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BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

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Note about contributors

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SENTINEL

SUSTAINABLE ENERGY TRANSITIONS

SENTINEL
SUSTAINABLE ENERGY TRANSITIONS

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Executive Summary

Although energy system models have become more complex, it does not necessarily mean that they are better suited to answer the questions, or address the challenges, faced by decision- and policymakers. To increase the usefulness of models as decision-making tools, the SENTINEL project explicitly addresses critical issues and challenges of the European energy transition towards climate neutrality by 2050, as these were identified and validated through a series of structured stakeholder engagement activities. At the same time, the project seeks to increase the transparency and the understandability of modelling tools and assumptions by providing accompanying documentations for each model.

In this report, we showcase the applicability and usefulness of the SENTINEL modelling suite in the context of three case studies, as these have been specified in the SENTINEL Deliverable 7.1 (Stavrakas et al., 2021), namely: **a.** a **Continental** level case study (European Union, Iceland, Norway, Switzerland, the United Kingdom, and some Balkan countries), **b.** a **Regional** level case study (Nordic countries), and **c.** a **National** level case study (Greece). Specifically, this report provides details on input data, as well as model linkages and results, and serves two purposes. It provides **(i).** detailed specifications for the application of the SENTINEL models in the context of policy-relevant scenarios and energy and climate targets, and **(ii).** answers to stakeholders' critical research questions through scientific evidence from the SENTINEL models. These research questions have already been collected for different stakeholder groups around Europe in the context of Deliverable 7.1. In this follow-up deliverable, we present the results from the SENTINEL modelling ensemble to **76 different research questions** across all the three case studies, covering all the thematic areas that were considered critical for the European transition according to stakeholders.

To answer the research questions that were extracted based on the insights, preferences, and the domain knowledge of the different stakeholder groups, and instead of only using the SENTINEL models individually, which is often the typical approach followed by modelling projects, we made sure to also develop soft-linkages between the models, where appropriate. This holistic approach enabled us to generate results to more complex research questions, in which individual model runs often fail to answer. For example, we have strengthened the integration of political and social processes and preferences, enabling demand models to produce more realistic results on future energy demand, and energy systems and economic models to provide novel results on possible energy system designs and their distributional economic effects conditioned by different governance conditions. Furthermore, we have broadened the scope for environmental impacts of the energy transitions beyond greenhouse gases, such as demand for land and raw materials. As a last example, we have enabled the coupling of partial equilibrium generation capacity calculations with detailed power plant dispatching, to capture both high-level power generation requirements and deeper portfolio planning constraints.

Modelling results relevant to the **power sector's transformation** showcase that a significant capacity expansion of renewable energy sources would be required to achieve ambitious emission reduction targets,

and that the need for system flexibility will greatly increase, both on the supply and demand sides, to enable this expansion. Such solutions include both long-term (e.g., electrolysers paired with hydrogen-fuelled generation units, thermal storage, etc.) and short-term storage options (e.g., batteries, etc.) coexisting and complementing each other in the provision of power system services. The expansion of transmissions lines depends on the 'design-perspective' of the renewable capacity buildout, with significant upgrades required in a centralised vision with large renewable plants, while hardly any expansion would be needed in a decentralised vision with strong regional expansion of renewable energy. In any case, the transition from the current regime to a low-carbon power sector would need to consider potential lock-ins to intermediate technologies, such as natural gas, which could decrease European energy security, and increase import dependency. Modelling results suggest that a faster expansion of renewable capacity compared to investments in intermediate solutions would mitigate these risks.

Furthermore, modelling results show that **demand-side changes** could also play a significant role in achieving the overall vision of carbon neutrality. The potential for energy demand reduction in the European transport sector is large, while the industry sector presents inertia. However, electrification in both sectors is expected to become significant, which would decrease fossil-fuel extraction and use, and consequently direct fossil carbon dioxide emissions. Buildings also have a high potential to contribute to climate neutrality by reducing thermal energy demand through energy-efficiency improvements. Results suggest that achieving decarbonisation in the building sector by 2050 is possible but would require a higher annual rate of high-efficiency renovations and new buildings than currently prescribed, which would also require strong political support to accelerate the implementation of measures. A highly effective measure for the sector is the replacement of old heating systems with energy-efficient heating, ventilation, and air-conditioning systems, such as heat pumps. In fact, investments in heating electrification could lower total costs compared to investments in natural gas as a transition fuel.

Overall, increasing electrification across all sectors is expected to cause changes in total and hourly power demand, which could potentially increase peak demand. In this context, **sector coupling** can provide the necessary flexibility to the power system and ensure an adequate balance between energy supply and demand. Sectoral contributions towards integration include: **a.** flexibility provision through demand-response services from the electrified transport fleet, or production of synthetic fuels using surpluses of renewable generation, **b.** storage of waste heat from industrial processes as a cost-efficient alternative to the use of batteries, or use of it to fuel district heating networks and electrify parts of the supply through large-scale heat pumps, or **c.** production of synthetic fuels from capture and utilisation and electrolysis complemented with sustainable bioenergy products to decarbonise industrial processes and stabilise the power system during low solar and wind generation.

In addition to technoeconomic assessments, SENTINEL models also shed light on the **environmental impacts** of the energy transition. Our results indicate that a potential increase in biomass use by 2050 would lead to a significant increase in land use for energy crops in Europe. Interestingly, while greenhouse-gas emissions in sectors outside the emissions trading system could decrease by more than half until 2050, the largest part of these emissions could come from land use by 2050, highlighting the impact of land-use increase. In this context, we highlight that greenhouse-gas emission reductions should not be looked at solely, as the effect of the energy transition on other aspects (such as for example, human toxicity, human health, water depletion, particulate matter formation, terrestrial acidification, etc.) may be negative. Furthermore, modelling results highlight a major issue with respect to raw material depletion. While efforts have begun to expand intermittent renewables and need to be intensified to reach climate neutrality, wind and solar technologies may be exposed to increased risks regarding the availability of critical raw materials.

Finally, modelling outcomes also highlighted **socioeconomic implications** of different energy system configurations built under diverse socio-political storylines. A key takeaway is that an absolute decoupling of emissions (declining) and economic activity (rising) is possible. Yet not all configurations have the same economic costs and distributional effects. Interestingly, we show that although a people-powered, decentralised energy system has the highest system cost, it has the largest economy-wide welfare benefits, including positive aggregate EU27+ employment effects by 2030 and by 2050.

Abbreviations & Acronyms

ATOM	Agent-based Technology adOption Model
BC	Black Carbon
BEV	Battery Electric Vehicles
BEVPO	Battery Electric Vehicle Potential
BSAM	Business Strategy Assessment Model
C-	Cluster
CCGT	Combined Cycle Gas Turbines
CCS	Carbon Capture and Sequestration
CCUS	Carbon Capture Utilisation and Storage
CN	Carbon Neutrality
CNB	Climate Neutral Behaviour
CNN	Carbon Neutral Nordic
CO_2	Carbon Dioxide
COVID-19	Coronavirus Disease 2019
CRF	Capital Recovery Factor
CRM	Critical Raw Material
CS	Case Study
DC	Direct Current
DNK	Denmark
DESSTINEE	Demand for Energy Services, Supply and Transmission in EuropE
DH	District Heating
DR	Demand-Response
DREEM	Dynamic high-Resolution dEmand-sidE Management
DSM	Demand-side Management
EPBD	Energy Performance of Buildings Directive
EC	European Commission
EEM	Energy-efficiency measures
EFTA	European Free Trade Association
EMMA	Electricity Market Model
EMS	Energy-Mix-Shift
ENBIOS	Environmental Impacts and Constraints
ENTRANZE	Policy to ENforce the TRAnsition to Nearly Zero Energy buildings in the EU
ENTSO-e	European Network of Transmission System Operators for Electricity
ENTSOG	European Network of Transmission System Operators for Gas
EoLRIR	End-of-Life Recycling Import Rate
ETS	Emissions Trading System
EU	European Union
EV	Electric Vehicles
FEC	Final Energy Consumption
FIN	Finland
FiT	Feed-in Tariff
GDI	Government-directed
GDP	Gross Domestic Product
GHG	Greenhouse Gas

GU	Generating Unit
H_2	Hydrogen
HDD	Heating Degree Days
HEB	High Efficiency Buildings
HVAC	Heating, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
IMAGE	Integrated Model to Assess the Global Environment
IPTO	Independent Transmission System Operator
ISL	Iceland
LCA	Life-Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Costs of Energy
LCSE	Levelized Cost of Saved Energy
LLF	Light Liquid Fuel
LTS50	Long-Term Strategy for 2050
LULUCF	Land Use, Land-Use Change and Forestry
MDR	Market-driven
NCES	Nordic Clean Energy Scenarios
NECP	National Energy and Climate Plan
NEM	Net Metering
NERC	Nordic Energy Research Council
NETP	Nordic Energy Technology Perspectives
NMVOC	Non-methane volatile organic compounds
NOR	Norway
NPH	Nordic Powerhouse
NTC	Net Transfer Capacity
OC	Organic Carbon
OCGT	Open Cycle Gas Turbines
P2X	Power-to-X
PHEV	Plug-in Hybrid Electric Vehicles
PMV	Predicted Mean Vote
PPC	Public Power Corporation S.A.
PPO	People Powered
PV	Photovoltaics
QCW	QTDIAN-Calliope-WEGDYN
QTDIAN	Quantification of Technological Diffusion and Social Constraints
RCP	Representative Concentration Pathways
(V)RES	(Variable) Renewable Energy Sources
RE	Renewable Electricity
RF	Reference
RGI	Renewable Grid Initiative
RQ	Research Question
SARSA	State Action Reward (next)State (next)Action
SENTINEL	Sustainable Energy Transitions Laboratory

SMP	System Marginal Price
SSP	Shared Socioeconomic Pathways
SWE	Sweden
TABULA	Typology Approach for Building stock Energy Assessment
TDO	Top-Down Only
TYNDP	Ten-Year Network Development Plan
UPRC	University of Piraeus Research Centre
VOC	Volatile Organic Compound
WP	Work Package
WT	Wind Turbine

1. Introduction

1.1. Background

The European Green Deal is the European Union's (EU) framework to combat climate change and environmental degradation, laying the groundwork for Europe to be the first continent to achieve climate neutrality by 2050 (European Commission, 2019a). Critical issues and challenges with regards to Europe's transition to climate neutrality necessitate the coordinated action of numerous stakeholders and imply multifaceted trade-offs (Stavrakas et al., 2021). This increases the complexity of energy and climate decision-making, and thus, model-based policy advice has become of paramount importance (Süsser et al., 2021b). In this respect, over the last years, energy system models have proven to be a valuable tool for understanding the dynamics of the energy system, and for supporting well-informed decision- and policymaking, as they are able to simulate multiple energy transition scenarios and pathways as well as to reflect on different possible energy system evolutions (Michas et al., 2020; Süsser et al., 2020).

