha/year by 2050 (i.e. a 60% reduction), to be careful about the use given to these areas after the fire, ensuring smaller total areas affected by fires, considering the suitability of the species used in reforestation, reducing the deforestation caused by fires (forests converted into scrubland) and making greater use of fire prevention techniques, including increased use of small ruminants to reduce combustible material. It will be necessary to increase the rate of new afforestation to 8 000 ha/year (expansion of the forest area from other land uses) and to reduce the rate of expansion of other land uses, particularly from urbanised areas, flooded areas (including dams) and scrubland.

Table 38: Portugal GHG emissions projections according to its long-term strategy

MtCO$_2$-eq	2030	2035	2040	2050
Agriculture	6.42	NA	6.33	6.19
LULUCF	-9.25	NA	-10.54	-11.92

Source: https://unfccc.int/process/the-paris-agreement/long-term-strategies, access in April 2021

Table 39: Portugal GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO$_2$-eq	2030	2035	2040
Agriculture	5,647.2	5,699.3	5,751.3
LULUCF	-6,926.0	-7,360.5	-7,795.1
Total CO$_2$ emissions without LULUCF	4,2433.9	37,335.3	32,528.2

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Source: European Environment Agency

3.1.6.16 Slovakia

An essential part of the vision is the horizon of the nearest strategic decade, which is crucial for the achievement of the 2030 climate and energy targets. Plus, an essential fact in the case of Slovakia is that, if additional measures are not implemented beyond those used in WEM and with additional measures (WAM) models and scenarios, then Slovakia will not meet the climate neutrality target in 2050. Removals are developed mainly by the land use, land-use change, and forestry sector (LULUCF), which in the case of sustainable management has great potential to reduce CO_2 emissions (Table 40).

- *LULUCF*: The WEM scenario assumes an overall CO_2 removal in the sector from –6,642.32 (2017) to –4,206.56 (2035) $GgCO_2$. The projections of CO_2 removals in the period between 2017 and 2035 show a decreasing trend. This is mainly due to a decrease in removals in the categories FL (Forest land), CL (Cropland) and GL (Grassland) and an increase in emissions from SL (Settlements) and OL (Other land). After 2035, removals are expected to increase in the FL (Forest land) and GL (Grassland) categories. The Scenario WAM shows the trend of emissions after two other additional measures have been implemented: Afforestation of 23 000 ha of grassland by 2040; Grassing of 50,000 ha of cropland after 2016.

Table 40: Slovakia GHG emissions projections taking into account the (current) existing domestic policies and measures

ktCO$_2$-eq	**2030**	**2035**	**2040**
Agriculture	2,419.8	2,497.1	2,570.2
LULUCF	-4,434.0	-4,155.8	-4,231.2
Total CO_2 emissions without LULUCF	41,399.0	39,525.7	38,521.2

Source: European Environment Agency

3.1.6.17 Spain

The objective of the Spanish long-term strategy is to articulate a coherent and integrated response to the climate crisis, which takes advantage of the opportunities for the modernization and competitiveness of our economy and is socially fair and inclusive. It is a roadmap to move towards climate neutrality by 2050, with intermediate milestones in 2030 and 2040 (Tables 41-42).

- *Agriculture*: The path outlined for the primary sector achieves a significant reduction in non-energy greenhouse gas emissions, namely 53% compared to the reference year 1990. The main lines of work that is considered to be on the horizon to 2050 to achieve the reduction of emissions from the agricultural sector are: biogas production; crop management and soil conservation; digitalization and smart technologies for the irrigation and fertilization; improved livestock feeding; use of nitrogen fertilizer coated and with inhibitors of nitrification; increasing the surface area for the promotion of the rotations in arable crops, such as dry, including legume and oilseed, and replace the monoculture cereal; cultivation techniques advanced; optimization of the contribution of nitrogen to the needs of farming with respect to the total surface fertilizable; management and implementation of treatment of manures and slurry minimize the generation of emissions; reduction of waste in the food chain of national consumption; the promotion of the Mediterranean diet and consumption of local products; agricultural practices that promote greater resilience to the impacts of climate change and, in turn, an increase in the fixation of CO_2 by sector.

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Table 41: Spain GHG emissions projections according to its long-term strategy

$MtCO_2$-eq	2030	2035	2040	2050
Agriculture	40	NA	28	19
LULUCF	NA	NA	NA	NA

Source: https://unfccc.int/process/the-paris-agreement/long-term-strategies, access in April 2021

Table 42: Spain GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	34,534.9	34,039.0	33,543.1
LULUCF	-31,588.5	-31,444.6	-31,610.5
Total CO_2 emissions without LULUCF	310,632.1	299,028.3	287,193.3

Source: European Environment Agency

3.1.6.18 Sweden

The LULUCF sector contributes to the Swedish long-term emission reduction by increasing carbon removals, which contribute to net negative emissions in the long term. At the same time, bio-based fuels and bio-based materials that can replace materials based upon fossil raw materials are of great value to a society undergoing a climate transition. Sweden is well placed to combine active forestry with high environmental requirements as well as maintaining a significant carbon sink (Table 43). In 2021, a new scheme will be established in order to rewet previously drained wetlands and thereby reduce greenhouse gas emissions.

Table 43: Sweden GHG emissions projections taking into account the (current) existing domestic policies and measures

$ktCO_2$-eq	2030	2035	2040
Agriculture	6,219.5	6,137.4	NA
LULUCF	-40,592.2	-38,982.6	NA
Total CO_2 emissions without LULUCF	46,128.9	45,553.8	NA

Source: European Environment Agency

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3.2 The impact of COVID-19 pandemic on a 2030 European Green Deal scenario: a double modelling exercise on the European energy system[27]

This section presents a work used to assess the potential long-term impacts of the COVID-19 pandemic on the EU energy system.

3.2.1 Introduction

By the end of 2019, a new virus, the SARS-CoV-2, has emerged in Wuhan, China, causing the zoonotic coronavirus disease 2019 (COVID-19) (World Health Organisation, 2020a). The high transmissibility of the virus has rapidly spread the disease worldwide that has been declared as a pandemic in March 2020 (World Health Organisation, 2020b). To limit the progress of the disease, many governments have imposed restrictive measures such as lockdowns, curfews, travel restrictions or quarantines as well as self-isolation or social distancing (Cheng et al., 2020; Hale, 2021; European Centre for Disease Prevention and Control, 2021). Even if these non-pharmaceutical interventions (NPIs) have allowed to reduce the incidence of the COVID-19 outbreak (Hou et al., 2020; Huang et al., 2020, Mégarbane et al., 2021), they have led to a severe global economic recession (International Monetary Fund, 2021) and particularly in European Union (EU) where the pandemic and the NPIs have been particularly severe (European Commission, 2021a; Conte et al., 2020), despite large and efficient economic backing measures. As other consequences, fossil CO_2 emissions have significantly dropped in 2020 (Le Quéré et al., 2020; 2021), and energy markets and systems have been disrupted (Hoang et al., 2021; Hanieh, 2020; International Energy Agency, 2020c).

By the end of 2020, the rapid availability of vaccines has allowed to be more optimistic about the ending of the COVID-19 pandemic, but crisis recovery remains uncertain (Badiani et al., 2020; Blanchard and Pisani-Ferry, 2021a) due to some questioning on the long-term efficiency of the vaccines (Sandmann et al., 2021), their worldwide availability (UNICEF-WHO, 2021) as well as the appearance of new virus variants (Fontanet et al., 2021). Nevertheless, some governments have already planned short-to-long term supports, such as the American Rescue Plan (White House, 2021) or the Next Generation EU program (European Union, 2020b). Numerous scientists claimed to seize this opportunity of the post-COVID-19 crisis to boost climate mitigation actions (Allan et al., 2020; Amankwah-Amoah, 2020, Mukanjari and Sterner, 2020), avoiding supporting fossil fuel dependent economic activities as it may have been the case after the 2008-2009 global financial crisis (Peters et al., 2012) and to engage fiscal recovery actions into sustainable development paths (Hepburn et al., 2021; International Energy Agency, 2020b).

In Europe, the Next Generation EU (NGEU) program has been launched to reinforce the planned 2021-2027 Multiyear Financial Framework (MFF). The program is built in synergy with the European Green Deal strategy launched by von der Leyen Commission (European Commission, 2019b) few months before the beginning of COVID-19 pandemic and includes green commitments: at least 37% of the total financial support, realized through several mechanisms, the most relevant being represented by the Recovery and Resilience Facility (RRF), must support green investment (European Council, 2021). The European Green Deal aims, inter alia, to reduce greenhouse gas (GHG) emissions by at least 55% in 2030 in comparison with 1990 (European Commission, 2020d) instead of the former -40% milestone (European Council, 2014).

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[27] This section takes to Cassetti, G., Boitier, B., Elia, A., Le Mouël, P., Gargiulo, M., Zagamé, P. and A., Chiodi, 2021 "*The impact of COVID-19 pandemic on a 2030 European Green Deal scenario: a double modelling exercise on the European energy system*". Submitted to a peer-review journal in September 2021.

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Moreover, due to the restrictive measures, the COVID-19 pandemic has brought important changes in EU citizens' habits, of which some may have long-term impact on the EU energy system, mostly through home working and transportation. Such changes represent an acceleration of existing dynamics in people behaviour that were already considered as option for mid-century European carbon neutrality (van de Ven et al., 2017, Gossling et al., 2020).

This study discusses the potential long-term impact of the COVID-19 pandemic on EU GHG emissions identifying the contribution of three layers of: (*i*) the pace of COVID-19 economic recovery, (*ii*) the EU climate ambition and (*iii*) the potential long-term transformations in citizen behaviour induced by the COVID-19 crisis. Previous publications focused on long-term impacts of the COVID-19 pandemic (Foster et al., 2020; International Energy Agency, 2020c) or national (Gillingham et al., 2020; Malliet et al., 2020), but none, except to some extent (European Commission, 2020d), deal with these triple layers. Therefore, this study aims to identify the contribution may have each layer on different climate and energy-related indicators.

The explorations are based on two soft-linked energy models, i.e. NEMESIS and EU-TIMES. In section 3.2.2, the methodology used to soft-link these two models and develop the scenario analysis is presented. Results are showed in section 3.2.3. Scenarios are presented and compared with pre-COVID-19 forecasts to develop findings related to CO_2 emissions pathways for the European Union, energy consumption, behavioural change's role in energy transition, and investments. Finally, the study discusses the possible contribution of the NGEU program in the long-term energy transformation.

3.2.2 Methodology

The methodology developed to perform the study is based on a set of scenarios for the European Union and United Kingdom (for simplicity we refer to EU+ in the paper) designed to assess the potential long-term impact of the COVID-19 pandemic on the energy system. These scenarios have been implemented by soft-linking two different modelling tools:

- The NEMESIS model: a sectoral detailed macroeconomic model specifically designed for the EU+ (Brécard et al., 2006; Capros et al., 2014a). It is a system of economic models for every European country (including the United Kingdom), devoted to study issues that link economic development, competitiveness, employment and public accounts to economic policies, and notably all structural policies involving long term effects (Ravet et al., 2019). NEMESIS includes a detailed energy-environment module that allows the model to deal with climate mitigation policies, at EU and EU-national level (Capros et al., 2014b; Nikas et al., 2021b).
- The EU-TIMES model: an enhanced version of the open source JRC-EU-TIMES model (Simoes et al., 2013). It is a multi-region European version of TIMES and represents the EU Member States and neighbouring countries. The model is designed for analysing the role of energy technologies and innovation needs for meeting European energy and climate policy targets (Nikas et al., 2021b). It can consider policies affecting the entire energy system, sectors, group of or individual technologies/commodities (Sgobbi et al., 2016; Blanco et al., 2018).

3.2.2.1 Scenario design

The scenario design focuses on the decade 2020-2030 and is built around three key dimensions: (*i*) the economic outlook in the EU+ before and after the COVID-19 pandemic, (*ii*) the impacts of the EU+ climate action, and (*iii*) the potential long-term transformations due to behavioural changes induced by environmental concerns and by the COVID-19 pandemic.

The aim of the economic layer is not to forecast the European economy up to 2030 (for such attempt see Foroni et al., In proof) but it allows considering the short- to long-term consequences of the COVID-19 pandemic on the different economic activities in EU+ and to assess how it can influence the European energy system when coupled with the two other dimensions. Three economic futures for the European economy are considered:

- a pre-COVID-19 case where potential GDP growth projections are part of a set of harmonised assumptions (Giarola et al., 2021) developed in the framework of the Horizon 2020 research project Paris Reinforce[28] for scenarios called "Where are We Heading?" (WWH) (Sognnaes, et al., in revision). In this outlook the socioeconomic assumptions are harmonized, using the EUROPOP database for population (Eurostat, 2019c), the 2018 Ageing Report for GDP per capita (European Commission, 2017) as well as technoeconomic assumptions for representative technologies, based on the European National Energy and Climate Plans (NECP) reports (Mantzos et al., 2017) for power and buildings and fossil fuel prices projections from 2019 World Energy Outlook "Current Policies" scenario (International Energy Agency, 2019).
- a post-COVID-19 case with full economic recovery, where it is assumed that well-designed public support mechanisms implemented during the pandemic and particularly after the crisis are efficient to support a complete economic recovery in 2025 (Blanchard and Pisani-Ferri, 2021b).
- a post-COVID-19 case with limited economic recovery, either because of continuation of the COVID-19 pandemic beyond 2020 or of the remanence of the COVID-19 pandemic economic impact; the economic activity in EU+ by 2030 does not reach back to the pre-COVID-19 GDP levels.

The second dimension covers the strength of the European climate action for 2030. To comply with Paris Agreement, the European Commission updated its climate change mitigation action. In December 2019, von der Leyen Commission has launched the European Green Deal strategy (European Commission, 2019b) that, inter alia, reinforces the GHG emissions reduction target for 2030: with -55% relative to 1990 levels (European Commission, 2020d). In this context, we analyse two options for the EU climate action: (*i*) a current policy (CP) that includes all the measures and policies included in the EU 2030 Climate and Energy Framework (European Commission, 2013) and (*ii*) a more ambitious context that refers to the European Green Deal (EGD) and particularly on the latest 2030 climate perspective aiming to reduce GHG emissions by at least 55% by 2030 in comparison to 1990 levels.

Finally, the third layer looks at the potential impacts of behavioural changes on transformations that could affect the EU+ energy system in the long term. In our scenario design, the drivers of behavioural changes can result from post COVID-19 pandemic long-lasting behavioural changes as well as from raising of environmental concerns, as such lower international business trips in favour of remote conferences.

The combination of these three dimensions lead to six different scenarios, as summarised in Table 44:

Table 44: Summary of the scenarios' design

Scenario ID	EU+ economy	EU Climate policy	Long term transformations
WWH-CP	Pre-COVID-19 national GDP growth (based on Eurostat, 2019 and European Commission, 2017)	Current Policy (2020-2030 EU Climate and Energy Framework)	none
WWH-EGD		European Green Deal – 2030 Climate Target Plan	
WWH-EGD-Beh			Moderate
COVID-FR-EGD	Full economic recovery	European Green Deal – 2030 Climate Target Plan	none
COVID-LR-EGD	Limited economic recovery		
COVID-FR-EGD-Beh	Full economic recovery	European Green Deal – 2030 Climate Target Plan	Marked

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[28] www.paris-reinforce.eu

3.2.2.2 Model soft-link

Both models employed in this study can individually deliver outputs on the European climate mitigation and energy system, but to take advantage of the different models' capability, they have been soft-linked. First, key economic variables produced by NEMESIS for each scenario (namely national GDP and sector value added) are used in the EU-TIMES model as input drivers for energy service demands projections. Second, according to the scenario analysed, EU climate policy or/and behavioural changes are introduced in each model and related energy demand and supply as well as CO_2 emissions are calculated. Before comparing results, selected energy variables (namely CO_2 emissions, primary energy by fuel, etc.) are benchmarked across the two models. The results are then compared and analysed to check models' outputs consistency with respect to the scenarios design and understand potential models' divergence. In case of inconsistent results, new runs and iterations are performed. Otherwise, models' results are considered as final scenario outputs. Figure 39 outlines how the two models are linked.

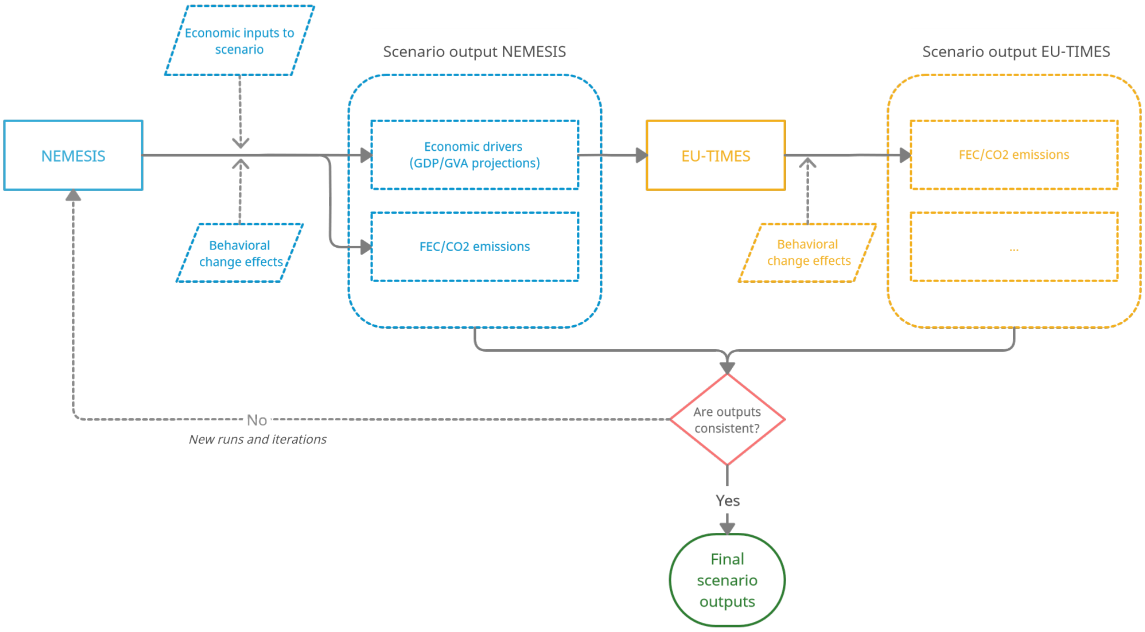

Figure 39: NEMESIS-EU TIMES soft- link

3.2.2.3 Scenarios' implementation

The economic dimension and particularly the post-COVID-19 pandemic economic situation is quantified by the NEMESIS model. The economic impact of the COVID-19 pandemic in 2020 is based on the DG ECFIN[29] economic forecast (European Commission, 2021b) allowing to reproduce in NEMESIS, GDP through its counterparts: households' final consumption, public consumption, gross fixed capital formation, exports and imports for each Member State. Furthermore, the impacts are differentiated by economic sector by using quarterly data available in Eurostat for every Member State up to the third quarter of 2020 (Eurostat, 2021b). The calibration procedure for 2020 consists in introducing gap variables in behavioural equations in the model: (*i*) households' consumption by purpose to mimic the impacts of non-pharmaceutical interventions imposed to households, (*ii*) in employment and income to consider job retention schemes implemented by public authorities and (*iii*) in intra- and extra-EU+ demand to reproduce the reduction in trades of goods and services. After 2020, according to scenarios, these gap variables are either completely or partially phased out and with different temporality.

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[29] Acronym of Directorate-General for Economic and Financial Affairs

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Table 45: GDP in the pre- and post-COVID-19 economic context

		EU+ GDP (bn€$_{2010}$/y.)			Average EU+ GDP growth rate (%/y.)		
		2020	2025	2030	2021-2025	2026-2030	2021-2030
Pre-COVID-19	**Where are we headed (WWH)**	14 806.9	15 771.5	16 817.6	1.3%	1.3%	1.3%
Post-COVID-19	**Full economy recovery (FR)**	13 702.2	15 725.3	16 676.6	2.8%	1.2%	2.0%
		-7.5%	*-0.3%%*	*-0.8%*			
	Limited economic recovery (LR)	13 702.2	15 321.7	16 165.7	2.3%	1.1%	1.7%
		-7.5%	*-2.9%%*	*-3.9%*			

Source: NEMESIS model, in italic percentage deviation with respect to the pre-COVID-19 WWH scenario (WWH-CP)

NEMESIS runs three different scenarios, a pre-COVID-19 scenario, with an EU average annual GDP growth of 1.3% between 2021 and 2030 and two post-COVID-19 scenarios, one with a full recovery in 2025 and a second one with a limited economic recovery, considering an EU+ GDP loss of 3.9% compared with the pre-COVID-19 situation (Table 45). For the "Full economic recovery" scenario, the European economy strongly upturns in 2021 and 2022 allowing the EU+ economies to fill the GDP gap with pre-COVID-19 economic outlook by the year 2025. The methodology used assumes that the behavioural changes observed in production and production patterns in 2020 are only temporary and vanish totally in 2025. Consequently, after 2025, the economic growth in the EU+ countries come back close to the potential GDP growth rate assumed before the COVID-19 crisis, with a yearly growth rate of EU+ GDP of 1.2%. In the "Limited economic recovery" case, the EU+ economy upturns more slowly and weakly between 2021 to 2023, the EU+ GDP is 2.9% lower in 2025 in comparison with the pre-COVID-19 scenario and 3.9% lower in 2030. Furthermore, in the "Limited economic recovery" case, economic crisis has long-term impact on the productivity (Conseil National de Productivité, 2021): after 2025, the EU+ long-term potential GDP growth rate is slightly reduced with -0.2 ppt/y.

Fossil fuels markets have been strongly impacted by the abrupt stop of the world economy, and, in the medium long-term, they will be influenced by the path of global economic recovery. The International Energy Agency (2020c) projects different trajectories for the fossils fuels prices up to 2030. We also assume two different trajectories for fossil fuels prices according to post-COVID-19 economic outlook (fossil fuels prices projections are available on Appendix). In the "Full economic recovery", we just assume a transitory shock on the fossil fuels markets, with prices going back to their pre-crisis level rapidly, between 2021 and 2022 whereas in the "Limited economy recovery", fossil fuels prices are expected to be lower than the pre-crisis projections. The difference is about 14% in 2030 for oil prices and about 6% for natural gas and coal prices, following updated projections from International Energy Agency (2020c).

The EU climate action dimension take places through two contexts and related set of EU climate policies. In the "Current Policies" case, we implement a set of EU current climate policies as close as possible of legal texts and according to model's capability, key policies are summarised in Table 46 (for details on the policy package see (Nikas et al., 2021b). The European Green Deal (EGD) context considers, on top of current policies, a 55% (relative to 1990) CO_2 emissions reduction target for EU in 2030, in line with its long-term strategy submitted to UNFCCC in 2020 (European Union, 2020a) of net-zero objective in 2050. Here, both models need assumptions about non-CO_2 emissions and LULUCF emissions. For the current policies case, we use projections from the European Commission with the EUCO scenarios (European Commission, 2019a) whereas in the European Green Deal context, we use the European Commission's impact assessment of the EU 2030 Climate Target Plan (European Commission, 2020) as reference. The projected land-use, and land-use change and Forest (LULUCF) GHG sink of about -225 $MtCO_2eq$. in 2030 corresponds also to the EU agreement on the maximum contribution of the LULUCF sector to the -55% emissions reduction in 2030 (European Council, 2021). Furthermore, we assume that United Kingdom continues to participate to the EU Emissions Trading System (EU ETS) and other EU climate policies after 2020, despite the Brexit.

Table 46: Measures included in "Current policies" case

EU Emissions Trading Scheme (EU ETS) emissions 2030	Non-EU ETS 2030	Renewable energy share in final energy consumption in 2030	Energy Efficiency in 2030	Nuclear outlook	Coal power pants outlook
Current policy (-43% w.r.t 2005)	Effort Sharing Regulation 2030 (National Targets)	Current policy EU (-32% at 2030)	Current policy EU (-32.5% at 2030)	National current plants and planning to phase out or renewing	National phase-out plans

Table 47: CO_2 emissions caps according to EU+ climate action context

			2030	
$GtCO_2eq.$	1990	2005	Current Policy (-40% wo LULUCF & Int' bunkers)	EU Green Deal (-55% w LULUCF & Int' bunkers)
CO_2 (wo LULUCF & w Int' bunkers)	4.65	4.61	2.96	2.23
CO_2 Int' bunkers	0.18	0.29	--	--
Non-CO_2 (wo LULUCF & w Int' bunkers)	1.18	0.93	0.66	0.50
LULUCF	-0.25	-0.32	-0.23	-0.23
Total (wo LULUCF & Int' bunkers)	5.65	5.24	3.39	--
Total (w LULUCF & Int' bunkers)	5.58	5.22	--	2.51

Source: Historical data from European Environmental Agency (2020), non-CO_2 emissions projections in Current Policies (European Commission, 2019b) and in EGD (European Commission, 2020d), LULUCF emissions projections (European Commission, 2020d). EU+ includes UK.

As previously mentioned, an important focus of the study concerns on behavioural changes and their impacts on the EU+ energy system in the long term. The two main changes in behaviour investigated in the study involve the diffusion of home/remote working and the limitation of flights. These changes are driven by two key driving forces: (*i*) the impulse driven by the contingent situation of COVID-19 pandemic, and (*ii*) the so-called behavioural changes due to "environmental concerns", due to increasing awareness that different changes in behaviour can positively contribute to a net-zero transition.

According to the International Energy Agency (2020c) the behavioural changes required to achieve a net-zero emission transition involve a wide range of sectors and modes. However, since the uncertainty on the entity of the changes is currently very high, here we limit our analysis on the residential and transport sectors. In the residential sector, in a net-zero emission scenario context, an increased number of people are expected to work from home in 2030 compared to 2020, due to the necessity of limiting private commuting and following transformation in the working habits. According to International Renewable Energy Agency (2020) and Eurostat (2020), the range of workforce working from home might reach up to 40%, three days per week by 2030. The COVID-19 pandemic may have accelerated this change.

Similarly, in a net-zero emission context, a reduction in the number of flights in the aviation sector, due to the increased costs related to the decarbonization and increased environmental concerns of passengers, is foreseen (Gössling et al., 2020). The International Energy Agency (2020c) indicates a possible reduction of 34% of flights of less than 6 hours, and a 50% reduction of flights longer than six hours. Furthermore, the diffusion of teleconferences during the pandemic may have accelerated the reduction of business flights in the long term. In

Table 48 how behavioural changes are interpreted and translated into the modelling is described.