However, there has been a long-expressed concern about the legitimacy of energy and climate modelling tools (Schneider, 1997). For example, it remains an open question why should, and to what extent do model users have confidence in modelling outputs (Iyer and Edmonds, 2018). Given also the increased granularity that has come with designing an energy system based on high shares of renewable energy sources (RES), models' complexity has grown to the point where it is extremely difficult to comprehend why they produce the results that they do (Welsch et al., 2014). To attain full decarbonisation based on legitimate and trustworthy modelling results, the energy and climate modelling community must collaborate among themselves, as well as work closely with numerous stakeholders representing government, industry, research/academia, and civil society, and generate transdisciplinary strategies (Pade-Khene et al., 2013).

In this context, the SENTINEL[1] project is developing an open-source modelling platform that attempts to explicitly address critical issues of the European energy transition towards climate neutrality, while ensuring the clarity of modelling algorithms and assumptions by providing accompanying documentations for each model. This modelling platform provides a resilient and robust approach by establishing a modelling framework in which different models can be combined in a modular way to answer stakeholders' pressing questions, as identified, or validated through structured engagement activities (Stavrakas et al., 2021). A key objective of SENTINEL is to apply this modelling platform to a variety of user applications, while also considering stakeholders' and model users' insights and needs (Gaschnig et al., 2020), to test its usefulness in a variety of contexts.

To this end, WP7 includes a set of case studies at three different geographical levels as depicted in **Figure 1**: National (Greece), Regional (the Nordic region), and Continental (EU, Norway, Switzerland, the United

[1] https://sentinel.energy/

Kingdom, and some Balkan countries), with diverse energy transition issues and challenges that policymakers might face in the future. These cases were chosen to represent different spatial scales of the European energy transition as well as geographical contexts with varying demographic, economic, energy and climate characteristics, as well as different governance levels. In this regard, Greece is an interesting case because it has a relatively isolated energy system, whereas the Nordic countries deregulated their electricity markets in the early 1990s and integrated them into a common Nordic market (Nord Pool, 2020). Finally, the European energy system encompasses a wide range of geographical contexts under one umbrella.

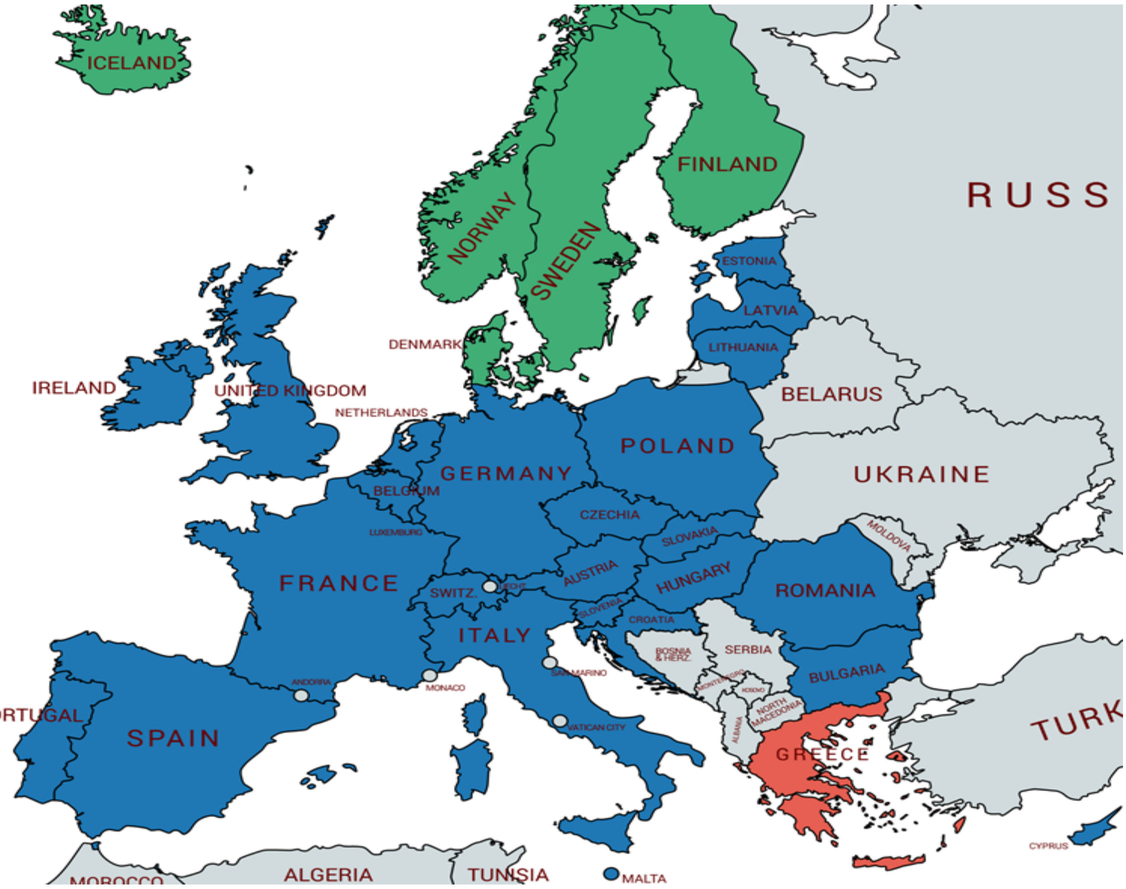


Figure 1. SENTINEL case studies: **a. National** level case study (Greece), **b. Regional** level case study (Nordic region), and **c. Continental** level case study. Source: (Stavrakas et al., 2021).

1.2. Objectives and scope of this deliverable

Deliverable 7.1 prepared the ground for the application of the SENTINEL modelling framework in the three case studies. Reference and disruptive energy transition scenarios leading to climate neutrality have been specified at the national, regional, and continental levels. In addition, a large number of research questions (RQs) has been compiled and grouped according to their relevance using the "Three types of knowledge" tool (Swiss Academies of Arts and Sciences: Network for Transdisciplinarity Research, 2020). The "Three types of knowledge" tool serves in formulating RQs in order to check what knowledge demands the questions meet. The generated questions stress different types of required knowledge, namely: **(i)** "*Knowledge about what is*" or "*System knowledge*", which in our case reflects the status quo of the energy transition ("*Where we are*"),

(ii) "*Knowledge about what should be*" or "*Target knowledge*", i.e., energy targets and scenarios by sector ("*Where we want to get to*"), and **(iii)** "*Knowledge about how we come from the point where we are, to the point where we should be*" or "*Transformation knowledge*", meaning the policy tools and technological configurations needed to achieve climate and energy targets ("*How do we get there*").

In this deliverable, we test the applicability and show the usefulness of the updated models in the context of the SENTINEL case studies. In particular, the report includes details on input data, as well as model linkages and results, and serves two key objectives: **I.** it provides the specifics for model applications in the context of policy-relevant scenarios and energy and climate targets, and **II.** it provides an opportunity for stakeholders to observe the value added from the SENTINEL models, by answering critical RQs. The main research question guiding this work is: "*How would energy systems in different geographical contexts around Europe evolve in light of the goal of climate neutrality by 2050?".* **Table 1** presents a brief description of the SENTINEL modelling framework.

Table 1. The SENTINEL modelling framework.

Work Package (WP)	Model	Description
WP2: Social and environmental transition constraints	Quantification of Technological Diffusion and Social Constraints (**QTDIAN**)	**QTDIAN** includes qualitative and quantitative descriptions of social and political drivers and constrains of the energy transition. The main objective of this toolbox is to provide socio-political storylines and empirical data to improve the representation of social and political aspects in existing energy system models.
	Environmental Impacts and Constraints (**ENBIOS**)	**ENBIOS** helps energy modellers to include environmental concerns in their models. It combines the ability of life-cycle assessment (LCA) processes to provide detailed environmental impacts and resource-use indicators with the ability of the multi-scale integrated analysis of societal and ecosystem metabolism approach to analyse the metabolism of a system.
	Agent-based Technology adOption Model (**ATOM**)	**ATOM** simulates the expected effectiveness of technology adoption under policy schemes and allows to quantify uncertainties related to agents' (e.g., consumers/citizens, households, etc.) preferences. The novelty of the model lies in obtaining realistic uncertainty bounds and splitting the total model output uncertainty in its major contributing sources, while accounting for structural uncertainty.
WP3: Energy demand	Demand for Energy Services, Supply and Transmission in EuropE (**DESSTINEE**)	**DESSTINEE** investigates the effects of demographic, economic, and technological changes on future final energy demand and power supply, both at a yearly and an hourly dimension. It has a country-level geographical resolution, which can easily be expanded to cover sub-regions within a country. The model has been used for simulating load curves under different decarbonisation scenarios.
	High Efficiency Buildings (**HEB**)	**HEB** calculates energy demand of the residential and tertiary building sector under four different scenarios until 2060, based on macroeconomic indicators and technological development. It includes detailed technological information for the building sector and benefits from certain macroeconomic and sociodemographic data, i.e., population, urbanisation rate, and floor area per capita.
	Dynamic high-Resolution dEmand-sidE Management (**DREEM**)	**DREEM** serves as an entry point in Demand-Side Management (DSM) modelling in the building sector, by expanding the computational capabilities of existing Building Energy System models, by not only calculating energy demand, but also by assessing the benefits and limitations

		of demand-flexibility, primarily for consumers as well as for other power actors involved.
	Battery Electric Vehicle Potential (**BEVPO**)	**BEVPO** creates car traffic and parking density maps given the time that vehicles need to travel between different city zones throughout an entire day. The resolution of the model depends on the granularity of travel-time measurements, deriving from Origin-Destination matrices. Its accuracy in space is dependent on the arbitrary granularity with which the modeller divides a city into different zones.
WP4: System design	**Euro-Calliope**	**Euro-Calliope** models the greenfield deployment of components of the energy system at a sub-national level, in 98 regions across 35 countries in Europe, as a linear programming problem. Its objective function is to minimise total system costs. The model is set up at an hourly resolution for a full year, and it deploys technologies overnight to fulfil hourly demand in each modelled region.
	Advanced Energy Systems Analysis Computer Model **(EnergyPLAN)**	**EnergyPLAN** simulates the operation of national energy systems on an hourly basis, including the electricity, heating, cooling, industry, and transport sectors. The key objective is to model a palette of options for the energy system so that they can be compared with one another, rather than model one 'optimum' solution based on defined pre-conditions.
	Integrated Model to Assess the Global Environment (**IMAGE**)	**IMAGE** is suited to large scale and long-term assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. The model identifies socioeconomic pathways and projects the implications for energy, land, water and other natural resources, subject to resource availability and quality.
WP5: Economic impacts	Electricity Market Model (**EMMA**)	**EMMA** is a technoeconomic model that models the dispatching of, and the investment in power plants, minimising total costs with respect to investment, production, and trade decisions, subject to a large set of technical constraints. In economic terms, it is a partial equilibrium model of the wholesale electricity market with a focus on the supply side.
	Business Strategy Assessment Model (**BSAM**)	**BSAM** is an agent-based model which simulates the Day-Ahead Scheduling of wholesale electricity markets. It consists of three main modules that model: **(i)** the bidding strategy of generating units (GUs), **(ii)** market operations, e.g., spinning reserves, residual demand, price caps, curtailment, etc., and **(iii)** the cost-optimal dispatching of GUs.
	WEGDYN computable general equilibrium model **(WEGDYN)**	**WEGDYN** is a global multi-region, multi-sector, multi-agent economic impacts model built to analyse economy-wide effects from local system intervention and to isolate corresponding feedback effects. The main modelling mechanism concerns changes in relative prices across input and factor markets leading to changes in the structure of production, consumption patterns, and international trade relations.

To answer the RQs identified in Deliverable 7.1, several links between the SENTINEL models have been established. Model interlinkages allowed to address inquiries, which individual models would lack the capacity or would require a significant amount of input parameter assumptions to do so. All potential model linkages were identified and established in the context of the modelling WPs, namely WP2, WP3, WP4, and WP5 (**Table 1**), while in Deliverable 7.2, a subset of these linkages has been applied based on the needs in each case study (CS). **Figure 2** presents an overview of the SENTINEL model linkages used in the context of the SENTINEL CSs, while more detailed descriptions are provided in **Sections 3.1.2.9** and **3.3.2.9**.

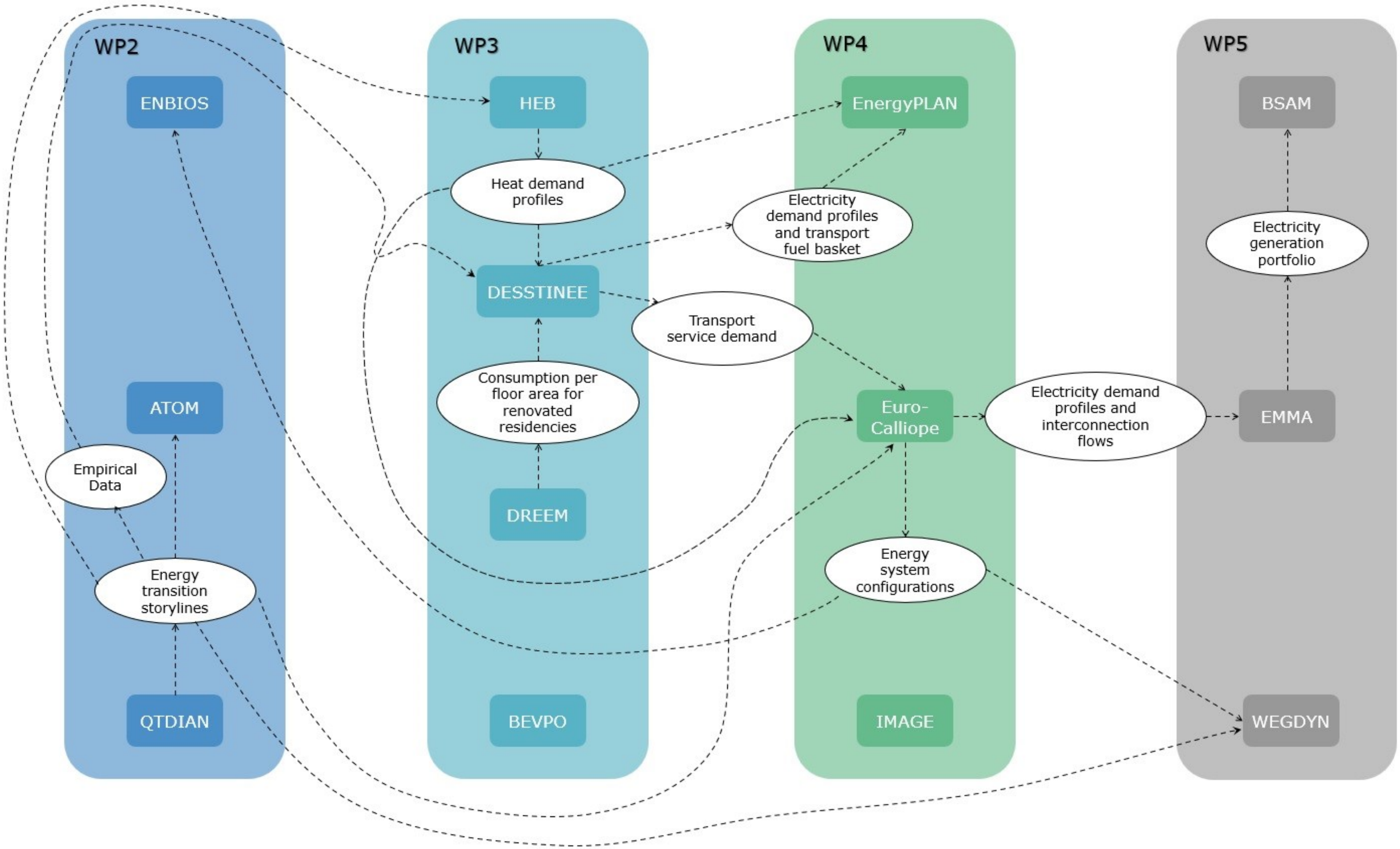


Figure 2. Linkages established in the context of the application of the SENTINEL modelling framework to the three SENTINEL case studies.

1.3. Structure of this deliverable

The remainder of this deliverable is structured as follows: **Section 2** summarises the analytical framework employed for coordinating the SENTINEL model application process in order to provide answers to part of the RQs identified in the context of Deliverable 7.1. **Section 3** presents updates to the CS scenarios, model assumptions, model linkages, and simulation results for the various RQs in each CS. Finally, **Section 4** synthesises key modelling outcomes across CSs and discusses the thematic coverage of RQs addressed by the SENTINEL modelling framework, identifying in parallel areas of further improvement in the field of energy system modelling.

2. From case specification and scheduling to coordination of model application

To test the applicability and the usefulness of the updated modelling framework in the context of the SENTINEL CSs, we applied a three-step approach, in order to reach from the general set of RQs (as derived in Deliverable 7.1) to structured subsets/clusters of RQs for which the modelling teams could provide meaningful results. Our approach consisted of three steps as shown in **Figure 3**, which took place during the period March 2021-July 2022:

i. **(i) Matching** the RQs that were identified under the Deliverable 7.1 to the different models' capacities, so that the SENTINEL modelling teams get a better understanding of the context to which they should apply their models.

ii. **(ii) Clustering** the RQs based on their thematic relevance to the SENTINEL modelling tools for each one of the SENTINEL CSs.

iii. **(iii) Coordinating** the model application process, i.e., data exchange between models, model calibration based on historical and census data and CS specifications, model simulation, as well as reporting of modelling results.

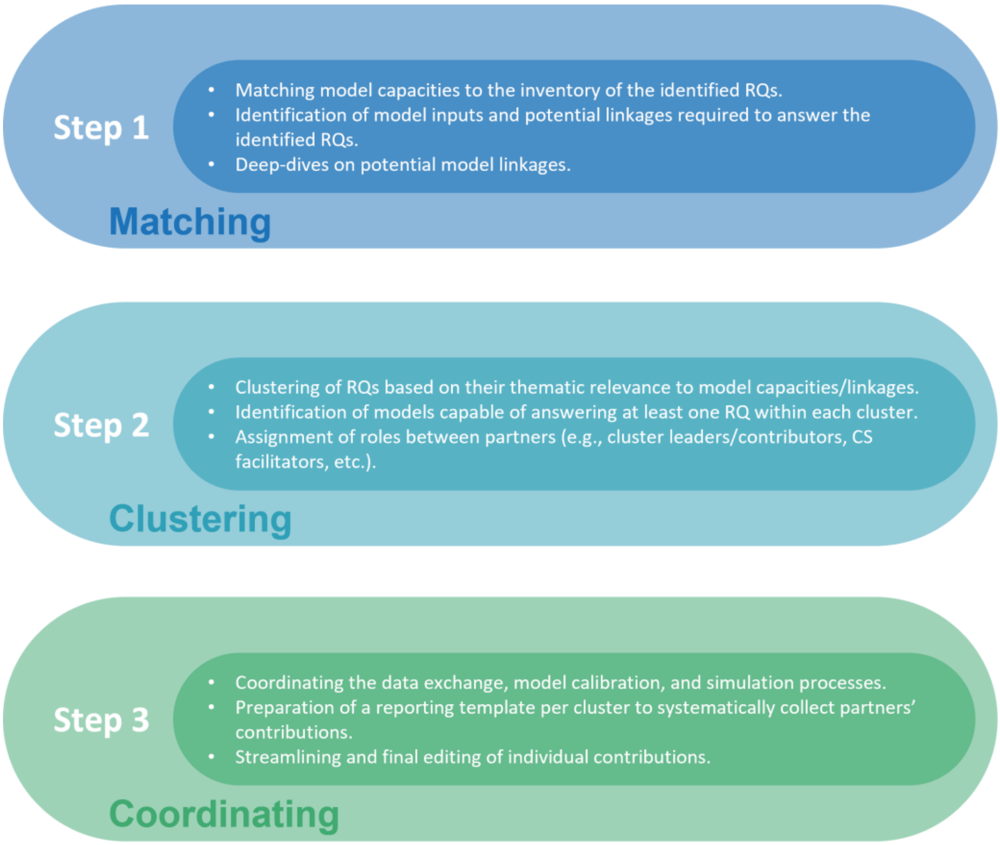


Figure 3. Three-step approach used to validate the applicability and the usefulness of the SENTINEL modelling framework in the context of the three SENTINEL case studies.

In particular, as a first step, during the period March-September 2021, the inventory of the identified RQs was discussed with the SENTINEL modelling teams for each one of the SENTINEL CSs. For each CS, we have asked each one of the modelling teams to indicate the RQs that their models could potentially answer, those that should be rephrased/restructured in order to be answered, as well as the RQs that could not be answered due to model constraints. After collecting this feedback, we organised a first round of intra-WP online modelling workshops to discuss model capacities in terms of answering the final set of RQs. During these meetings, modellers could confirm their initial answers, reflect on them, and start discussing potential model linkages with other modelling teams. In this context, modellers provided feedback on the simulation feasibility of the different CS scenarios, historical data, census data and other CS specifications (i.e., variables/parameters and assumptions) necessary to calibrate their models, required model inputs and expected outcomes, and potential model linkages for answering the identified RQs in each CS. We should also note that since the engagement activities with the SENTINEL stakeholders is an ongoing procedure, some additional RQs have been elicited by SENTINEL partners after the finalisation of Deliverable 7.1, which reflect stakeholder inquiries that have risen given new developments around Europe and respective implications to the case study contexts (e.g., the energy crisis stemming from Russia's invasion of Ukraine). These RQs are denoted as "**RQNX**" in **Section 3**, with X representing the incremental number of each new RQ.

Table 2 summarises the intra-WP workshops that took place in summer 2021, including the total involvement of the SENTINEL models and the RQs discussed.

Table 2. Summary of the online intra-Work Package (WP) modelling workshops held to match the identified research questions to the different models' capabilities in each one of the SENTINEL case studies.

	Greek		***Nordic***		***European***		***Total***
Intra-WP Workshops held	**4**	09.06.21 09.06.21 10.06.21 14.06.21	**3**	07.07.21 13.07.21 15.07.21	**4**	05.07.21 12.07.21 14.07.21 08.09.21	**11**
Total Models involved	**11**		**8**		**11**		
Total RQs discussed	**84**		**71**		**82**		**237**

The recordings of the meetings were transcribed and stored into spreadsheets summarising all the different potential applications in each CS and then shared with partners, who were asked to assess the RQs that they could potentially respond to in the context of Deliverable 7.2. **Figure 4** shows an example of how the feedback received has been analysed and documented.