Table 48: Modelling interpretation of behavioural changes

Transformation	Modelling interpretation
Behaviour changes due to environmental concerns.	• **Remote working:** on the maximum of 40% (Eurostat, 2020), we assume the percentage of workforce concerned by remote working of 25% and the share of commutes to work is considered as the 40% of total passenger journeys for 3 days per week (Carbon Tracker, 2021; European Commission, 2021c). The increase in energy demand of the residential sector is calculated as one third of the decrease in the transportation sector. As a consequence, the change is modelled by projecting 6% less private car commutes in the transportation sector and by 2% higher energy demand in the residential sector. The same increase is accounted to electric consumption and to space heating demand (International Energy Agency, 2020c)[30]. The effect on the tertiary sector is not modelled in this work due to lack of estimates in literature to date. • **Environmental concern and increase of prices in aviation sector:** change is modelled by projecting 34% lower demand in the aviation sector in 2030. (In the NEMESIS, the demand for aviation is influenced by prices, the effect of environmental concerns in not imposed a priori in this case).
Behaviour changes due to COVID-19 pandemic	• **Remote working:** here, the percentage of workforce considered is 40% (the maximum) and the share of commutes to work is considered as the 40% of total passenger journeys for 3 days per week. The increase in energy demand of the residential sector is calculated as one third of the decrease in the transportation sector. As a consequence, the change is modelled by 10% less private car commutes in the transportation sector and by projecting 3.3% higher energy demand in the residential sector. The same increase is accounted to electric consumption and to space heating demand (International Energy Agency, 2020c)[31]. The effect on the tertiary sector is not modelled in this work due to lack of estimates in literature to date. • **Travelling restrictions:** change is modelled by projecting additional 10% lower energy demand in the aviation sector in 2030 compared to the reduction due to environmental concern.

We limit the presentation of this study to the methodology because the results from models' runs and their analysis will be included in the update of this document.

3.2.3 Results

3.2.3.1 CO_2 emissions pathways

In the whole range of scenarios analysed, this paper first assesses the impacts of different levels of climate ambition for 2030 in a pre-COVID-19 economic context. The WWH-CP and WWH-EGD scenarios analyse transformations required by the EU+ energy system to move from the 2020-2030 EU Climate and Energy Framework policies (i.e. -40% GHG emissions by 2030 compared to 1990) to the European Green Deal reinforced target (i.e. -55% GHG reduction by 2030), considering an economic and demand outlook pre-pandemic crisis.

Figure 40 compares the EU+ CO_2 emissions trajectories from energy and industrial processes, identifying which are the sectors contributing the most to the reduction. From 3.7 $GtCO_2$ in 2019, both models reach the -55% reduction target in the WWH-EGD scenario, with 2.24 Gt of CO_2 emissions in 2030, while they show slightly different CO_2 emissions in the WWH-CP scenario, with 2.98 for EU-TIMES and 2.84 $GtCO_2$ in NEMESIS. This difference is explained by the national burden sharing in those sectors framed in the Effort Sharing Regulation (ESR), as such burden is not constraining in some members states. In addition, CO_2 emissions from international bunkers are not included in the CO_2 emissions perimeter in the WWH-CP scenario, but they are in WWH-EGD.

Both models agree that the power generation and supply are the main sectors driving the decarbonisation. By 2030, these sectors drive a reduction of 275 $MtCO_2$ in NEMESIS and 404 $MtCO_2$ in EU-TIMES. Contributions to decarbonisation are foreseen also from end-use sectors. The EU-TIMES model shows mitigation potentials by 2030 from the transportation, industry and building sector (both residential and commercial) by 141, 117 and 80 $MtCO_2$

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[30] Estimates of behaviour changes are derived from NZE scenario

[31] Estimates of behaviour changes are derived from NZE scenario

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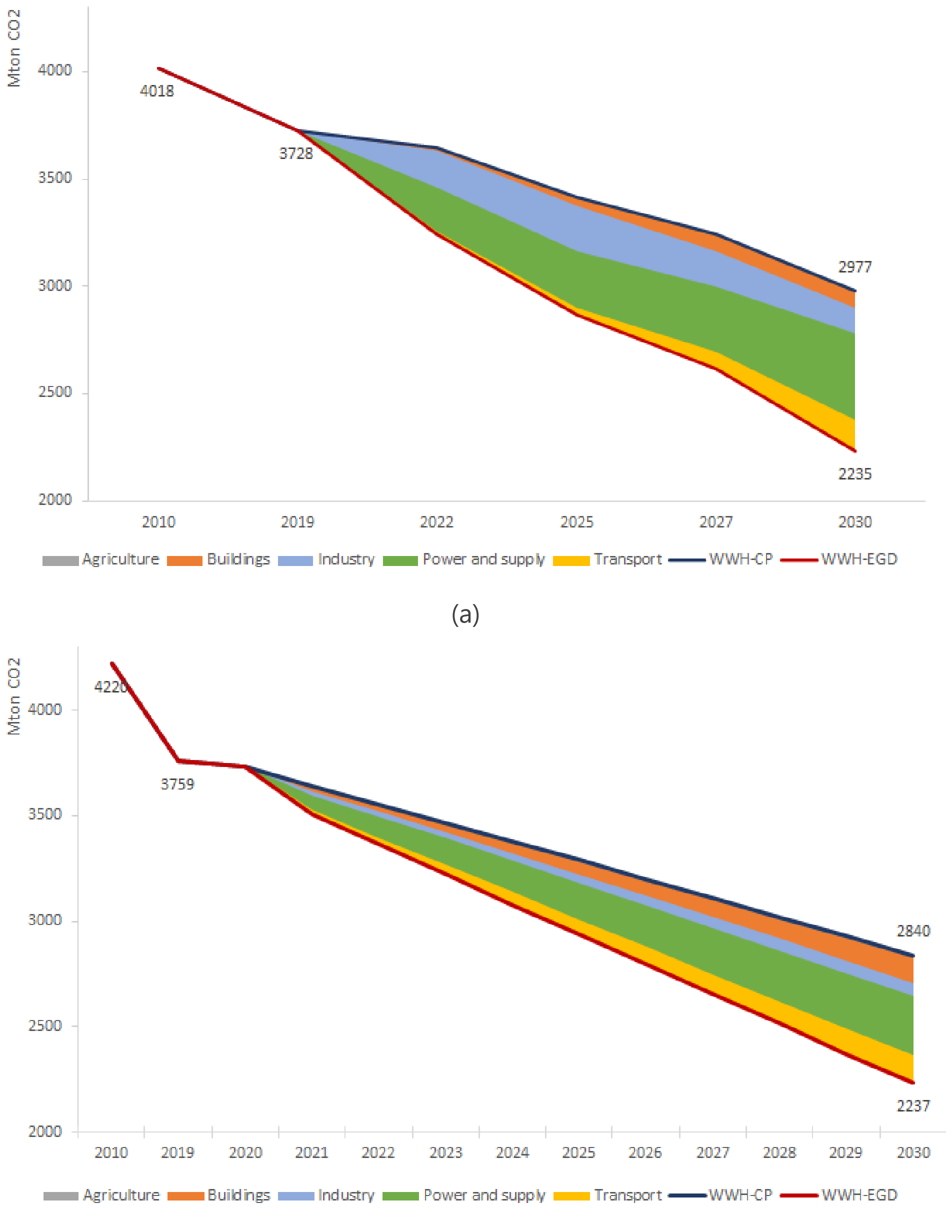
respectively. The NEMESIS model indicates transportation, building and industry sectors contributing for 132, 117 and 66 $MtCO_2$ respectively (Figure 40). Overall, both models indicate that transitioning toward the European Green Deal climate policy requires coordinated contribution from all energy sectors. No single silver-bullet solution is foreseen. By comparing these results with European Commission impact assessment of its 2030 Climate Target Plan (European Commission, 2020d), the CO_2 mitigation by sector to reach the -55% GHG reduction target is relatively similar, with the strongest effort done by the power and supply sector representing the 60% of the total CO_2 mitigation effort. Nevertheless, European Commission (2020d) expects smaller contribution from industry and transportation, which is largely explained by more ambitious emissions reduction in these sectors in their baseline scenario (current policy scenario).



(a)

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(b)

Figure 40: EU+ CO2 emissions from energy and industrial processes - comparison between WWH-CP and WWH-EGD scenarios for (a) EU-TIMES and (b) NEMESIS. Transportation includes international EU+ aviation emissions, industry includes industrial processes emissions, agriculture is only related to energy (AFOFI sector: IPCC category 1A4c)

The decarbonisation path identified by the WWH-EGD scenario is then used to benchmark scenarios which consider economic implications of the COVID-19 pandemic, namely COVID-FR-EGD and COVID-LR-EGD. These scenarios foresee limited implications[32] in total emissions trajectories (driven by policy targets), but implications are shown at sectoral level. In Figure 41, the difference at sectoral level is benchmarked with the WWH-EGD scenario. In EU-TIMES, COVID-LR-EGD scenario presents a marked reduction in transportation sector (-63 $MtCO_2$) and an increase in other sectors in 2022 (45 $MtCO_2$ in industry and 9 $MtCO_2$ in other sectors). These differences reduce in the following periods, as short-term implications of COVID-19 phase out. However, the building sector maintains a small positive balance increasing its emissions by 21 $MtCO_2$. In the COVID-FR-EGD, the faster recovery results in less visible impacts on sectoral CO_2 emissions[33]. In 2022, the scenario shows a reduction in emissions from the transport sector (-16 MCO_2) and a contextual increase from other sectors (2 $MtCO_2$ in buildings, 7 $MtCO_2$ in industry, 8 $MtCO_2$ in power and supply). In 2030 the power generation and supply sectors emit 16 $MtCO_2$ more, while other sectors reduce slightly. NEMESIS results confirm that major impacts of COVID-19 pandemic on energy-related emissions are expected on the short-term: CO_2 emissions are 12% lower (-460 $MtCO_2$) in 2020 in both post COVID-19 pandemic scenarios (COVID-FR-EGD and COVID-LR-EGD) than in the pre-COVID-19 scenario (WWH-CP). In 2020, the transport sector reduces its emissions by 310 $MtCO_2$, and emissions reduce considerably also in the power and supply sectors (-119 $MtCO_2$) and industry (-47 MtO_2). Moving towards 2030, the EU+ CO_2 emissions tend to realign to WWH-EGD scenario, more rapidly in the full recovery case (COVID-FR-EGD).

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[32] The EU-TIMES indicates that emissions pathways do not differ significantly comparing with WWH-EGD scenario, given its limited capability of capturing short term shocks (the model considers average multi-year periods). The NEMESIS is running with an annual level resolution; hence the model is capable to show implications for specific years (i.e. 2020), and the rapid recovery in the following years.

[33] The EU-TIMES model utilized here cannot capture short term shocks (i.e. 2020, 2021) given its limited resolution. The period 2022 represents an average period between 2021 and 2023.

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Figure 41: EU+ CO2 emissions from energy and industrial processes - difference at sectoral level between post COVID-19 pandemic scenarios (COVID-FR-EGD and COVID-LREGD) and pre-pandemic scenario (WWH-EGD) (a) in EU-TIMES and (b) NEMESIS. The total CO$_2$ emissions trajectory between EGD scenarios is unchanged in EU-TIMES

Anticipating some findings related to energy consumption, that are described in detail in the following section (3.2.3.2), we look at the CO$_2$ emissions intensity of primary energy consumption. In the short time, both models display declining values. In NEMESIS – which is better equipped to consider short-term shocks from the COVID-19 pandemic – results indicate that the restrictive sanitary measures significantly affected the activity of the transportation sector, and, due to its importance on total energy consumption and the share of oil in its energy

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mix, its decline in the short-term (for post COVID-19 scenarios) leads to a reduction of the CO_2 intensity. In EU climate ambitious scenarios (EGD scenarios), besides short-term, the CO_2 intensity in both models declines more compared to the "current policies" context (WWH-CP scenario). In EU-TIMES, CO_2 intensity reduces up to 1.47 $MtCO_2$/Mtoe by 2030 compared to 1.91 in WWH-CP and, in NEMESIS, up to 1.94 $MtCO_2$/Mtoe instead of 2.15.

These results demonstrate that an important part of the European CO_2 emissions mitigation effort to reach the EU Green Deal ambition takes place by a decarbonation of the EU+ energy mix. Furthermore, in EU-TIMES and NEMESIS, CO_2 intensity is slightly higher in the low recovery economic context (COVID-LR-EGD) than in the full recovery case (COVID-FR-EGD). This is the result of slightly lower prices of fossil fuels in the low recovery context (see section 3.2.2.3).

Table 49: EU+ CO_2 emissions intensity by scenario

Emissions intensity on PEC (CO_2 emissions/Primary Energy Consumption) *[Mt CO_2/Mtoe]*

EU-TIMES

	2019[34]	2022	2025	2027	2030
WWH-CP	2.30	2.34	2.18	2.07	1.91
WWH-EGD	2.30	2.11	1.88	1.75	1.47
COVID-LR-EGD	2.30	2.17	1.91	1.78	1.50
COVID-FR-EGD	2.30	2.13	1.89	1.76	1.48
WWH-EGD-Beh	2.30	2.13	1.91	1.78	1.52
COVID-FR-EGD-Beh	2.30	2.17	1.92	1.80	1.53

NEMESIS

	2019	2020	2021	2022	2025	2027	2030
WWH-CP	2.38	2.38	2.37	2.35	2.29	2.24	2.15
WWH-EGD	2.38	2.38	2.34	2.31	2.19	2.10	1.94
COVID-LR-EGD	2.38	2.30	2.35	2.33	2.23	2.14	1.98
COVID-FR-EGD	2.38	2.30	2.36	2.32	2.20	2.11	1.95
WWH-EGD-Beh	2.38	2.38	2.34	2.30	2.19	2.09	1.93
COVID-FR-EGD-Beh	2.38	2.30	2.35	2.31	2.19	2.09	1.93

To better analyse the impact of the three layers, we look also at the carbon prices (marginal CO_2 abatement cost) in each scenario (Table 50). Despite differences between NEMESIS and EU-TIMES in carbon price values, both expect a significant carbon price increase with the implementation of the European Green Deal (WWH-EGD). In EU-TIMES, the CO_2 price grows from 120€$_{2010}$/tCO_2 in WWH-CP to 607 while in NEMESIS from 59 €$_{2010}$/tCO_2 to 187. Behavioural changes due to environmental concerns (WWH-EGD-Beh) positively impact on the European Green Deal climate burden in the EU-TIMES, which foresees a reduction of 16% in the marginal CO_2 abatement cost relative to WWH-EGD. In NEMESIS, these impacts are rather more limited, with a decline of 2%. Post-COVID scenarios indicate a reduction in carbon prices in both models, even when a full economy recovery is considered. This drop is more marked when introducing behavioural changes (COVID-FR-EGD-Beh), i.e. -20% in EU-TIMES and -9% in NEMESIS compared with WWH-EGD. Here, the lower demand for transportation services reduces the CO_2 emissions reduction burden, mostly in aviation which is particularly challenging to decarbonise. In the limited economic recovery case (COVID-LR-EGD), NEMESIS shows lower carbon price values than all EU Green Deal-

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[34] 2019 values of emission intensity slightly differ in the two models because they have a different base year. Therefore, values are modelled and not based on 2019 EU+ energy balance.

related scenarios. The lower economic activity in EU+ (-3.9% of GDP, see Table 45) in COVID-LR-EGD leads to carbon prices 11% lower than in the WWH-EGD scenario. This carbon price is also lower in EU-TIMES, but in line with the WWH-FR-EGD scenario, thus indicating that the economic recovery has not necessarily negative impacts on the delivery of climate targets. In brief, results from both models suggest that reinforced mitigation ambition in the EU (delivering -55% GHG emissions) will contribute to an increase of carbon prices from three to five times, but this carbon burden may be alleviated by lifestyle changes (here remote working and lower flights).

Table 50: Carbon prices in EU+ in 2030 by scenario

	Carbon price	
€$_{2010}$/tCO$_2$	**EU-TIMES**	**NEMESIS**
WWH-CP*	120	59
WWH-EGD	607	187
WWH-EGD-Beh	508	184
COVID-FR-EGD	571	181
COVID-FR-EGD-Beh	437	170
COVID-LR-EGD	575	166

*: *Average weighted carbon prices among Member States and between ETS and non-ETS*

3.2.3.2 Energy consumption

The implications of COVID-19 pandemic are also reflected in the EU+ primary energy consumption (PEC) patterns. In NEMESIS, PEC is expected to reduce by 140 Mtoe in 2020 in both post COVID-19 scenarios. In EU-TIMES, PEC reduces by 2022 of 42 Mtoe and 14 Mtoe in COVID-LR-EGD and COVID-FR-EGD, respectively. In full economic recovery scenarios (COVID-FR-EGD), both models indicate a transitory reduction of PEC in the EU+: the European energy system goes back progressively to the pre-COVID-19 level (WWH-EGD) in 2030. With limited economic recovery, PEC difference with pre-COVID-19 outbreak remains. Nevertheless, this gap is limited, i.e. -23 Mtoe in NEMESIS and -31 Mtoe in EU-TIMES by 2030. In NEMESIS, the lower fossil fuels prices imply that the reduction of the primary energy demand does not affect fossil fuels, while other fuels, mainly renewable energy and nuclear, show a reduction. The EU-TIMES shows diversified reductions of primary energy between fuels, even if renewable energy and hydrogen represent more than two third of the total primary energy reduction in 2030 in comparison with WWH-EGD, with -18 and -6 Mtoe respectively on a total of -33 Mtoe. These results remind other findings about important fossil fuels consumption rebound after worldwide economic crisis (*e.g.* Peters et al., 2012; Jotzo, et al., 2012) and supports the idea of a relevant design of recovery plans to avoid fossils fuels-based recovery (e.g. Hoang et al, 2021; Allan et al., 2020).

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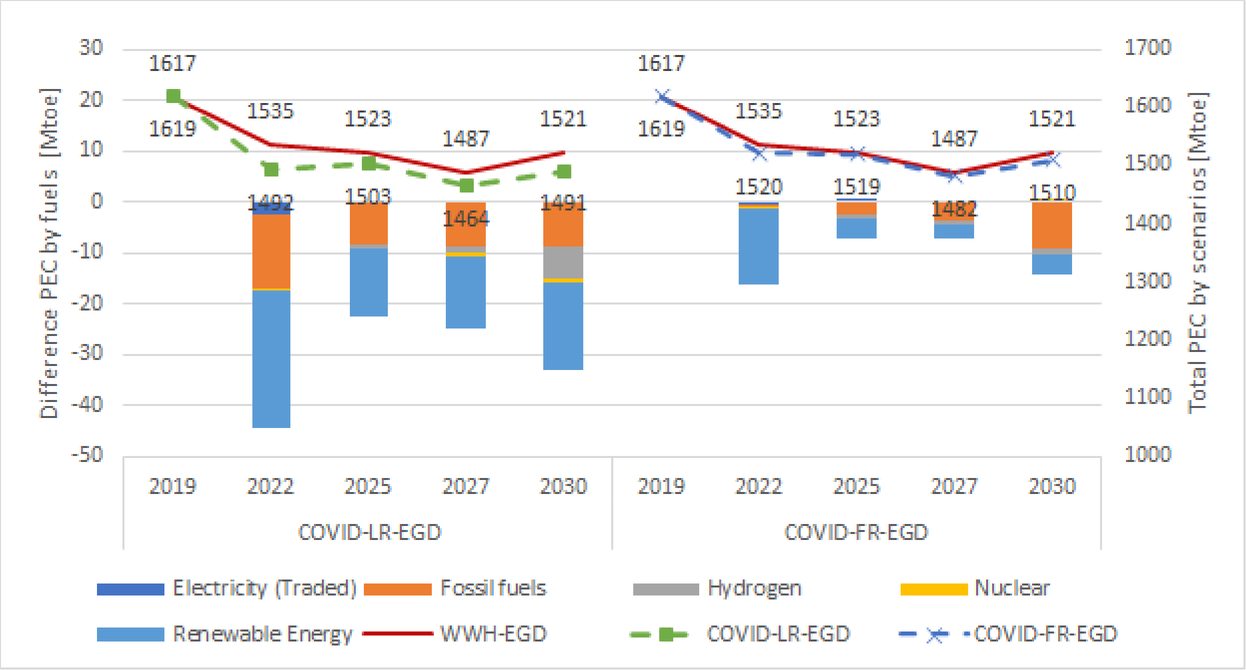
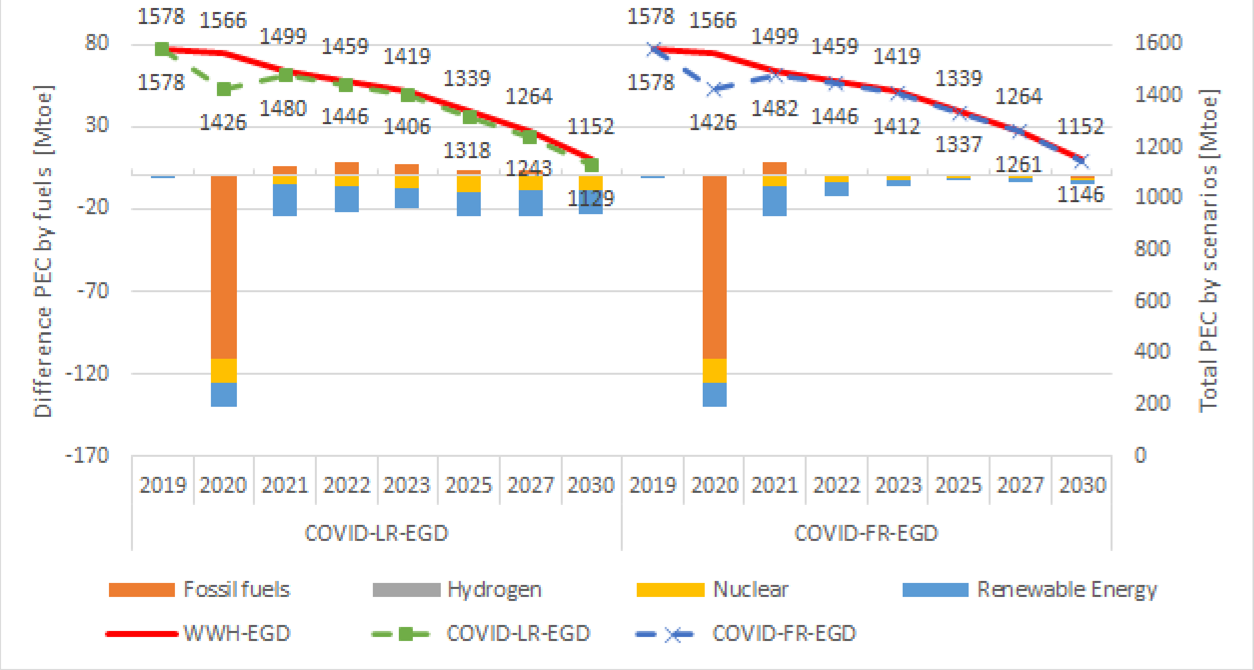


(a)



(b)

Figure 42: EU+ primary energy consumption variation in post COVID-19 pandemic scenarios compared with pre-COVID-19 pandemic scenario (WWH-EGD) in (a) EU-TIMES and (b) NEMESIS models.

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Table 51: EU+ energy intensity by scenario

Energy intensity (PEC/GDP) [Mtoe/ Million euro 2010]					
EU-TIMES					
	2019	**2022**	**2025**	**2027**	**2030**
WWH-CP	0.111	0.103	0.100	0.097	0.093
WWH-EGD	0.111	0.101	0.097	0.092	0.091
COVID-LR-EGD	0.111	0.102	0.098	0.093	0.092
COVID-FR-EGD	0.111	0.102	0.096	0.092	0.090
WWH-GD-Beh	0.111	0.102	0.096	0.092	0.090
COVID-FR-EGD-Beh	0.111	0.100	0.094	0.090	0.087

NEMESIS							
	2019	**2020**	**2021**	**2022**	**2025**	**2027**	**2030**
WWH-CP	0.108	0.106	0.102	0.099	0.091	0.086	0.079
WWH-EGD	0.108	0.106	0.100	0.096	0.085	0.078	0.069
COVID-LR-EGD	0.108	0.104	0.104	0.099	0.086	0.079	0.070
COVID-FR-EGD	0.108	0.104	0.104	0.097	0.085	0.078	0.069
WWH-EGD-Beh	0.108	0.104	0.104	0.097	0.085	0.078	0.069
COVID-FR-EGD-Beh	0.108	0.104	0.104	0.098	0.086	0.079	0.069

Energy efficiency is a cornerstone of the EU climate strategy (European Union, 2018a) and both models confirm its importance in all scenarios, even if to a different extent. The EU+ energy intensity, the energy content by unit of GDP, is expected to decline between 2019 and 2030 by 27% in NEMESIS and by 16% in EU-TIMES in the WWH-CP scenario, and by 36% and 18% in WWH-EDG. In absolute, PEC in the EGD scenarios reaches by 2030 approximately 1,500 Mtoe in EU-TIMES and around 1,150 Mtoe in NEMESIS. These differences are largely due by the different structure of the models (i.e., EU-TIMES includes extra-EU aviation consumption), but findings of both models are largely in line with existing studies in the literature. Tisropoulos et al. (2020), reviewing a set of scenarios in line with 2030 European Green Deal ambition, indicates a range of gross inland consumption (GIC) between 1,430 and 1,175 Mtoe[35] whereas the GIC reaches around 1,160 Mtoe in latest European Commission projections (2020d). Thus, primary energy consumption projected by EU-TIMES and NEMESIS mark out the boundaries of the literature, with EU-TIMES on the higher end and NEMESIS on lower end.

Both models indicate slightly lower energy efficiency gains in the limited economic recovery context (COVID-LR-EGD) than in the full recovery one (COVID-FR-EGD). The reduction of PEC is mainly driven by the drop of the European economic activity. Furthermore, COVID-FR-EGD scenario show EU+ energy intensity levels aligned in the longer term with pre-COVID-19 scenarios (WWH-EGD), indicating that a rapid economic recovery will limit the impact of COVID-19 pandemic on the path towards decarbonisation under European Green Deal climate policies.

3.2.3.3 Role of behavioural changes on energy transition

Behavioural changes considered in this analysis refer to two key independent causes (see section 3.2.2.3): the environmental concern in the frame of the decarbonization of the EU+ energy system, and behavioural changes caused by COVID-19 pandemic.

First, Figure 43 displays the EU+ final energy consumption (FEC) in the residential sector in both models,

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[35] Primary energy consumption equals gross inland consumption (GIC) minus the final non-energy consumption.