					EMMA	BSAM
RQs descriptions	EMMA	Assumptions/ comments	BSAM	Assumptions/comments	Expected outcomes (timeframe/resolution)	
What is the maximum RES penetration (defined as system limit) that could be accommodated within the Greek electricity system with acceptable levels of curtailment? Curtailment should not surpass the 5% threshold, according to the EU regulation.	rephrase	Greece it treated as an island and if we quantify “acceptable”, then this can be accounted for in the optimization with some code additions, i.e. by adding the following inequality (where t is the set of hours of the year): ∑_t(Capacity · Availability_t-Genration_t)≤CurtailmentShare·∑_t(Capacity·Availability_t) Curtailments is calculated and we can say is the system cost optimal solution is more of less than 5%	yes	BSAM could provide answer to this question by calculating the electricity mix of different RES configurations with and aim to maximise their penetration to it and trying not to surpass the 5% threshold for curtailment.	Cannot constrain curtaiment but check the results and examine the level of curtailment	Electricity mix of different RES configurations with an aim to maximise their penetration trying not to surpass the 5% threshold for curtailment.

Figure 4. Example of feedback received by modelling teams on the different research questions for each case study.

Furthermore, we organised a second round of inter-WP online modelling workshops for each CS to make deep dives on the potential model linkages in each one of the SENTINEL CSs, as well as to inform the modelling teams about the recent policy updates of scenarios and targets for the Nordic and European CSs (**Sections 3.1.1** and **3.2.1**). **Table 3** further summarises the three inter-WP modelling workshops that took place in autumn 2021.

Table 3. Summary of the online inter-Work Package (WP) modelling workshops held to make deep dives on the potential model linkages in each one of the SENTINEL case studies.

	Greek	*Nordic*	*European*
Workshop Date	**21.10.21**	**23.09.21**	**04.10.21**
Total Models Involved	**11**	**8**	**11**

Discussions in these meetings revolved around the feedback collected from the modelling teams from the first round of intra-WP online modelling workshops, as depicted in **Figure 5**.

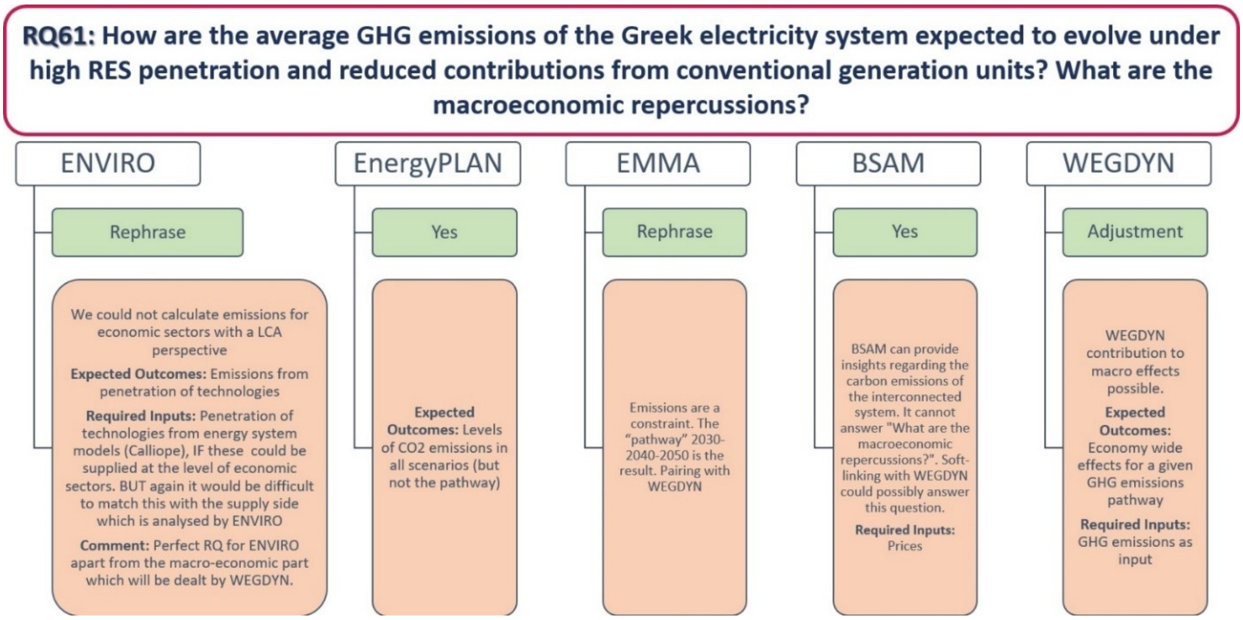


Figure 5. Example of a deep dive on the potential model inter-linkages in the Greek case study.

As a second step, the initial set of RQs as identified and presented for each CS in Deliverable 7.1 were clustered based on their relevance to each other, namely those that address similar challenges and issues within a thematic priority area. Each model that indicated the capability to answer at least one of the RQs assigned to a cluster, even after rephrasing an RQ, was identified and included as contributor to the respective cluster. Specific roles and allocation of responsibilities, i.e., leaderships and contributions, were assigned to the different modelling teams based on model capacities that were collected during the first step of our approach. Leaders for each research cluster were assigned to facilitate the work of the different parties involved. Alongside the different leaderships in each RQ cluster, for each CS, one WP7 partner was assigned as the overall coordinator, constantly keeping track of progress, facilitating, and coordinating the process. The national CS coordinator was UPRC, while the Renewables Grid Initiative (RGI) was responsible for the Nordic case. For the continental case, this role was shared among UPRC and RGI depending on the RQ cluster.

Next, during the period November 2021-May 2022, the modelling teams involved in each research cluster coordinated among themselves, and in collaboration with WP7 partners, for data exchanges, model calibrations and simulations, and presentation of results. The simulation flows, i.e., within and across WP linkages, and the RQs to be answered by each model were decided among the modelling teams within each research cluster. To facilitate the coordination among modelling teams, WP7 developed a tailor-made template, where the modelling teams could report their results (**Figure 6**).

SENTINEL
SUSTAINABLE ENERGY TRANSITIONS

1. Case study applications

Each case study application of SENTINEL will be presented as a chapter of Deliverable 7.2. Each chapter will be formatted as a working document, with main focus points being the RQs and the simulation results. The RQs are grouped in clusters (C) based on their relevance.

1.1. [National/Regional/Continental] Case Study

1.1.1. Scenario Updates

Here the scenario updates of each Case Study will be included by WP7 partners.

1.1.2. Key assumptions

In this section, each modelling team will present the assumptions that were used for their simulations under the [National/Regional/Continental] case study. Please differentiate your assumptions in three subsections:

- **Harmonized Data:** if you used harmonized data (used by other models of the consortium too), briefly present it and use references to cite its sources.
- **Model-specific assumptions:** if you had to make data assumptions, analytically present them, and cite the sources where you derived your data.
- **Model-linkages:** Mention here any data that were given to you by another modelling team. Briefly describe the data. Mention if the data given to you, were the outcome of answering another RQ by another modelling team.

1.1.2.1. ***GR-C1:****RQ1, RQ3, RQ5 and RQ10, by QTDIAN, EnergyPLAN, Calliope, EMMA, WEGDYN and BSAM*

Replace the subsection's title with a paper-like, catchy title.

Research Questions' Overview

Based on Deliverable 7.1, give a brief overview of the storyline behind the RQs. Conclude this section by presenting the RQs that will be answered, rephrased appropriately if deemed necessary, without changing the key message of the original RQ.

- **RQ1:** Does planning long-term transition pathways for a decarbonized energy system account for capacity adequacy and security of supply?
- **RQ3:** What is the expected contribution of fossil fuels (BL: 19.13 TWh (2030), 9 TWh, RE: 0 TWh, P2X: 0 TWh) and RES GUs in the electricity mix in view of the "delignitization" (i.e., lignite phase-out) of the Greek power system?
- **RQ5:** How much thermal (BL: 6.91 GW (2030), 6.5 GW, RE: 4.9 GW, P2X: 7.9 GW) and RES (BL: 19 GW (2030), 26.5 GW, RE: 33.9 GW, P2X: 63.8 GW) capacity is needed in 2030 and 2050 to meet demand requirements with an aim to maximize RES penetration?
- **RQ10:** What is the contribution of interconnections (BL: 4.58 TWh (2030), 3.4 TWh, RE: 3.4TWh, P2X: 3.4 TWh) to the operation of the Greek power system under high RES penetration? What level of power independency can be achieved?

Results and Discussion

In this section, analytically present the results that answer the RQs of the cluster. Mention the data flow among models (if any) and try to make clear which model answered which (part(s) of the) RQs.
Make a discussion of the results your modelling group has reached. Describe the implications you managed to derive by answering the RQs. Make a summary of the challenges you met when trying to answer the RQs (e.g. data assumptions, model improvements, etc.).

Figure 6. Template for reporting of simulation results.

The template is divided into two sections: **a.** the "**research clusters"** section, which reiterates RQs based on the narratives of Deliverable 7.1 and reports modelling results, and **b.** the "**key assumptions"** section**,** in which, all data and assumptions used for each CS are reported by each modelling team. Regardless of the research clusters that each modelling team was included in, this section was only completed once per CS.

Finally, as a third step, to provide responses to the identified critical issues and challenges, each modelling team simulated the scenarios according to the CS specifications defined in Deliverable 7.1 and updated in Deliverable 7.2. In cases where models were soft-linked, suitable input data deriving from model outputs were used, rather than the main specifications for the case studies. In these cases, new case specifications based on SENTINEL modelling outputs were developed. Models with an EU-wide granularity ran simulations for the European CS and presented results for the countries specified in the Greek and Nordic case studies. Moreover, in order to feed different and diverse SENTINEL models with an adequate input data (encompassing diverse sources), we developed a Data Gathering Protocol that helped in organising the data collection process (**Appendix A** – Data Gathering Protocol). In this regard, we formulated a standardised data request template, which included a detailed description of the CS data and its desirable format.

3. Case study applications

In this section, updates to each CS scenarios are presented, along with modelling assumptions, model linkages, and simulation results for each cluster of RQs in each CS. It is important to note that the scenario updates are included as a reference for future researchers and do not necessarily reflect the outcomes of model simulations in this deliverable, since they were collected in parallel with model runs. The specific model assumptions for this deliverable are included in the respective subsections of each CS, or in specific clusters, as deemed appropriate. In addition, some RQs may have been rephrased in order to match the capabilities of the models answering them.

3.1. Continental (European) case study

After the Paris Agreement in 2016, the EU adopted the "Clean Energy for All Europeans" and the "Clean Planet for All" strategies, which outlined the economic and societal changes required to achieve net-zero Greenhouse Gas (GHG) emissions by 2050 (European Commission, 2018a). The EU presented the Green Deal at the end of 2019 as a set of policy initiatives with the goal of achieving climate neutrality in Europe by 2050 (European Commission, 2019a). A recovery plan for Europe was established in 2020, allowing European countries to deploy multiple financing instruments to repair the economic and social damage caused by the Coronavirus Disease 2019 (COVID-19) pandemic (European Commission, 2020a). In 2021, the EU worked on revising its energy and climate legislation to align its laws with the 2030 and 2050 ambitions, as part of the "Fit for 55" package (European Commission, 2021).