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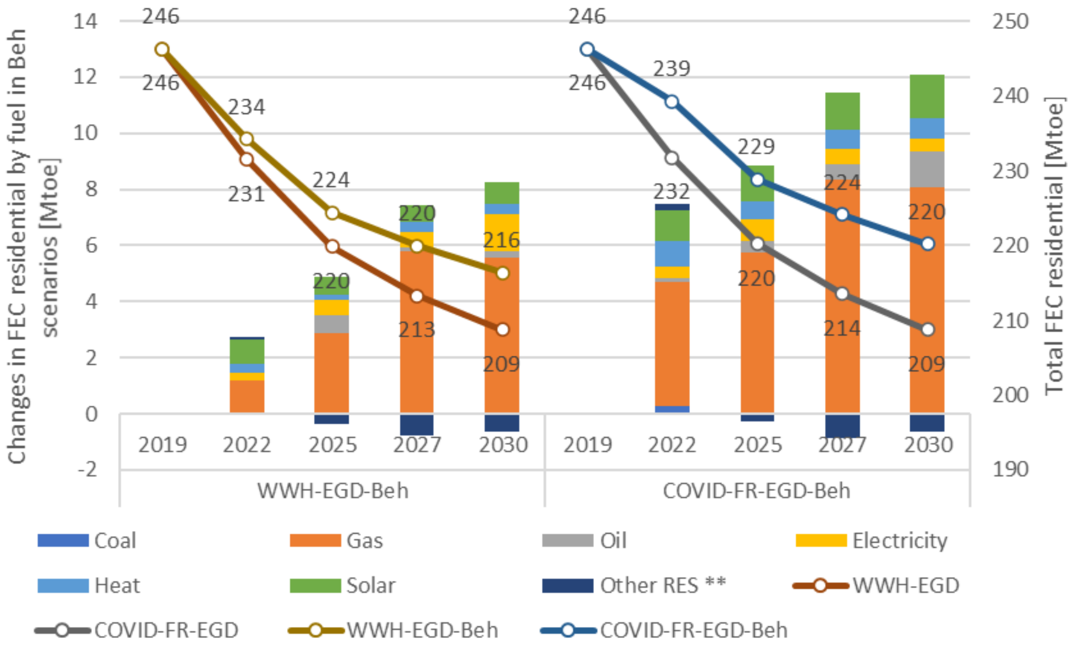
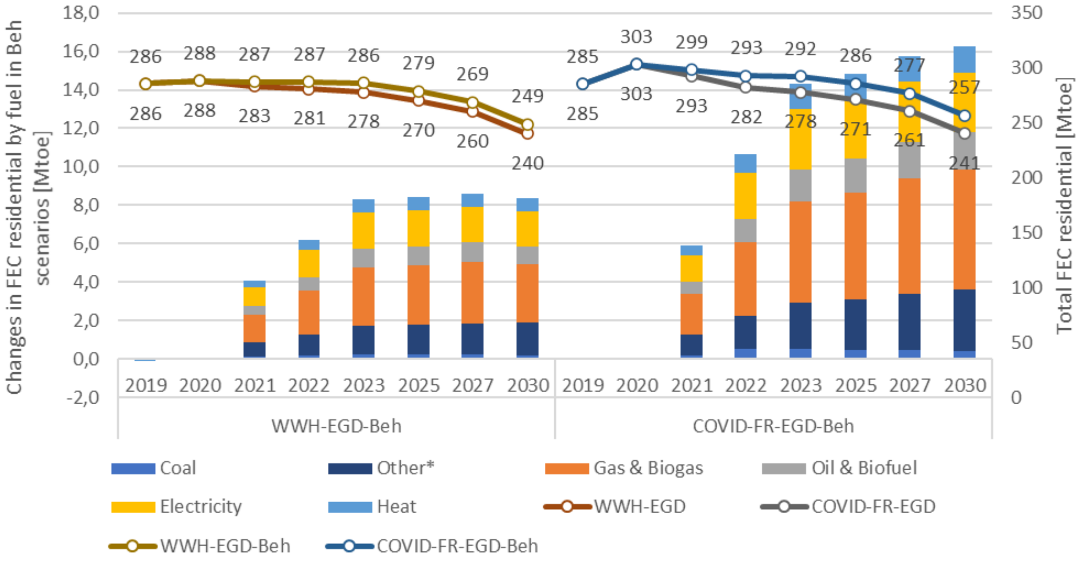
comparing pre-COVID-19 case including behavioural changes (WWH-EGD-Beh) with WWH-EGD scenario, and post-COVID-19 full recovery case including behavioural changes (COVID-FR-EGD-Beh) with COVID-FR-EGD scenario. Impacts driven by behavioural changes lead to an increase of FEC by between 3.6% and 5.5% in EU-TIMES and between 3.4 and 6.7% in NEMESIS. All fuels consumption increase (with the exception of "*other RES*" in the EU-TIMES, that primarily accounts for ambient heat from heat pumps), in particular natural gas, which contributes to CO_2 emissions increase in the residential sector. Compared to scenarios with no behavioural changes, in the EU-TIMES, CO_2 emissions increase by 15% in the pre-COVID-19 case and by 21% in the post-COVID-19 case; while, in NEMESIS, CO_2 emissions grow by 3% and by 7%. An analogous comparison is done for transportation sector in Figure 44. Total FEC decreases in all relevant cases, as expected. In NEMESIS reductions occur for all the fuels, in particular oil. Similarly, in the EU-TIMES, jet-kerosene is the main fuel reducing consumption, due to the flight reduction, followed by hydrogen and, in specific years, natural gas and gasoline. The reduction of fossil fuels consumption in these scenarios contribute to a reduction of CO_2 emissions in transportation sector by 12% for both pre- and post-COVID-19 analysis in EU-TIMES, and by 3% and 6% in NEMESIS. In brief, results show that pandemic may accelerate trends foreseen by the increase of environmental awareness, namely with a switch in energy consumption from transportation to residential sectors.

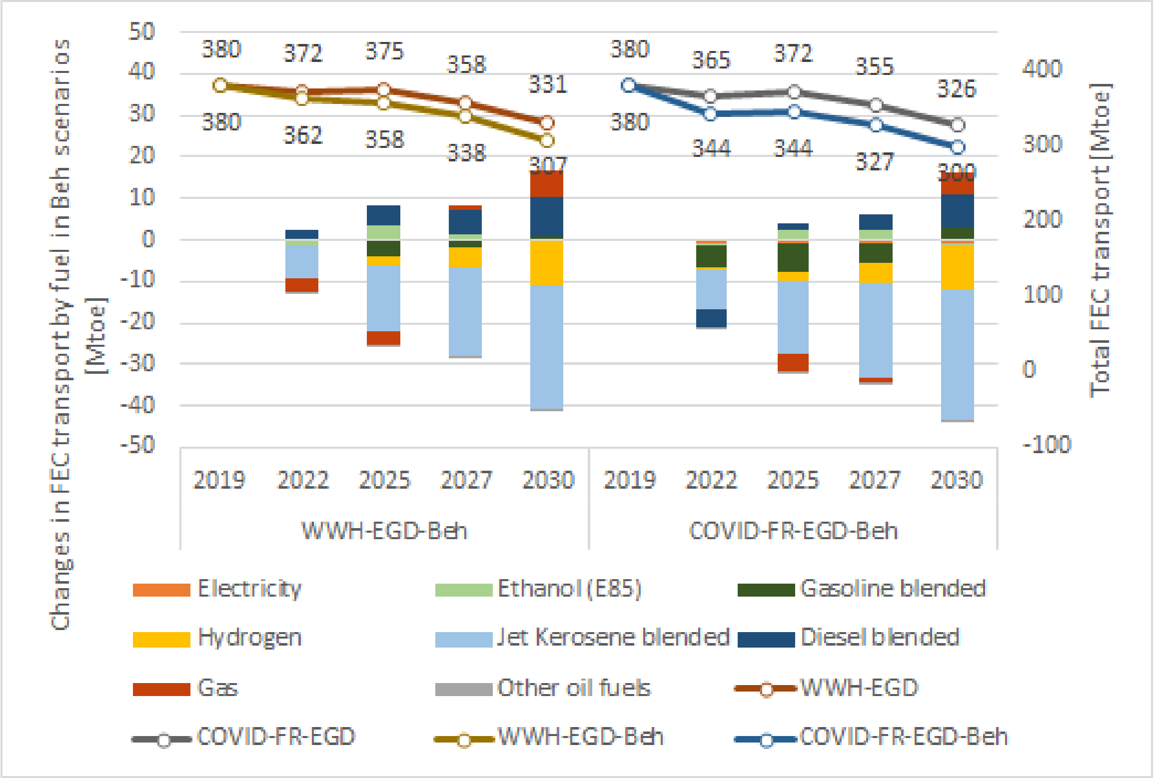


(a)



(b)

Figure 43: EU+ final energy consumption in residential sector - differences between scenarios with behavioural changes (WWH-EGD-Beh and COVID-FR-EGD-Beh) and their respective reference scenario (WWH-EGD and COVID-FR-EGD) for (a) EU-TIMES and (b) NEMESIS. Other RES includes: ambient heat, solid biomass, biogas and Geothermal. Other* includes: renewable and non-renewable wastes, industrial wastes, ambient heat, thermal solar, geothermal, and solid biomass.**



(a)

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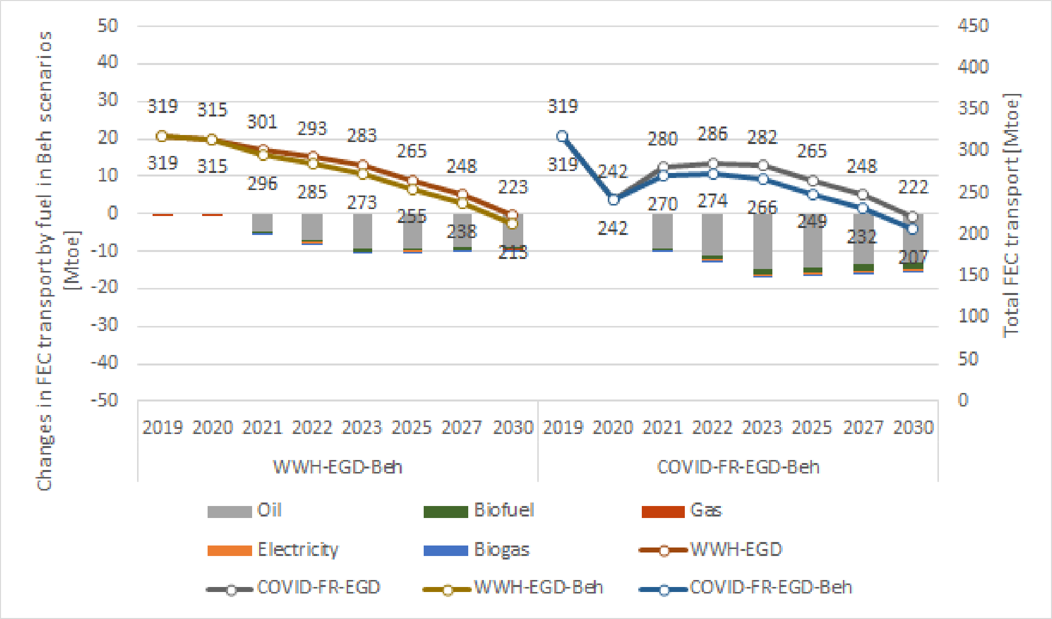
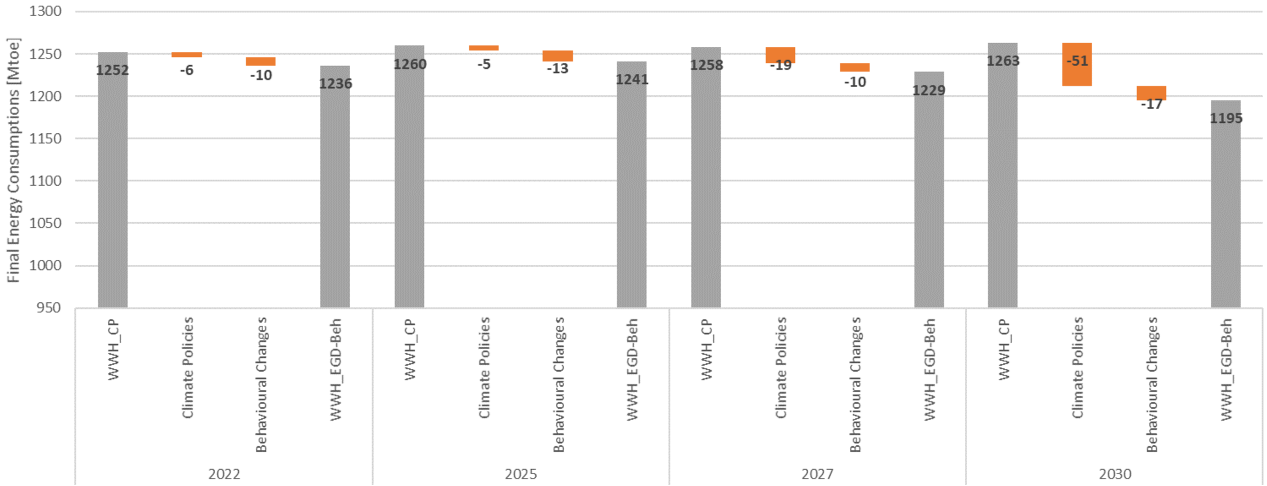


(b)

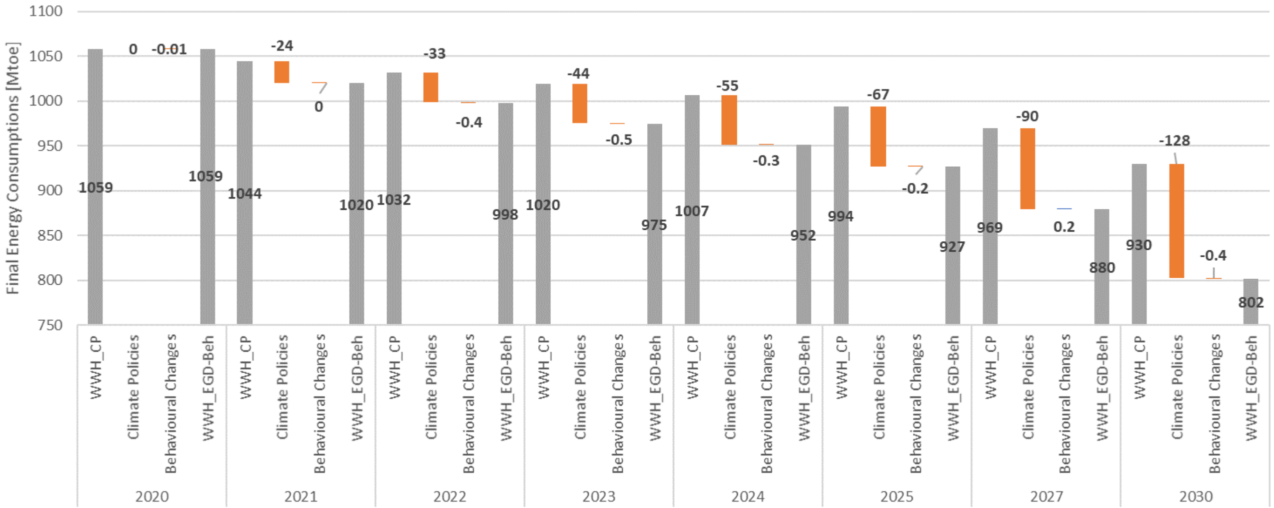
Figure 44: EU+ final energy consumption in transportation sector - differences between scenarios with behavioural changes (WWH-EGD-Beh and COVID-FR-EGD-Beh) and their respective reference scenario (WWH-EGD and COVID-FR-EGD) for (a) EU-TIMES and (b) NEMESIS. Blended fuels include a mix of biofuels and fossil fuels according to the fuels' quality directive and renewable energy directive (European Union, 2019)

Figure 44 shows how the EU+ final energy consumption is affected by including European climate policy (WWH-EGD) and behavioural changes due to environmental concern (WWH-EGD-Beh), excluding the impacts of COVID-19 pandemic. In the short-term (2022), EU-TIMES shows higher contributions from behavioural changes on energy savings than the climate policy impact: from a total of 1.3% reduction of FEC, only 0.5% is due to climate policies. In NEMESIS, energy savings are driven mostly by climate policies. By 2030, for both models the main contributors to FEC reductions are the EU climate policy improvements. In EU-TIMES, out of the total reduction of 68 Mtoe between WWH-CP and WWH-EGD-Beh, 51 Mtoe are driven by stronger EU climate ambition and 17 Mtoe by behavioural changes. In NEMESIS, the total FEC reduces by 128 Mtoe, all from the increased ambition of the EU climate action. Here, the results of the models diverge. On the one hand, while both models give a positive impact of European climate policy on energy saving, NEMESIS shows larger impacts than EU-TIMES. On the other hand, EU-TIMES displays impacts of behavioural changes related to environmental concerns on final energy consumption, while NEMESIS doesn't.

Figure 45 shows how FEC is affected by behavioural changes caused by COVID-19 pandemic. In the EU-TIMES, results show that the impacts on FEC reduction due to COVID-19 are more important in the short-term. In 2022, the three factors induce a FEC reduction of 39 Mtoe: 6 Mtoe are due to EU climate policy, 16 Mtoe to the COVID economic impact and 17 Mtoe to the behavioural changes induced by COVID-19 pandemic. In 2030, on the decline of 75 Mtoe of FEC reduction, 51 Mtoe come from climate policies, 8 Mtoe from economic impact and 15 Mtoe from behavioural changes. In NEMESIS, in 2020, the reduction of the FEC is driven by COVID-19 economic recession, with -94 Mtoe. Thereafter, the progressive economic recovery in EU+ reduces the drop of FEC with almost no impact after 2023, whereas the reinforcement of climate ambition in EU+ drives some energy efficiency gains, reaching a reduction of 128 Mtoe of FEC in 2030. Finally, the behavioural changes resulting from COVID-19 pandemic do not impact total EU+ FEC in NEMESIS.



(a)



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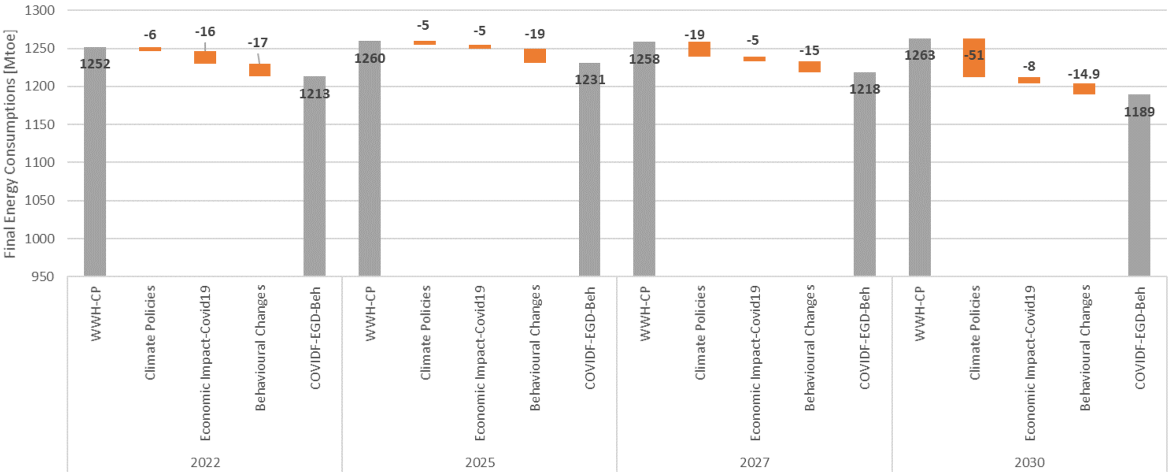
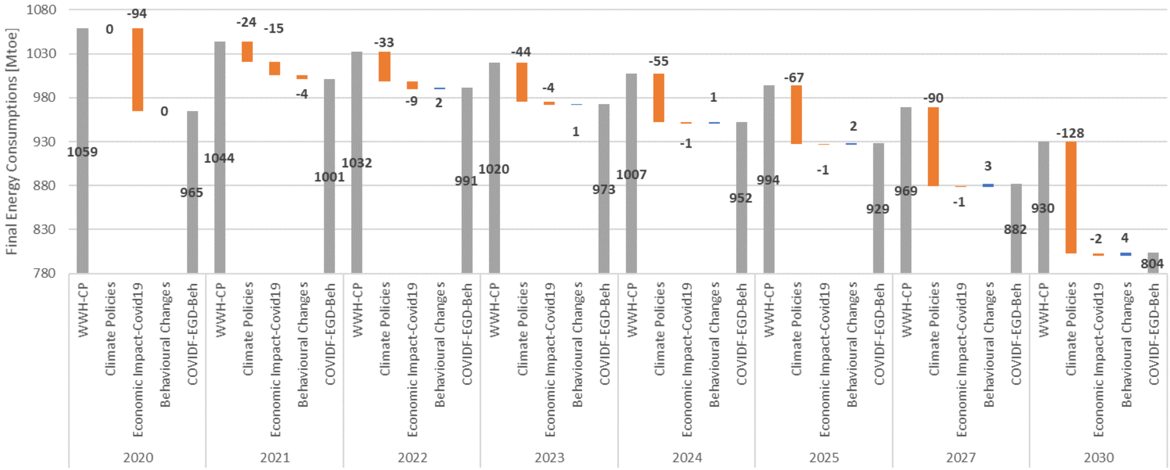
(b)

Figure 45: Variation of final energy consumption highlighting behavioural changes due to new environmental concern by comparing final energy consumption of WWH-CP, WWH-EGD, WWH-EGD-Beh for (a) EU-TIMES and (b) NEMESIS.



(a)



(b)

Figure 46: Variation of final energy consumption by inputs highlighting behavioural changes induced by COVID-19 pandemic by comparing final energy consumption of WWH_CP, WWH_EGD, COVID-FR-EGD and COVID-FR-EGD-Beh for (a) EU-TIMES and (b) NEMESIS.

3.2.3.4 Investment patterns of the transitions

Both models provide indicators about the investments requirement to achieve the climate ambition of the European Green Deal, but indicators delivered differ in terms of approach. In NEMESIS, investment refers to the gross fixed capital formation based on the European national accounting framework (Eurostat, 2013), whereas, in EU-TIMES, it follows a techno-economic approach based on technology investment overnight costs.

With NEMESIS, the comparison of EU total gross fixed capital formation between pre- and post-COVID-19 scenarios allow the assessment of the investment losses caused by the pandemic. Between 2020 and 2022, NEMESIS quantifies a loss of the EU investments between 860 billion euros constant 2010 (bn€$_{2010}$) in COVID-FR-EGD and 994 bn€$_{2010}$ in COVID-LR-EGD scenario in comparison with WWH-EGD. In addition, the comparison between the total investments in the European Green Deal (WWH-EGD) and the current policies case (WWH-CP) informs about the EU investment needs to shift GHG emissions from -40% to -55% in 2030 (with respect to 1990). The model assesses these cumulative investments about 410 bn€$_{2010}$ between 2020 and 2030. Table 52 shows these investments variations by sector. Major part of the investment losses due to COVID-19 pandemic take place in the buildings sector (between -537 and -619 bn€$_{2010}$), which includes services and households' investments, followed by industry, with a reduction of the gross fixed capital formation from 198 to 221 bn€$_{2010}$. While for achieving the 2030 GHG emissions reduction target of the EU Green Deal, NEMESIS displays important investment needs in industry with 195 bn€$_{2010}$ for the 2021-2030 decade and more moderated ones for transport and buildings with 110 and 106 bn€$_{2010}$ respectively.

Table 52: Cumulative EU investment deviation due to COVID-19 pandemic and European Green Deal by sector, NEMESIS model

	Cumulative EU investment deviation from 2020 to 2022 due to COVID-19 pandemic *(bn€$_{2010}$ w.r.t. WWH-EGD)*		Cumulative EU investment deviation from 2021 to 2030 due to European Green Deal *(bn€$_{2010}$ w.r.t. WWH-CP)*
	COVID-FR-EGD	**COVID-LR-EGD**	**WWH-EGD**
Agriculture	-15.9	-17.1	23.7
Power and supply	-16.1	-20.3	-25.9
Industry	-198.1	-221.3	195.1
Transportation	-103.4	-116.1	110.0
Buildings	-537.1	-619.4	106.2
Total	-870.5	-994.4	409.0

EU-TIMES investment indicators are related to gross investment requirements in the energy system (Table 53). The scenario with the highest cumulative investment is the pre-COVID-19 WWH-EGD scenario, confirming the economic effort required to achieve the EU Green Deal emissions reduction target. In comparison with the current climate policies scenario (WWH-CP), it corresponds to an additional investment for the whole system of around 530 bn€$_{2010}$ between 2020 and 2030. The sectors requiring most investments differ between the two models, as in EU-TIMES they are transportation and power sector, coherently with the results obtained for the CO$_2$ emissions. The additional investments for transportation and power sector are 188 bn€$_{2010}$ and 184 bn€$_{2010}$, respectively. By including behavioural changes in WWH-EGD, the total amount reduces of 459 bn€$_{2010}$ (WWH-EGD-Beh.), 335 of which are avoided in the transportation sector. This means that behavioural changes, by reducing the energy demand, will have a reduced requirement of advanced mitigation technologies such as electric vehicles and hydrogen technologies, which have a remarkable impact on the investments.

The role of behavioural changes is even more relevant when considering the COVID-19 impact, as the post COVID-19 scenario (COVID-FR-EGD-Beh) requires 966 bn€$_{2010}$ less than the pre-COVID-19 scenario (WWH-EGD), with the transportation sector reducing most investments. The post COVID-19 scenario (COVID-FR-EGD-Beh) requires even less investments than the current policy scenario (WWH-CP, -434 bn€$_{2018}$).

The range of the investments needs to achieve the -55% of GHG emissions reduction in 2030 is in line with the European Commission estimates (2020d), that assessed the need of additional investments in the power generation sector between 110 and 165 bn€$_{2010}$ between 2021 and 2030. The overall additional investment requirement estimated by the Commission are higher, between 590 and 1080 bn€$_{2010}$, however, it is necessary to consider that the models do not include costs for infrastructures.

Table 53: Cumulative investment deviations per sector in EU from 2021 to 2030 [bn€$_{2010}$], EU-TIMES model.

WWH-EGD	WWH-EGD-Beh	COVID-FR-EGD	COVID-FR-EGD-Beh	COVID-LR-EGD

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	(w.r.t. WWH-CP)		(w.r.t. WWH-EGD)			
Industry	63		-14	-9	-27	-32
Residential	24		1	12	1	-16
Services	45		-22	9	-22	-17
Transformation	28		-13	-2	-16	-6
Transportation	188		-335	-93	-808	-370
Power sector	184		-76	-7	-93	-69
Total	532		-459	-89	-966	-511

In addition, the European Union has constrained that NGEU program foresees that *at least* 37% of the financing mechanisms be addressed to climate action (European Union, 2021) - improving the 30% required in the original MFF. A comparison between the results obtained in this analysis and the EU investment capacity is therefore interesting, though based on assumptions. By considering only the NGEU stimulus, amounting to 750 bn€$_{2018}$, the 37% corresponds to 277.5 bn€$_{2018}$, including grants and loans. Now, comparing with the additional investment needs to go from current EU climate policies to –55% GHG emissions reduction of the EU Green Deal, the green part of the NGEU program represents from 55% to 70% (after conversion in constant euro 2018 and excluding United-Kingdom from the perimeter) of the investment needs calculated by the two models.