3.1.1. Scenario Updates

Deliverable 7.1 (Stavrakas et al., 2021) specified scenarios that enable the exploration of different policy responses to climate change, which evolve with different modes of policy implementation. The reference scenario “**Current Trends**” represents the current progress on implementation of climate and energy policies. The “**Climate Neutrality**” scenario is linked to the long-term strategy (European Commission, 2020b), and together with the “**Current Trends**” scenario, it allows to produce insights into the impact of proposed policies on the energy system needed to achieve the climate neutrality goal. In addition, an “**Early Neutrality**” scenario was also introduced, in which the EU aims to become climate neutral by 2040. The storylines for these scenarios describe different potential configurations of the future energy system in Europe, based on different progress of political, social, and technological drivers. **Table 4** summarises climate and energy targets of the energy transition by 2030 & 2050 for the different European CS scenario.

Table 4. Climate and energy targets of the energy transition by 2030 & 2050 for the different European case study scenarios.

	Past		***“Current trends”***		***“Climate neutrality”***		***“Early neutrality”***
	1990	**2005**	**2030***	**2050**	**2030****	**2050**	**2040**
Total GHG reductions (incl. LULUCF) in **Mt $CO_{2,eq.}$**	5413	4940	2870	1950	2435	<25	<25

Reduction 1990 (%)	-	9%	47%	64%	55%	Nearly 100	Nearly 100
Total GHG reductions (excl. LULUCF) in **Mt $CO_{2,eq.}$**	5659	5164	3150	2130	2640	(350-500)	(350-500)
Total CO_2 emissions in **Mt $CO_{2,eq.}$**	4475	4319	<2400	< 1600	<2000	< 200	< 200

*The values in here considered assume that the new targets, approved in September 2021, will also apply to the UK despite having left the EU. It must be noted that the UK has recently approved more ambitious targets by 2030, comprising reductions of up to **68%** in comparison with the 1990 levels (Committee on Climate Change, 2020).

3.1.2. Key assumptions

3.1.2.1. EMMA-specific assumptions

The emissions allowed in the electricity sector reflect the CS assumptions summarised in **Table 4**. Fuel cost assumptions are based on (Duić et al., 2017) and are harmonized with the Calliope model. Further assumptions, including the projected build-out costs and installed capacities, are captured with the model's default parametrization, see documentation (Hirth and Ruhnau, 2021). Key assumptions on the technology-specific parametrisation are summarised in **Table 5**. For further details, please consult the referenced documentation, or the EMMA GitHub repository[2].

Table 5. Technical parameters. *Batteries are subject to an additional investment cost component of 167 and 150 EUR/kWh in 2030 and 2050, respectively.

	Investment ($€/kW_e$)		**Lifetime** (years)	**Fixed O&M** ($€/kW_e*a$)		**Variable O&M** ($€/MWh_e$)		**CO_2 intensity** (t/MWh_t)	**Conversion efficiency** (MWh_e/MWh_t)	
Year	**2030**	**2050**	**-**	**2030**	**2050**	**2030**	**2050**	**-**	**2030**	**2050**
Nuclear	6000	6000	50	115	105	7.0	8.0	0.00	38%	38%
Lignite	2000	2000	40	42	39	4.0	3.0	0.40	42%	44%
Hard coal	1700	1700	40	35	31	3.5	3.0	0.34	46%	47%
CCGT	770	750	30	15	15	2.0	2.0	0.20	61%	63%
OCGT	600	550	25	7	7	2.0	2.0	0.20	39%	40%
Lignite (CCS)	3420	3200	40	65	61	6.3	4.0	0.04	33%	35%
Hard coal (CCS)	3350	3150	40	66	62	7.4	7.0	0.03	38%	39%
CCGT (CCS)	1625	1500	30	38	34	2.9	2.7	0.02	46%	50%
CCGT (H_2 fuelled)	770	750	30	15	15	2.0	2.0	0.00	61%	63%
OCGT (H_2 fuelled)	600	550	25	7	7	2.0	2.0	0.00	39%	40%
Wind onshore	1075	865	25	16	14	0.2	0.2		100%	100%

[2] https://github.com/emma-model/EMMA

Wind offshore	2250	2065	25	34	32	0.4	0.4	100%	100%
Solar	655	450	25	11	10	0.0	0.0	100%	100%
Electrolysers	900	450	25	18	9	3.0	3.0	75%	75%
Batteries*	83	75	12	0	0	0.6	0.6	92%	92%

3.1.2.2. WEGDYN-specific assumptions

WEGDYN is a macroeconomic model, which has been developed to explore policy-relevant questions. The method focuses on exploring macroeconomic implications of either policy measures or externally set developments. Derived results, however, are not connected to any likelihood or probability and hence they are not forecasts or predictions of the future but depict scenarios to explore their implications. It thus can be well applied directly for a range of SENTINEL RQs as given in detail in the following sections. Another set of RQs in the case specification reported in (Stavrakas et al., 2021) has a normative dimension indicated by them including "should" or "must". To address RQs of this type, the WEGDYN module can only be used together with a normative analysis specifying the objective or targets against such "should" is to be measured. The WEGDYN module alone cannot be used to derive policy-prescriptions. By contrast, the objective is to quantify the relevance of known socio-economic impact channels for plausible "what-if" projections of the future. This approach generates alternatives to provide insights, not numbers (Schinko et al., 2017). This statement applies to all case studies where WEGDYN is applied to.

A usual analysis using the globally resolved WEGDYN model follows two steps. First, region-specific growth of Gross Domestic Product (GDP) is calibrated to projections in line with shared socioeconomic pathways (SSP) (Dellink et al., 2017) using total factor productivity and autonomous energy efficiency improvements. Second, the implementation of a global emissions constraint reflects specific representative concentration pathways (RCP). The combination of SSP and RCP scenarios provides a menu of region-specific economic and environmental outcomes as a starting point from which specific RQs can be analysed. Hence, the study design can be twofold. First, top-down implementations of local shocks in the economic system allow investigating direct and indirect impacts, for instance, of mitigation measures induced by various policy instruments. This can be a stricter emissions cap leading to rising emission allowance prices, which initiate structural changes in the economy based on profit and utility maximization using production and consumption functions calibrated to historically observed behaviour approximated by statistically estimated elasticities of substitution. A second study design integrates bottom-up information from models that are tailor-made and resolved to issues concerning the energy system itself, thus bypassing and complementing aggregate price-driven changes by incorporating backstop technologies and behavioural options in (or linking to) the top-down model.

We compare these two study designs, which highlights their relative merits and problems. We compare the QTDIAN-Calliope-WEGDYN (QCW*)* soft-linked market-driven storyline (MDR) (see (Süsser et al., 2021c) for a description of storylines) with a "top-down only" (TDO) run of WEGDYN. Globally, both runs share the same SSP2-RCP4.5 calibration[3] and a (production-based) EU27+[4] emissions cap leading to climate neutrality by 2050 as specified in Stavrakas et al. (Stavrakas et al., 2021) with a targeted level of around 2 billion tons of Carbon Dioxide (CO_2) by 2030 and less than 0.2 billion by 2050. The revenues of carbon pricing flow into regional public budgets; hence, there is no targeted compensation or revenue recycling through cuts in other taxes or excise duties assumed. **Figure 7** shows the binding emissions cap for EU27+ regions (covering all production-based emissions in this region) leading to rising allowance prices. However, as the economy approaches climate neutrality, emissions abatement becomes increasingly costly in the TDO run due to structural frictions signalled by a soaring allowance price. By contrast, the bottom-up implemented structural changes in the energy system represented by the MDR storyline allows cost-effective mitigation also for hard-to-abate areas of the economic system. Consequentially, the soft-linked study design MDR shows larger macroeconomic benefits as GDP is rising at a faster pace than in the TDO design. Note that both study designs show absolute decoupling of economic and environmental outcomes but to a different degree. Note also that the effective carbon price in the soft-linked study design (MDR) is zero in 2050 because the almost decarbonized socio-economic structure leads to lower demand for allowances than there are available allowances.

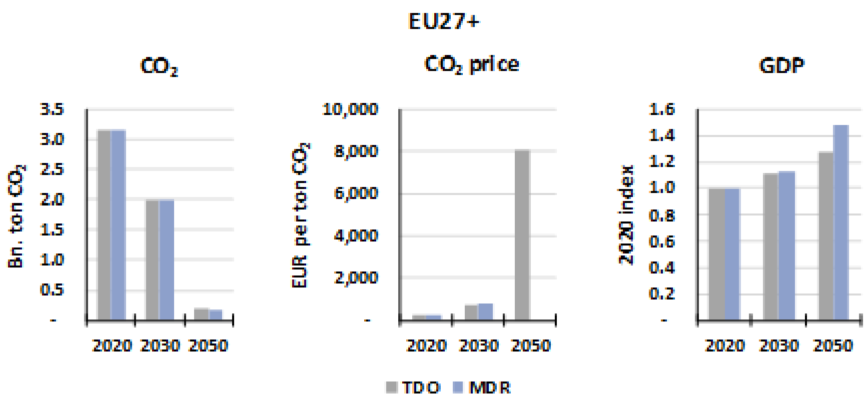


Figure 7. EU27+ Carbon Dioxide (CO_2) emissions, allowance (CO_2) prices and Gross Domestic Product (GDP) for the Top-down only (TDO) and Market-driven (MDR) model runs.

Before turning to individual research clusters of the European CS, convergence of the QCW model ensemble requires scrutiny. WEGDYN fixes the productivity and mix of energy based on Calliope but allows

[3] Assumptions on growth of GDP and of population for EU27+ regions are taken from the 2021 Ageing Report (European Commission, 2021c) to warrant consistency with energy demand assumptions of the models DESSTINEE and HEB.

[4] Details regarding regional resolution are given below.

for endogenous output changes as response to indirect effects. In **Figure 8**, we compare system supply from a cost and price perspective, the former is the Calliope-derived input to WEGDYN and the latter its translation in WEGDYN outputs. The isolated WEGDYN run without carbon pricing (middle) mirrors well Calliope inputs (**Figure 8)**. However, the economy-wide productivity gain of the MDR energy system induces positive income effects raising aggregate demand and may stimulate emission-intensive production and consumption without further economy-wide emission constraints. Hence, WEGDYN assumes an emissions certificate market, first, to circumvent such rebounds and, second, to warrant a consistent reference point of comparison across model runs. The implementation of carbon pricing, which has an effective positive allowance price only in 2030, cushions energy demand and thus supply, which becomes steeper and turns inwards (top right panel). This instrument is implemented to mimic a central EU policy fostering emission reductions, although the size of dynamic efficiency gains induced by pricing instruments is subject to academic debate (Lilliestam et al., 2021; van den Bergh and Savin, 2021). Finally, and most crucially, all three storylines imply cheap electricity supply by 2030 and even more by 2050, also compared to the current situation due to strong roll-out of cheap renewables. In the individual research clusters in the sections that follow, we provide model results in the setting that includes carbon pricing. The core advantage of this soft-linked model ensemble is visible by its modularity and flexibility to address certain aspects of reality in a transparent manner.