3.2.4 Conclusions and policy implications

To comply with Paris Agreement, the European Union has revised its 2050 climate strategy (European Union, 2020a) as well as the 2030 milestone with the EU 2030 Climate Target Plan (European Commission, 2021b). The EU Green Deal, a set of policy initiatives, embracing updated EU climate ambition, has been launched by von der Leyen Commission few months ago before the arrival of the COVID-19 pandemic, which has significantly affected European economies, energy system and citizen lifestyles. This study tried with the support of two applied large-scale modelling tools, the EU-TIMES and NEMESIS models, to deal with these two dimensions: the reinforcement of the EU climate ambition for 2030 and the post-COVID-19 economic recovery in EU. An additional third dimension, which considers potential behavioural changes induced by the previous two, enriches the analysis.

By analysing and comparing a set of scenarios embodying different stories for each dimension, both models delivered some converging results and emphasised some important differences. The two models show relatively similar CO_2 emissions pathways to reach -55% GHG emissions reduction in EU+ in 2030, with around 50% of effort to match the gap with the previous -40% target mainly allocated to the power and supply sector. The transportation sector also contributes significantly, around 20%. It is then followed by the buildings sector and the industry in NEMESIS and inversely in EU-TIMES.

At short term, NEMESIS shows a strong decline of EU+ CO_2 emissions (-12%) and energy consumption (-9% for PEC) resulting from the COVID-19 pandemic. Both models expect moderated impacts in the long run, confirmed by the carbon prices, as values are relatively similar between pre- and post-COVID-19 scenarios.

The models agree on the increase of energy efficiency for the decarbonisation of the EU+ energy system, with an interesting difference. On the one hand EU-TIMES favours CO_2 emissions reduction through fuel shift, with a reduction of the CO_2 intensity of the EU+ primary energy consumption up to 36% between 2019 and 2030 and then more limited energy efficient gains. On the other hand, NEMESIS show important energy efficiency gains, with energy intensity in terms of GDP declining up to 36% between 2019 and 2030, but lower fuels shift. Furthermore, models show that lower fossil fuels prices, as assumed in the limited economic recovery case, may slow down the deployment of renewable energy sources, and that lower economic activity benefits to fossil fuels

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consumption even if it reduces CO_2 emissions.

Behavioural changes (here we limit our analysis on remote working and flights reduction), induced by the COVID-19 pandemic and the raising of environmental concerns, lead to converging results between models for specific sectors (lower energy consumption in transport and higher in residential) but different results for aggregated figures. In EU-TIMES, they contribute to the reduction of the FEC in climate ambitious scenarios, increasing the reduction driven by climate policies by 20%, with a stronger impulse in the short term. Conversely, in NEMESIS they have limited impact. These results emphasise the need of further analysis on the potential contribution of behavioural changes to deep decarbonisation transitions (Trutnevyte et al., 2019; Nikas et al., 2020) and question which policy support to ensure long lasting environmental virtuous behaviour as observed during the COVID-19 pandemic. Furthermore, beyond the impacts on the energy system considered in this study, wider impacts on environment of behavioural changes should be further investigated, for example including long-term impacts of the remote working on land use and private trips (Moeckel, 2017; De Abreu e Silva and Melo, 2018).

Finally, the financial stimulus launched by the European Commission to recover from the COVID-19 pandemic, represented by the Next Generation EU program and in particular the Recovery and Resiliency Facility mechanism, is compared at high level with the results obtained by the two models. The comparison shows the importance of this initiative in supporting the EU energy system toward a green transition. Indeed, the needs to reach the European Green Deal 2030 climate target is assessed 410 bn$€_{2010}$ from 2021 to 2030 by the NEMESIS model, whereas the additional gross investment in the power generation is evaluated around 184 bn$€_{2010}$ by the EU-TIMES model. Considering the share of financing dedicated to the climate action, the Next Generation EU program would cover from 55% to 70% of the investments assessed by the two models.

4 Concluding remarks

This document has compiled the first modelling work of the PARIS REINFORCE modelling exercises at the EU level. The main work has looked at where EU current policies will lead the European CO_2 emissions and energy system in 2030 and in 2050, assuming constant effort after 2030. This analysis has been done with eleven different modelling tools: two global general equilibrium models (GEMINI-E3 and ICES), two global partial equilibrium models (GCAM and TIAM), three energy system models with two global (MUSE and 42) and one EU level one (EU-TIMES), two macro-econometric models with one global (E3ME) and the other at EU level (NEMESIS) and two EU sectoral models (FORECAST and ALADIN). This modelling exercise has allowed going through stakeholders' research questions, that have been collected at the beginning of the project and even if the "Where are We Headed" scenario framework does allow dealing with all the questions, we have already studied a good part of them.

Among key findings, we found that the EU is currently on track to achieving its outdated 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. We also complete the EU-wide figures some with some members states level figures, showing for instance the important German contribution to the 2030 EU CO_2 emissions mitigation efforts, between 25% and 30% of the total in 2030 according to models.

The document delivers also some sectoral detailed results for the buildings, industry and transports sectors. In the buildings sector, the EU current policies do not imply drastic changes. By 2050, coal phase-out is complete, whereas heating oil is not yet phased out and biomass and district heating shares increase reaching around 40%. CO_2 emissions decline by about 30% in 2030 and 50% in 2050 in comparison with 1990 equally driven by energy efficiency and fuel switch. In a more ambitious scenario, the CO_2 emissions reduction reach 70% in 2050, in comparison with 1990, the only remaining fossil fuels in the heating fuel mix in EU is the natural gas, with 37%.

In the industry sector, the EU total final heating energy demand remains relatively stable between 2015 and 2050, biomass and ambient heat gain substantial market shares from 2015 to 2050 leading to a decrease in fossil energy demand for fuel oil (-70%), coal (-62%) and other fossils and then, CO_2 emissions reduce slightly up 2030, around -10% in comparison with 2015, and significantly more in 2050, with -40%, despite emissions from industrial processes declining weakly.

In the transport sector, the market share of passenger electric vehicles in car registrations in the EU rises rapidly reaching more than 50% before 2030 and almost 90% by 2040. For heavy duty vehicles, the battery electric vehicles will dominate the stock of trucks smaller than 3.5 t similar to passenger cars in 2050. For heavy duty vehicles higher (>12t) hybrid Diesel catenary trucks will be the most cost-efficient alternative (following the assumption that electric overhead lines will be partly constructed on European highways). Hydrogen plays a minor and natural gas a neglectable role. Consequently, the electricity demand by the transport sector raises, from 40 TWh (almost entirely for rail transport) to 170 TWh in 2030 and up 640 TWh in 2050 of which 55% for cars, one third for trucks, the remaining for rail transport.

The last section explores the first elements of deep decarbonisation scenario in the EU and especially the Paris Agreement Compliant scenarios. We performed a large literature review on existing quantitative figures for GHG emissions of the Land Use, Land Use Change and Forestry and the Agriculture sectors. LULUCF can absorb between 240 to 340 $MtCO_2$/y. in 2030 and between 250 and 340 $MtCO_2$/y. in 2050 (and even up to 500 $MtCO_2$/y. with a payment for the carbon capture at 150€/tCO_2). For the GHG emissions from Agriculture, mainly methane and nitrous oxide, decarbonisation is more challenging. The projections for agricultural GHG emissions for 2050 are relatively stable compared to 2015 in current policies scenarios, around 400 $MtCO_2$-eq./y. In a more ambitious scenario, the GHG emissions range between 280 and 230 $MtCO_2$-eq./y. in 2050.

These results mean that in an EU carbon neutral economy in 2050, the negative CO_2 emissions for the LULUCF sector will be, from partially to completely, offset by the remaining agricultural GHG emissions, with a net AFOLU GHG emissions between -100 to +170 $MtCO_2$-eq./y in 2050. Then, it means that CO_2 emissions from energy and industrial process should be nearby zero in 2050 and even negative in some cases, pointing the importance of key technologies such as CCS and negative emissions technologies but also of behavioural changes that could limit the extent of their deployment.

Finally, the last section present also a study on the potential the impact of the COVID-19 pandemic on European Green Deal scenarios. EU-TIMES and NEMESIS have run several scenarios that combine: (*i*) two different economic recovery in EU up to 2030 (a full and a limited one), (*ii*) two European climate ambition (current policies and EU 2030 Climate Target, i.e. -55% with respect to 1990) and (*iii*) two potential long-lasting behavioural changes (remote working and fligths reduction) resulting from increasing environmental concerns and COVID-19 pandemic. The two models show relatively similar CO_2 emissions pathways to reach -55% GHG emissions reduction in EU in 2030, with around 50% of effort to match the gap with the previous -40% target mainly allocated to the power and supply sector. The transportation sector also contributes significantly, around 20%. It is then followed by the buildings sector and the industry in NEMESIS and inversely in EU-TIMES. At short term, NEMESIS shows a strong decline of EU CO_2 emissions (-12%) and energy consumption (-9% for PEC) resulting from the COVID-19 pandemic. Both models expect moderated impacts in the long run, confirmed by the carbon prices, as values are relatively similar between pre- and post-COVID-19 scenarios.

Behavioural changes lead to converging results between models for specific sectors with lower energy consumption in transport and higher in residential but different results for aggregated figures. In EU-TIMES, they contribute to the reduction of the FEC in climate ambitious scenarios, increasing the reduction driven by climate policies by 20%, with a stronger impulse in the short term. Conversely, in NEMESIS they have limited impact. Nevertheless, both models comfims that these behavioural change can alleviate the GHG emissions reduction burden.

Finally, both models assessed the investments requirement to achieve the climate target of the European Green deal, that represent 410 billion euro (constant 2010) from 2021 to 2030 in the NEMESIS model, whereas the additional gross investment for the power generation is evaluated around 184 billion euro (constant euro 2010) by the EU-TIMES model. By comparing them with the EU Recovery Plan, the Next Generation EU program targeted towards climate action would cover from 55% to 70% of the investments assessed by the two models.

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Annex I – Where are the EU Member States headed - Results

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Table 54: Deviation of CO2 emissions from energy by Member State across models

	2000	2005	2010	2015	2020			2030			2040			2050		
					EU-TIMES	ICES	NEMESIS	EU-TIMES	ICES	NEMESIS	EU-TIMES	ICES	NEMESIS	EU-TIMES	ICES	NEMESIS
Austria	2.9	14.6	7.0	0.6	21.8		-0.6	2.1		-13.6	0.8		-16.9	-2.7		-19.5
Belgium	2.8	2.5	-4.0	-16.5	-12.6		-25.0	-21.6		-28.1	-29.0		-35.1	-26.9		-36.4
Bulgaria	-29.4	-24.3	-23.9	-24.5	-32.1		-23.7	-34.5		-35.6	-34.7		-38.0	-40.4		-43.7
Croatia	-3.3	0.0	-1.8	-4.9	-1.3		-4.4	-4.7		-8.3	-4.9		-9.2	-5.2		-9.9
Cyprus	2.4	3.2	3.5	2.1	3.7		2.5	3.5		1.5	2.2		0.9	2.2		0.8
Czechia	-33.4	-34.2	-41.9	-54.2	-39.2	-39.3	-54.6	-70.5	-60.8	-76.9	-86.8	-59.6	-92.6	-84.3	-60.7	-99.5
Denmark	0.5	-2.2	-3.7	-17.9	-1.0		-20.8	-28.7		-31.4	-26.6		-34.0	-33.1		-35.6
Estonia	-21.3	-19.6	-17.5	-20.4	-22.0		-15.8	-30.0		-20.1	-29.6		-22.0	-29.4		-23.1
Finland	0.2	0.1	6.6	-12.9	18.8	-32.1	-15.8	-4.7	-32.6	-27.7	-11.1	-32.9	-32.9	-24.3	-34.3	-36.1
France	17.2	28.0	-5.5	-52.9	-62.7	-107.3	-54.8	-148.1	-157.3	-132.9	-150.9	-163.0	-124.7	-173.6	-156.5	-97.5
Germany	-150.0	-177.7	-205.1	-240.2	-244.2	-189.2	-253.5	-384.6	-460.2	-458.7	-570.9	-482.9	-507.9	-581.0	-514.7	-532.7
Greece	19.4	29.6	16.1	-5.4	-0.7	-0.7	-13.4	-29.9	-22.6	-29.9	-40.8	-26.1	-33.5	-40.2	-26.9	-34.6
Hungary	-12.2	-10.6	-17.9	-23.3	-20.8		-19.5	-32.5		-31.7	-28.2		-30.4	-28.2		-31.8
Ireland	11.6	14.8	9.6	5.9	10.4		13.4	-4.0		7.0	-1.5		4.9	-2.6		2.1
Italy	34.2	62.8	3.7	-63.1	-71.4	-158.7	-103.9	-146.1	-177.5	-183.9	-166.4	-206.9	-220.5	-187.0	-237.5	-229.3
Latvia	-11.6	-10.9	-10.5	-11.8	-10.3		-11.0	-11.1		-11.6	-10.7		-11.9	-10.4		-12.3
Lithuania	-21.8	-19.7	-19.7	-21.6	-17.6		-22.3	-24.3		-26.2	-25.2		-27.5	-28.2		-28.5
Luxembourg	-2.2	1.2	0.4	-1.4	4.4		-1.2	-0.1		-3.3	-2.2		-3.9	-2.0		-4.4
Malta	0.1	0.2	0.2	-0.7	0.4		-1.1	-0.1		-1.5	-0.1		-1.5	0.1		-1.6
Netherlands	9.0	15.0	19.9	4.1	-6.2		2.4	-31.4		-30.2	-27.0		-40.3	-40.4		-42.0
Poland	-56.8	-49.6	-38.1	-61.4	-44.3	27.8	-25.9	-137.3	-45.6	-121.5	-136.1	-108.6	-152.7	-130.8	-123.0	-186.8
Portugal	19.1	23.4	8.4	8.0	9.0		3.8	-4.3		-7.1	-6.7		-11.5	-9.1		-13.3
Romania	-63.2	-60.8	-72.5	-77.7	-76.3		-76.8	-79.0		-90.9	-79.2		-93.2	-79.6		-95.0
Slovakia	-19.5	-18.9	-22.6	-27.0	-26.0		-28.7	-32.3		-32.9	-30.0		-34.3	-27.6		-35.2
Slovenia	0.6	1.9	1.7	-1.1	1.3		-0.1	-4.4		-1.4	-5.0		-1.9	-6.1		-4.4
Spain	76.2	130.7	52.4	41.8	34.7	39.4	45.5	-6.9	6.8	-4.4	3.6	1.5	-14.7	-8.2	-5.9	-16.6
Sweden	-2.9	-4.0	-4.8	-14.0	12.8	-14.1	-14.6	-1.8	-20.1	-23.8	-3.4	-21.2	-28.1	-1.9	-24.0	-29.8
United-Kingdom	-29.8	-27.1	-79.2	-168.6	-171.1	-223.4	-196.6	-230.4	-282.3	-262.9	-227.2	-281.4	-270.5	-216.6	-290.3	-273.8
Other EU (ICES)						-226.7			-271.3			-263.2			-255.8	
EU	-261.5	-131.4	-439.2	-858.8	-742.5	-924.3	-916.5	-1 497.9	-1 523.6	-1 688.1	-1 727.4	-1 644.2	-1 883.8	-1 817.5	-1 729.7	-1 970.6

Deviation in MtCO$_2$/y. in comparison with 1990. Historical data from EEA (2020); Other EU (ICES): Austria, Benelux, Bulgaria, Cyprus, Denmark, Estonia, Croatia, Hungary, Ireland, Lithuania, Latvia, Malta, Portugal, Romania, Slovenia and Slovakia.

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Annex II - A Glimpse of the current EU Climate Policies

The EU commits to progressively reduce its greenhouse gas emissions with ambitious climate targets up to the year 2050. The EU Climate Strategies and Target consist of the 2020 Climate and Energy Package, followed by the 2030 Framework. The regulation includes a target on GHG emission abatement, renewables, and energy efficiency. It defines to put the EU on the path towards becoming a climate-neutral economy where targets are escalated between decades and potentially revised for higher abatement in line with the EU's long-term strategy of net-zero emissions and climate neutrality in 2050.

The EU ETS is a cornerstone of the EU's policy to combat climate change and its essential tool for reducing greenhouse gas emissions cost-effectively. The abatement target for EU ETS is more binding with a 43 percent reduction in 2030, from 21 percent in 2020 relative to the 2005 level. On the other hand, the Effort Sharing legislation establishes binding annual greenhouse gas emission targets for the Member States for the periods 2013–2020 and 2021–2030. These targets concern emissions from other sectors than EU ETS, such as transport, buildings, agriculture, and waste. The target for non-ETS sectors is expected to grow to 30 percent abatement in 2030 that has been translated as an individual's binding target for the Member States.

In terms of Climate Funding, the new EU innovation fund focuses on supporting the innovation of low carbon technologies in energy-intensive industries and Carbon Capture and Utilization (CCU). The fund also supports the construction and operation of CCS technology and innovative renewable energy generation. It will provide around EUR 10 billion of support over 2020-2030 to demonstrate innovative low-carbon technologies, aiming to bring to the market industrial solutions to decarbonize Europe and support its transition to climate neutrality. These innovation funds succeed the NER 300 Program. The unspent funds from withdrawn projects under the second NER 300 call, amounting currently to some EUR 735 million, will be channelled into this new funding mechanism.

The EU also sets new emission standards for transportation for each vehicle, fuel quality, shipping, and the aviation industry. The targets are more binding and defined as a percentage reduction from 2021 starting points. Incentives mechanism is provided for Zero and Low Emission Vehicles (ZLEV). At the same time, fuel quality is directed to significantly reduce GHG intensity and sustainability of biofuels as the alternative. A significant abatement target for the shipping and aviation industry is complemented by reliable monitoring, verifying, and reporting systems.

Additional action in EU law for 2021-2030 also incorporates land use and forestry into the EU's emission-reduction efforts for the first time. The approach to REDD+ builds on Forest Law Enforcement, Governance, and Trade Action Plan and international initiatives. Approximately €25 million a year is committed to initiatives piloting REDD+ in Asia, Africa, and Latin America. While for the energy used for building is managed through the Energy Performance of Buildings Directive that covers a broad range of policies and supportive measures to boost the energy performance of buildings and improve the existing building stock.

The Commission proposed to raise the 2030 GHG reduction target, including emissions and removals, to at least 55 percent compared to 1990. In December 2020, EU leaders agreed on this more ambitious goal for cutting greenhouse gases. Europe is currently on track to achieving the target of 40% emissions cuts, but still far from this newest ambition of 50-55% cuts by 2030 and net-zero emissions in 2050.

Aligning the short-term emissions target and to EU long-term strategy and the European-Green Deal is critical to achieving this new target. Table A.1 to A.5 lists the EU Climate policy currently in force for 2030 and 2050 climate targets.

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Table AII.1 Climate Strategies & Target

NO	Regulation	Sectoral Targets				Notes
		ETS Sectors	**Non ETS Sectors**	**Energy Efficiency**	**Renewable**	
a.	***2020 Climate & Energy Package*** • 20% cut in GHG from 1990 levels • 20% of EU energy from renewables • 20% improvement in energy efficiency	Emissions **21%** lower than in 2005	**Effort-Sharing Decision** The targets differ according to national wealth from a 20% cut for the richest countries to a maximum 20% increase for the least wealthy than in 2005		• **Targets are varied**: to reflect countries' different starting points for renewables production and ability to further increase it – from 10% in Malta to 49% in Sweden. • **10%** share of renewables in the transport sector.	
b.	***2030 Climate & Energy Framework*** • At least 40% cuts in GHG from 1990 levels* • At least 32% share for renewable energy • At least 32.5% improvement in energy efficiency	Emissions cut by **43%** compared to 2005	Cut emissions by **30%** compared to 2005 – this has been translated into individual binding targets for Member States	At least **32.5%** for energy efficiency to be achieved collectively by the EU in 2030, with an upward revision clause by 2023.	At least **32%** of final energy consumption	
c.	***The 2030 Climate Target Plan°*** • New GHG reduction target by 2030 compared to 1990 of at least 55% including emissions and removal.	• Expand Existing ETS sectors to Road Transport & Building. • Strengthening Cap of EU ETS -65% compared to 2005 for stationary ETS source (without extending the ETS scope)**	Carbon Pricing & Other Complementarity Policy Actions -39 to -40% compared to 2005 without changing the ESR scope)**		**Renewable Penetration Target in 2030)**** • At least 65% share of renewable electricity. • 40% in Heating and Cooling. • 24% renewable share in transportation. • At least 38-40% of final energy consumption.	Climate Target Plan of 55% (approved in December 2020) will be followed by revision on targets of renewable energy, energy efficiency and transport energy standard. **The current reported targets on ETS, Non ETS and Renewable Sectors are based on *Impact Assessment Report**

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						complement to The EU Communication Report.
d.	**European Climate Law - 2050 Long-Term Strategy** • Net Zero Emission / Climate Neutrality 2050 • Keep the global temperature increase to well below 2°C and pursue efforts to keep it to 1.5°C.					

Source : *https://ec.europa.eu/clima/policies/eu-climate-action_en*

https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562

* : *https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/impact_en.pdf*

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Table AII.2 Innovation Funds

NO	Regulation	Policies/ Targets	Notes
a.	**General Funds**, focus on:	• Innovative low-carbon technologies and processes in energy intensive industries, including products substituting carbon intensive ones • Carbon capture and utilization (CCU) • Construction and operation of carbon capture and storage (CCS) • Innovative renewable energy generation • Energy storage	• The EU Emissions Trading System (EU ETS), the world's largest carbon pricing system, is providing the revenues for the Innovation Fund from the auctioning of 450 million allowances from 2020 to 2030 • EUR 10 billion of support over 2020-2030 for the commercial demonstration of innovative low-carbon technologies
b.	Carbon Capture and Geological Storage CCS Directive	Coherent implementation of the CCS Directive throughout the EU.	
c.	Carbon Capture and Geological Storage NER 300 Program	Unspent funds from withdrawn projects under the second NER 300 call (EUR 735 million) will be channeled into the Innovation Fund	

Source : https://ec.europa.eu/clima/policies/innovation-fund_en

Table AII.3 Building

NO	Regulation	Policy Target
	Energy Performance of Buildings Directive (EPBD) (2018/844/EU)	The EPBD covers a broad range of policies and supportive measures that will help national EU governments boost energy performance of buildings and improve the existing building stock
		EU countries must make energy efficient renovations to at least 3% of the total floor area of buildings owned and occupied by central government. National governments are recommended to only purchase buildings that are highly energy efficient.

Source : https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

Table AII.4 Forestry & Agriculture

NO	Regulation	Policy Target
a.	**LULUCF**	• The European Commission now aims to enshrine the principle of an equivalent absorption of CO_2 made possible by additional action in the sector (no-debit rule) in EU law for the period 2021-2030, by incorporating land use and forestry into the EU's emission-reduction efforts for the first time. • The actions of forest owners and farmers to secure carbon stored in forests and soils will thus contribute to achieving the EU's commitment under the Paris Agreement on climate change.
b.	**REDD+**	• The EU's approach to REDD+ builds on its Forest Law Enforcement, Governance and Trade (FLEGT) Action Plan as well as international initiatives such as the REDD+ Partnership, the Forest Carbon Partnership Facility (FCPF) the EU REDD Facility, and the UN-REDD program. • The European Commission commits approximately €25 million a year to initiatives piloting REDD+ in Asia, Africa and Latin America. • The need to scale up financing for REDD+ is implicit in the pledge by developed countries to mobilize climate finance of $100 billion per year to the developing world by 2020.

Source : https://ec.europa.eu/clima/policies/forests_en

Table AII.5 Transportation

NO	Regulation	Policy Target
a.	**Road Transport** Cars and Vans Regulation (EU) 2019/631 per 1 Jan 2020	•These targets are defined as a percentage reduction from the 2021 starting points: • Cars: 15% reduction from 2025 on and 37.5% reduction from 2030 on • Vans: 15% reduction from 2025 on and 31% reduction from 2030 on
		• From 2021, phased in from 2020, the EU fleet-wide average emission target for new cars will be 95 g CO2/km.
		• The specific CO2 emission target of a manufacturer will be relaxed if its share of zero- and low-emission vehicles (ZLEV) registered in a given year exceeds the following benchmarks: • Cars: 15% ZLEV from 2025 on and 35% ZLEV from 2030 on • Vans: 15% ZLEV from 2025 on and 30% ZLEV from 2030 on
b.	**Road Transport** Heavy Duty Vehicles Regulation (EU) 2019/1242	• The targets are expressed as a percentage reduction of emissions compared to EU average in the reference period (1 July 2019–30 June 2020): • from 2025 onwards: 15% reduction • from 2030 onwards: 30% reduction
		• Incentive mechanism for zero- and low-emission vehicles (ZLEV) • Vehicle Energy Consumption Calculation Tool - VECTO
c.	**Fuel Quality** Emissions reporting covers full life-cycle Council Directive (EU) 2015/652	• The Fuel Quality Directive requires a reduction of the greenhouse gas intensity of transport fuels by a minimum of 6% by 2020. • Emissions reductions are calculated against a 2010 baseline of 94.1 gCO2eq/MJ.
d.	**Fuel Quality** Biofuel sustainability	• Greenhouse gas emissions from biofuels must be lower than from the fossil fuel they replace – at least 50% (for installations in operation before 5 October 2015) and 60% for installations starting operation after that date. • The feedstocks for biofuels cannot be sourced from land with high biodiversity or high carbon stock. • The number of biofuels produced from cereal and other starch-rich crops, sugars and oil crops and from energy crops grown on agricultural land that can be counted as a sustainable source of renewable energy is limited to 7% of the energy in transport in the Member States in 2020
d.	**Shipping** the IMO agreed in April 2018	• Reduce total annual GHG emissions from shipping by at least 50% by 2050 compared to 2008 levels • Pursue efforts to phase them out as soon as possible in this century.
e.	**Aviation**	• CO2 emissions from aviation have been included in the EU emissions trading system (EU ETS) since 2012. • Under the EU ETS, all airlines operating in Europe, European and non-European alike, are required to monitor, report and verify their emissions, and to surrender allowances against those emissions • The system has so far contributed to reducing the carbon footprint of the aviation sector by more than 17 million tonnes per year, with compliance covering over 99.5% of emissions.
		Airlines will be required to monitor emissions on all international routes; Offset emissions from routes included in the scheme by purchasing eligible emission units generated by projects that reduce emissions in other sectors (e.g. renewable energy). During the period 2021-2035, and based on expected participation, the scheme is estimated to offset around 80% of the emissions above 2020 levels.

Source : https://ec.europa.eu/clima/policies/transport_en

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Table AII.6 Non CO2 Emissions

Regulation	Policy Target
F Gases Regulation (EU) 517/2014	By 2030, the Regulation will cut the EU's F-gas emissions by two-thirds compared with 2014 levels (or 35% of 2015 level)

Source : https://ec.europa.eu/clima/policies/f-gas_en

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