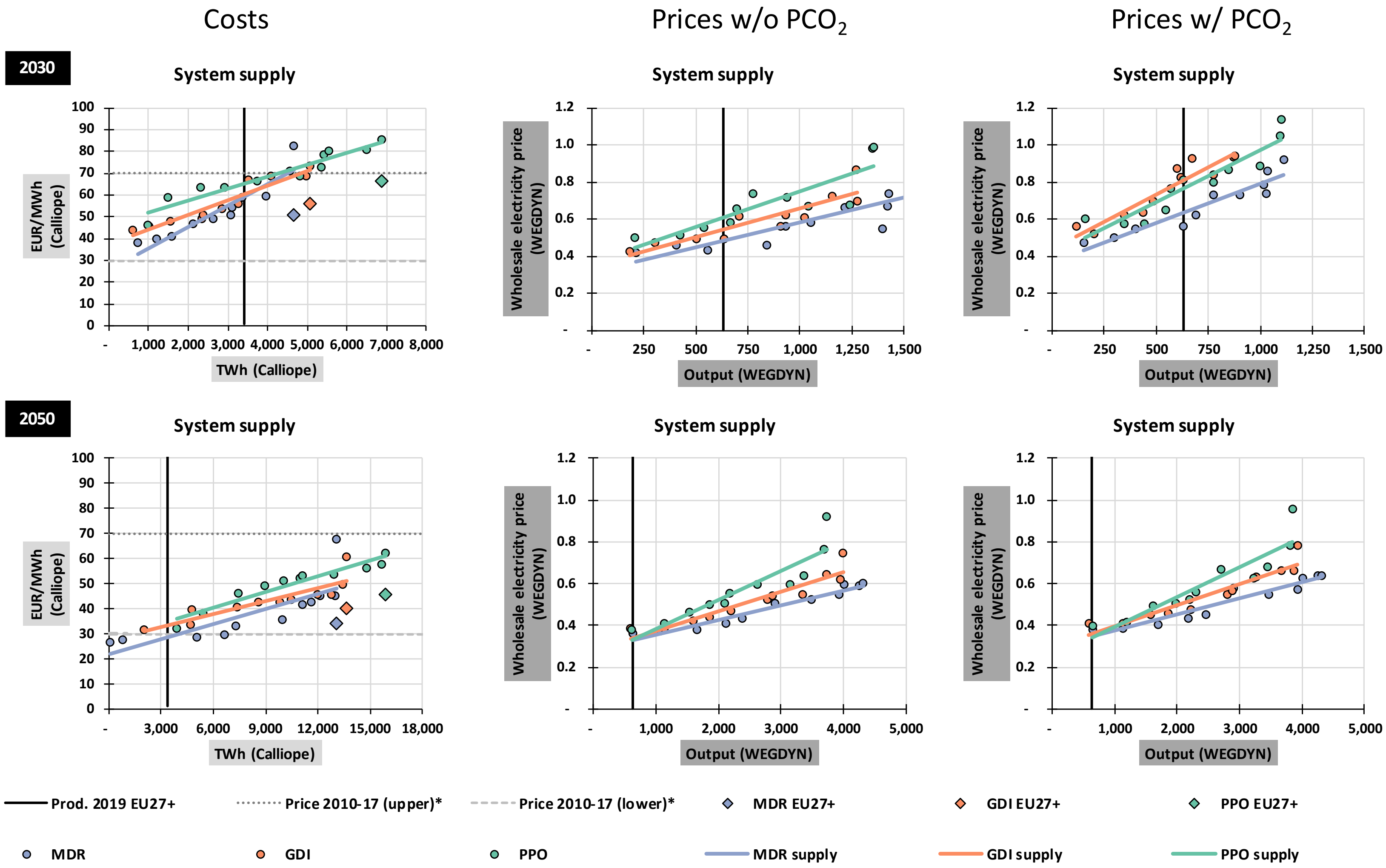


Figure 8. Electricity supply across storylines in 2030 (top row) and 2050 (bottom row) in cost terms (Calliope; left column) and prices (WEGDYN) excluding (middle) and including carbon pricing (right); single dots represent individual WEGDYN regions; wholesale electricity prices are normalized to unity in 2011 and output is measured in EUR2011; *range of average weighted wholesale market price of electricity in EU28 according to (European Commission et al., 2018).

The core comparison in the macroeconomic assessment focuses on the deviation of the Government-directed (GDI) and People-powered (PPO) compared to the MDR energy systems (see (Süsser et al., 2021c) for a description of storylines) at the EU27+ but also regional and sectoral level, as well as differences in the implications for private and public actors. The variation of the regional change in the levelized cost of energy is shown in **Figure 9** and represents core inputs and drivers of this assessment. Without economy-wide indirect effects, lower unit-cost are expected to show up as productivity gain and thus higher macroeconomic performance (and vice versa). With the help of WEGDYN, deviations from this expected relationship can be explained by considering indirect effects that are not accounted for in the bottom-up system design modelled by Calliope.

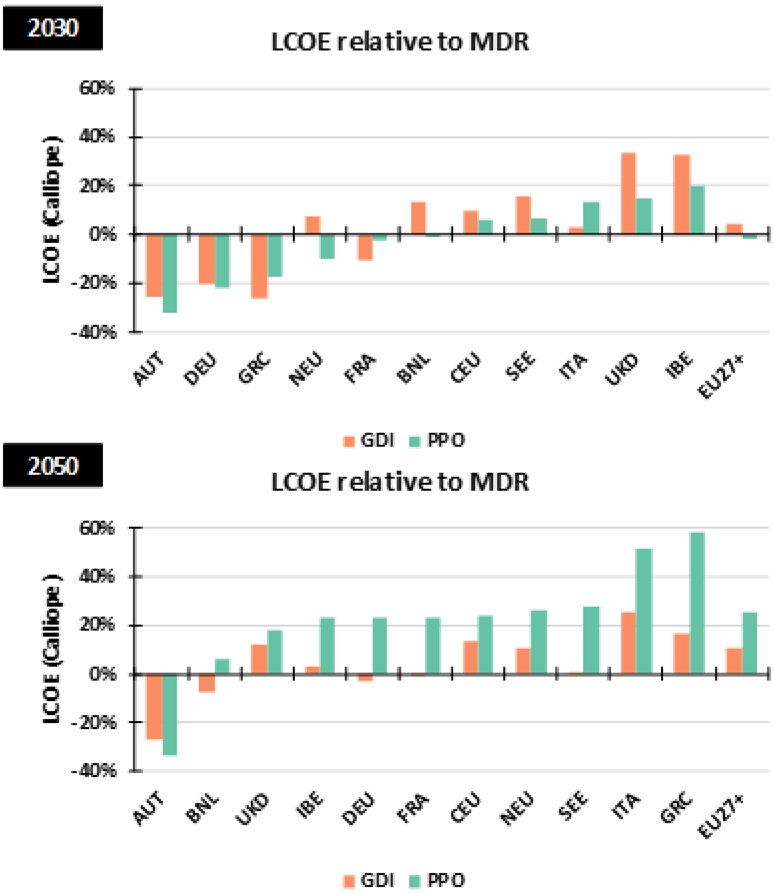


Figure 9. Regional Levelized Costs of Energy (LCOE) relative to the Market-driven (MDR) storyline for 2030 (top) and 2050 (bottom).

3.1.2.3. DESSTINEE-specific assumptions

Different modelling and linkage activities have been conducted to answer the RQs where DESSTINEE contributed. Below, a description of the generic approach is described. Further details are provided in each RQ section and in the suggested references.

Energy balances and associated electricity demand and supply profiles from Calliope and EnergyPLAN were simulated based on the energy service demand provided by DESSTINEE (travel demand for different transportation modes and vehicle types, and value added for several industrial categories) and HEB (required heat in buildings). Fuel baskets for each end-use and the energy industries were defined to meet emission reduction targets, compatible with the different decarbonisation scenarios (**Table 4**) and time horizons, aiming for the optimal solution in terms of mitigation costs. Service demands in DESSTINEE and HEB have been quantified by accounting for: population and GDP projections from the EU Reference Scenario (European Commission et al., 2021), and inputs for behavioural changes from QTDIAN – mostly for household areas, renovation rates and patterns for travel demand; and own assumptions on envelope efficiency for different types of buildings.

In the case of DESSTINEE, the fuel basket across final energy uses, at the country-level, have been defined, in view of meeting high level sectoral and continent-wide targets for emission reductions (Harmsen et al., 2020; Runge-Metzger, 2018), on the basis of current national and income-based energy consumption and technology-deployment patterns. This allowed the modelling of national representative service demand and final energy consumption (FEC) for heating in buildings, road transport, light and heavy industries. Further details are discussed in Deliverable 3.2 (Chatterjee et al., 2021), Deliverable 2.5 (Süsser et al., 2021c), Deliverable D.8.2 (Oreggioni et al., 2022) and in an upcoming publication on the DESSTINEE model (Oreggioni and Staffell, 2022).

3.1.2.4. IMAGE-specific assumptions

The IMAGE model simulates long-term interactions between human development and the natural environment (Stehfest et al., 2014), and integrates a range of economic sectors, ecosystems and indicators to gain better insight into the processes of global environmental change. The IMAGE model has a comprehensive description of energy and land systems. This, for instance, includes energy demand from all sectors, the capacity and resources of different fuels, technology trends, land use, emissions and other environmental impacts (Harmsen et al., 2020). The Europe region in IMAGE consists of Western Europe and Central Europe. Together, these regions have a few more countries than the EU27+UK regions (particularly Norway, Iceland, Switzerland, and the Balkan countries). As a result, total GHG emissions in 2020 are around 5% higher than EU27+UK (European Environment Agency, 2021).

The SENTINEL project developed three scenarios for the European CS, and IMAGE simulated two of them: "**Current Trends**" and "**Climate Neutrality**" (see **Table 4**). The "**Current Trends**" scenario includes current energy and climate policies. The current policies are defined as implemented policies adopted by governments (through legislation) or non-binding targets backed by effective policy instruments and planned policies in the pipeline to be adopted and have been implemented in the IMAGE model for the period up to 2030 (updated to 2021). Ambitions and pledges (e.g., Nationally Determined Contributions from the Paris Agreement) were not included. In addition, a carbon price is added to the policy model implementation to represent missing policies, necessary to achieve the EU emissions reduction targets for 2030 and 2050, and harmonise to the reference scenario from the Clean Planet for All (European Commission, 2018a). The "***Neutrality***" scenarios were developed under the SSP2 pathway (middle-of-the-road socio-economic pathway) (Fricko et al., 2017) with renewable trend as the baseline (van Vuuren et al., 2021). The carbon price in IMAGE was adjusted to enable technology incorporation compatible with the emission caps. IMAGE was run using the GDP and population growth rates from the EU Reference Scenario (European Commission et al., 2021) as inputs, aiming to fulfil the overall and sectoral emission reduction targets, at the continental level, from the scenarios conducted and released by the European Commission (EC) (European Commission, 2020c; Runge-Metzger, 2018).

The "**Climate neutrality**" scenario was implemented in IMAGE with two variants: "**Neutrality 1.5°C**" and "**Neutrality 2.0°C**", both meet the targets of the Climate Neutrality in **Table 4**. These scenarios keep global temperature increase below 1.5°C or 2.0°C respectively at the end of this century, while the EU follows the carbon neutrality (CN) target released by the EC (COM/2019/640). In this renewable variant of the SSP2 baseline, it is assumed that high electrification rates in all end-use sectors are feasible due to optimistic assumptions about the integration of variable RES (VRES) technologies and costs of transmission, distribution, and storage. As a result, it has a higher electrification rate and a higher renewable share. We simulated the carbon-neutral pathways by adjusting the EU carbon price in IMAGE which impacts the fuel price and technology development trends, determining the energy mix and emissions in 2050 in the Europe region. Note that the carbon price in the IMAGE model functions as a shadow price of climate policy. As more specific policy instruments after 2030 have not been implemented by the EU yet, this price represents a cost-effective implementation consisting of all possible instrument mixes between 2030 and 2050 (not only the Emissions Trading System (ETS)) that satisfy the shown reductions to achieve neutrality.

3.1.2.5. HEB-specific assumptions

The HEB model calculates the yearly and hourly energy demand of the residential and tertiary building sector until 2050 under four different scenarios based on the most recent data for macroeconomic indicators and technological development. The model takes a bottom-up approach, as it includes rather detailed technological information for the building sector, however, it also benefits from certain macroeconomic and sociodemographic data which include population, urbanisation rate, and floor area per capita. The four scenarios of HEB model are discussed below:

- "**Deep Efficiency Scenario**": This scenario demonstrates the state-of-the-art of construction and retrofit technologies that can substantially reduce the energy consumption of the building sector and hence, CO_2 emissions, while also providing full thermal comfort in buildings. This scenario includes exemplary building practices that have been implemented in the EU for both new and renovated buildings.

- **"Moderate Efficiency Scenario":** This scenario incorporates present policy initiatives as the implementation of the Energy Performance of Buildings Directive (EPBD) in the EU and building codes for new buildings in other regions.
- **"Frozen Efficiency Scenario":** This scenario assumes that the energy performance of new and retrofit buildings do not improve as compared to the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling. Furthermore, most new buildings have a lower level of energy performance than in moderate scenario due to lower compliance with building codes.
- **"Towards Net-Zero Scenario":** This last scenario models the potential of deploying "Net Zero Energy Buildings" − buildings that can produce as much energy locally through the utilisation of renewables as they consume on an annual balance. It differs from the other three scenarios to the extent that it not only calculates the energy consumption but already incorporates the local energy supply to arrive at the final energy demand. In other aspects, it uses the same parameters as the Deep Efficiency Scenario.

The aim of the scenario analysis is to capture the importance of different policy acts on building energy efficiency measures (EEMs) and show how much the FEC of the building sector can be reduced across the EU. Each of these scenarios has certain parameters (these parameters determine the future energy demand) and assumptions, based on which each of the scenarios varies from each other. **Table 6** summarises the actual parameters of the four scenarios. More precisely, the renovation data reflects any type of retrofit that has a significant influence on the heating and cooling energy demand of the building and thus, it also reflects the level of energy efficiency improvement when a retrofit is modelled within the different scenarios in HEB. Furthermore, in the HEB model, scenario-specific assumptions are made on what percentage of the renovated buildings are advanced (such as Net zero buildings, and passive houses) or non-advanced. These two categories reflect different energy efficiency levels where the non-advanced buildings are assumed to be the "business-as-usual", while advanced buildings are the technically possible best ones in terms of low energy consumption. Thus, for the deep-efficiency and nearly net-zero scenarios in the HEB model, we use the share of advanced buildings from the QTDIAN deep renovation data used in the GDI and MDR storylines (see (Süsser et al., 2021c) for a description of storylines).

Table 6. Key parameters of the four scenarios that are handled by the HEB model.

Parameter	Deep Efficiency Scenario	Moderate Efficiency Scenario	Frozen Efficiency Scenario	Towards Net Zero Scenario
Initial renovation rate	Country-specific data from the IPSOS-Navigant report.	Country-specific data from the IPSOS-Navigant report.	Country-specific data from the IPSOS-Navigant report.	Country-specific data from the IPSOS-Navigant report.
Accelerated renovation rate	MDR storyline renovation from QTDIAN after 2027.	GDI renovation data from QTDIAN after 2027.	Country-specific data from the PPO storylines from QTDIAN.	MDR storyline from QTDIAN after 2027.

EEMs of new buildings	New buildings are built to regional standards.	New buildings are built to regional standards.	New buildings do not improve as compared to the existing stock.	New buildings are built to regional standards.
EEMs of renovated buildings	Renovations reduce the energy demand approximately by 30%.	Renovations reduce the energy demand approximately by 30%.	Renovations reduce the energy demand approximately by 10%.	Renovations reduce the energy demand approximately by 30%.
Share of advanced buildings within new and retrofitted stock	All new and retrofitted buildings have very low energy demand (advanced buildings) after 2027 in the EU.	70% of the new and retrofitted buildings have very low energy demand (advanced buildings) after 2027.	Advanced buildings are only introduced by the same share as present share of advance buildings.	All new and retrofitted buildings have net zero energy demand after 2027 in the EU.

Source: (Süsser et al., 2021c)

Based on these four scenarios, the key outputs of the HEB model are floor area projection for different types of residential and tertiary buildings in different regions and EU Member States, the total energy consumption of residential and tertiary buildings, energy consumption for space heating and cooling, and energy consumption for hot water. To reflect realistic socio-political indicators in HEB scenarios, HEB model uses QTDIAN storylines for building renovation rates, and share of advanced buildings for each of the EU member states. Both data vary across different scenarios and accordingly the final energy demand of the building sector is calculated for each of the scenarios.

3.1.2.6. EnergyPLAN-specific assumptions

The reference scenarios modelled in EnergyPLAN for the European CS are built on the basis of the projections from the EC's "A Clean Planet for All" report (European Commission, 2018a) and represent the years 2015 and 2050. The scenarios are modelled aggregating data on a European level and take as initial reference inputs the capacity of conversion units, fuel shares, and annual fuel consumptions and energy demands. In addition, specific inputs related to modelling the heating sector were supplemented from the Heat Roadmap Europe project (Paardekooper et al., 2018). A detailed description of the assumptions used to replicate the EC scenarios in EnergyPLAN is presented in (Petersen et al., 2021).

Parting from the scenarios mentioned above, further adjustments were made to design a "**Smart Energy Europe**" scenario, or "**Climate Neutrality**" scenario. This scenario incorporates changes in heat, transport, and industrial demands and diversified supply sources for electricity, heat, and green fuels from power-to-X (P2X). Further details on the design of this scenario are provided in (Thellufsen, 2021).

3.1.2.7. DREEM-specific assumptions

Countries' and buildings' specifications

Using the DREEM model (Koasidis et al., 2022; Stavrakas and Flamos, 2020) we estimate the energy-saving potential of different EEMs in eight EU countries: Greece, Italy, Spain, Croatia, Romania, Latvia, France and Ireland (**Figure 10**). The rationale behind choosing these countries is to explore and compare the energy performance of buildings and the impact of different EEMs for countries with different characteristics in terms of climatic conditions and consumption patterns. Greece, Italy, Spain, and Croatia are Mediterranean countries in southern Europe and the climate in these countries is characterised by dry summers and mild, wet winters. With regards to consumption patterns, these countries have lower heating needs, while the diffusion of cooling equipment is progressing, with more than 80% of the dwellings being equipped with cooling equipment in Greece, 60% in Spain, and around 35% in Croatia and Italy (EEA, 2016). Romania and Latvia are located in eastern Europe, which is a region characterised by poor energy efficiency of buildings' heating systems and household appliances. Romania has a temperate-continental climate of a transitional type, specific to Central Europe, while Latvia has a temperate oceanic climate, with cool winters and mild pleasant summers, specific to Northern Europe. Due to the cold climate conditions, heating needs in Latvia can be over 160 kWh/m^2. Finally, France and Ireland are located in Western Europe, with France being a central-western country and Ireland being a north-western country. France generally enjoys cool winters and mild summers, while the climate in Ireland is mild, humid, and changeable, with abundant rainfall and a lack of temperature extremes. The selection of these countries enables us to investigate the energy saving potential and cost-effectiveness of specific EEMs taking also into account the significant disparities that exist among EU countries.

Figure 10. EU countries selected for the application of the DREEM model.

Furthermore, we investigate the energy-saving and cost-effectiveness potential of two categories of buildings based on their construction period. The first category (**Category I**) includes buildings that have been built before 1981, except for Croatia where the category includes buildings that have been built before 1987. The majority of these buildings have been built without insulation since the requirements for thermal insulation of buildings was set after 1981. The second category (**Category II**) includes newer buildings that have been built between 1981 and 2006. The aim is to identify how the different construction periods, and therefore building characteristics, can affect the energy-saving potential and cost-effectiveness of different EEMs. The building specifications for the selected case studies were retrieved from the **TABULA**[5] (Typology Approach for Building stock Energy Assessment) project, the **ENTRANZE** (Policy to **EN**force the **TRA**nsition to **N**early **Z**ero **E**nergy buildings in the EU) project and other national documents of the countries under study. TABULA was a three-year project (June 2009-May 2012) involving thirteen European countries, among which Greece, Italy, Spain, France and Ireland (Ballarini et al., 2014). The objective of the project was to create a harmonised structure for "European Building Typologies" in order to estimate the energy demand of residential building stocks at the national level and, consequently, to predict the potential impact of EEMs and to select effective strategies for upgrading existing buildings. Each participating country developed a "National Building Typology", which is a set of model residential buildings ("building types"), each representing a building age class (i.e., a construction period) and a building size class (e.g., single-family house, multi-family building, apartment block, etc.). Each building type is characterised by specific energy-related properties, which reflect typical technical systems, construction features, and geometric characteristics of the represented construction period. Croatia, Romania and Latvia were not among the countries engaged in **TABULA**, so we used the **ENTRANZE** project for the geometric and energy-related properties of the buildings under study. Furthermore, for all the case studies we used also national documents (e.g., national energy and climate plans (NECPs), national energy efficiency action plans, etc.) and scientific publications to fill in data that we were missing, or to complement/ validate data when needed.

Greece

For the case of Greece, two reference buildings in the city of **Athens** (Greek Climate Zone B) were selected to simulate the energy-saving potential of different EEMs. The first building was constructed before 1981 and the second building was constructed during the period 1981-2000. Building specifications are presented in **Table 7**.

Table 7. Specifications for the buildings under study in Greece.

Parameter	Specifications	
Year of construction	1981 (first class)	1981-2000
Type of building	Residential, detached	Residential, detached
No. of floors	1	1
Total floor area	102 m^2	88 m^2
Height	2.50 m	2.50 m

[5] https://webtool.building-typology.eu

Total roof area	110 m^2	150 m^2
Total walls area	182 m^2	350 m^2
Total windows area	46 m^2	42 m^2

Italy

For the Italian CS, two reference buildings in the city of **Rome** (Italian Climate Zone D) were selected for the analysis. The first building was constructed during the period 1960-1979, while the second building was constructed during the period 1980-2006. Building specifications are presented in **Table 8**.

Table 8. Specifications for the buildings under study in Italy.

Parameter	**Specifications**	
Year of construction	1961 - 1975	1990 - 2005
Type of building	Residential, detached	Residential, detached
No. of floors	2	2
Total floor area	156 m^2	172 m^2
Height	2.17 m	2.50 m
Total roof area	156 m^2	172 m^2
Total walls area	475.3 m^2	441.6 m^2
Total windows area	19.5 m^2	21.6 m^2

Spain

For the case of Spain, two reference buildings in the city of **Barcelona** were selected to simulate the energy-saving potential of different EEMs. The first building was constructed between 1960-1979 and the second building was constructed between 1980-2006. The building specifications are given in **Table 9**.

Table 9. Building specifications for Spain.

Parameter	**Specifications**	
Year of construction	1960-1979	1980 - 2006
Type of building	Residential, detached	Residential, detached
No. of floors	1	1
Total floor area	90 m^2	107 m^2
Height	2.50 m	2.50 m
Total roof area	64 m^2	132 m^2
Total walls area	312 m^2	234 m^2
Total windows area	13 m^2	66 m^2

Croatia

For the case of Croatia, two reference buildings in the city of **Zagreb** were selected to simulate the energy-saving potential of different EEMs. The first building was constructed during the period 1971- 1987, while the second building was constructed during the period 1988-2005. Building specifications are presented in **Table 10**.

Table 10. Specifications for the buildings under study in Croatia.

Parameter	Specifications	
Year of construction	1971-1987	1988-2005
Type of building	Residential, detached	Residential, detached
No. of floors	1	1
Total floor area	96.32 m^2	96.32 m^2
Height	2.80 m	2.80 m
Total roof area	96.32 m^2	96.32 m^2
Total walls area	118.72 m^2	118.72 m^2
Total windows area	12.48 m^2	12.48 m^2

Romania

For the Romanian CS, a reference building in the city of **Bucharest** was selected. The building was constructed before 1979. Building specifications are presented in **Table 11**.

Table 11. Specifications for the buildings under study in Romania.

Parameter	Specifications
Year of construction	<1979
Type of building	Residential, detached
No. of floors	1
Total floor area	99.7 m^2
Height	2.50 m
Total roof area	99.7 m^2
Total walls area	93.84 m^2
Total windows area	12 m^2

Latvia

For the Latvian CS, a reference building in the city of **Riga** was selected. The building was constructed during the period 1970-1979. Building specifications are presented in **Table 12**.

Table 12. Specifications for the buildings under study in Latvia.

Parameter	Specifications
Year of construction	1970-1979
Type of building	Residential, detached
No. of floors	1
Total floor area	96 m^2
Height	3.0 m
Total roof area	96 m^2
Total walls area	117.6 m^2
Total windows area	12 m^2

France

For the case of France, two reference buildings in the city of **Paris** were selected, with the first building constructed during the period 1975-1981 and the other one constructed during the period 1990-1999. Building specifications are presented in **Table 13.**

Table 13. Specifications for the buildings under study in France.

Parameter	Specifications	
Year of construction	1975 - 1981	1990 - 1999
Type of building	Residential, detached	Residential, detached
No. of floors	1	1
Total floor area	97 m^2	107 m^2
Height	2.50 m	2.50 m
Total roof area	113 m^2	107 m^2
Total walls area	174 m^2	133 m^2
Total windows area	38 m^2	15 m^2

Ireland

For Ireland, two reference buildings in the city of **Dublin** were simulated, with the first one constructed during the period 1967-1977 and the other one constructed during the period 1983-1993. Building specifications are presented in **Table 14**.

Table 14. Specifications for the buildings under study in Ireland.

Parameter	Specifications	
Year of construction	1967 - 1977	1983-1993
Type of building	Residential, detached	Residential, detached
No. of floors	1	1
Total floor area	125 m^2	157 m^2
Height	2.50 m	2.50 m
Total roof area	125 m^2	157 m^2
Total walls area	90 m^2	126 m^2
Total windows area	29 m^2	27 m^2

Energy-efficiency measures (EEMs)

The following EEMs are evaluated for all the aforementioned countries:

- **EEM1** - Exterior wall insulation: Insulating the main walls of the building under study from the outside, which commonly have solid walls with no cavities.
- **EEM2** - Roof insulation: Insulated between and under the rafters of the roof itself, reducing the overall heat transfer coefficient by adding materials with low thermal conductivity.
- **EEM3** - Double-glazed windows: Replacing single-glazing windows with energy-efficient glazing (double-glazed windows) to reduce heat loss.

- **EEM4** - Smart thermostat: Installation of smart thermostat maximising heating and cooling efficiency based on optimised setting of temperature set-points.
- **EEM5** - Energy-efficient heating system: In this case, an old diesel boiler is replaced by an efficient diesel boiler with a higher efficiency ratio.
- **EEM6** - Energy-efficient heating system: In this case, an old diesel boiler is replaced by an efficient gas boiler with a higher efficiency ratio.
- **EEM7** - Energy-efficient heating system: In this case, an old diesel boiler is replaced by an efficient biomass boiler with a higher efficiency ratio.
- **EEM8** - Energy-efficient heating system: In this case, an old diesel boiler is replaced by an Heating, Ventilation, and Air Conditioning (HVAC) system.
- **EEM9** - Energy-efficient lighting**:** In this case, the conventional tube lights and bulbs (fluorescent lamps) are replaced by high energy-efficiency ones (LED lamps).

Data acquisition

To simulate the EEMs in the countries mentioned above, we mainly modified the "*Weather-climate*" component, the "*Building envelope*" component and the "*HVAC*" component of the DREEM model (Stavrakas and Flamos, 2020). To do so we used the following data sources:

- Weather climate data: https://climate.onebuilding.org/
- Building envelope: https://webtool.building-typology.eu/#bm, https://www.entranze.eu/
- HVAC: https://webtool.building-typology.eu/#bm, https://www.entranze.eu/

Techno-economic analysis

The chosen indicator for cost-effectiveness in this study is the levelized cost per unit of energy saved (LCSE) over the economic lifetime.

The Levelized Cost of Saved Energy is calculated based using the following formula:

$$LCSE = \frac{CRF * Cost_{Total}}{Energy\ Savings\ (kWh)} = \frac{(CRF * Cost_{Investment}) + Cost_{O\&M}}{Energy\ Savings\ (kWh)}$$

- *LCSE* is the net levelized cost of saved energy.
- *CRF* is the capital recovery factor; $CRF = \frac{r * (1+r)^N}{(1+r)^N - 1}$
- *r* is the discount rate.
- *N* is the lifetime of measures.
- $Cost_{INVESTMENT}$ is the total investment cost to materialise the EEM, which is annualised using the CRF.

- $Cost_{OM}$ is the annual operational and maintenance costs of the energy-saving scenario.
- *Energy savings* is the total energy savings calculated, the difference in energy consumption between the reference and the energy efficiency scenario after applying the EEM under study.

Cost data were derived from EU and national data sources and scientific publications exploring the energy and economic performance of the building stock in the countries under study.

3.1.2.8. ENBIOS-specific assumptions

Within the SENTINEL project, the workflow of ENBIOS is such that its key data inputs are the energy system specifications for the different scenarios, projected by the outputs from other models within the project (predominantly "energy mix" and infrastructure capacity data from Calliope, with possible additional data being provided from WEGDYN). Secondary data is also provided from external reference sources that facilitate the calculations undertaken within. As such, aside from the fact that outputs from other models form the inputs to ENBIOS, the module does not use common, harmonized datasets in direct conjunction with other models within the project.

In order to calculate the various indicators that act as the final outputs from ENBIOS, reference data from a variety of external sources must also be included within the simulations. The most fundamental of these is LCA data sourced from the Ecoinvent database (Ecoinvent, 2021; Wernet et al., 2016). Two types of inputs are used: (1) Life cycle inventory (LCI) data provides a listing of the material and other inputs/outputs required to undertake each energy-related processes within the system, provided in the native Ecospold (.spold) format; and (2) Life cycle impact assessment (LCIA) methods define the factors that are applied to the individual listings within LCI datasets in order to transform LCI listings into specific indicator values. A listing of the Ecoinvent LCI data applied at each process in ENBIOS is provided in **B** – Supplementary Tables and Figures

Table B.1.

LCI listings are also used to provide the masses of specific critical raw materials (CRMs) required to undertake different energy-related processes. Of the 80 CRM candidate materials identified by the EC (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b) 55 are included within current LCI listings. Accordingly, LCI values are used in conjunction with additional data for each CRM to calculate final indicators for each process in relation to supply risk, local environmental impacts from extraction and circularity (end-of-life recycling import rate, or EoLRIR) in accordance with known methods (Martin et al., n.d.; Talens Peiró et al., 2022). Additional data relating to material supply risk and EoLRIR (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b), total EU consumption (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b, 2020a; Directorate-General for

Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020) and environmental performance (Wendling et al., 2020) is required to undertake these calculations and is provided in **Table B.2**.

Two further data sources are also required. Firstly, although LCI data for heat and electricity generation includes all sub-processes required to deliver one unit of energy for final consumption, LCI listings for fuels only include the provision of a unit mass of that fuel. While the consumption of heat and electricity is assumed to produce no further emissions, the consumption of fuels will produce significant amount of emissions during the final combustion phase. As such, an additional mass of GHG emissions must be added for fuels. Here, additional data inputs are provided to ENBIOS in the form of combustion factors (kg emissions per unit of energy) for each fuel type simulated (IPCC, 2021), as provided in **Table B.3**.

Finally, in order to assign human labour information to each energy-related process within the module, data is included that links the hours of annual human labour required for each watt of installed capacity of heat and electricity infrastructure and for each kilogram of final fuel production (Ram et al., 2020; Rutovitz et al., 2015), as provided in **Table B.4**.

3.1.2.9. Model linkages

QTDIAN-Calliope-WEGDYN (QCW)

Addressing RQs of the clusters **EU-C3 (Section 3.1.4.2), EU-C19 (Section 3.1.8.1), and EU-C20 (Section 3.1.8.2)**, we show the functionality of the soft-linking between the QTDIAN modelling toolbox (Süsser et al., 2021c, 2021a), the Euro-Calliope model (Pickering et al., 2021), and the WEGDYN model (Bachner et al., 2022). We denote this link as QCW and apply it in a sequential manner (**Figure 11**). First, QTDIAN provides storylines that build on governance logics allowing for the exploration of socio-political developments (Süsser et al., 2021c). Second, these storylines imply different boundary conditions (drivers or constraints), which are implemented in Calliope and shape energy system configurations of the future. The model improvements of Calliope (aligned to match user needs detailed in Pickering et al. (2021)) allow for a rich quantification of energy flows consumed, produced, converted and stored and the derivation of respective Levelized Costs of Energy (LCOE). Note that energy carrier demand of Calliope uses projected service demand profiles for industry, transport and heating from the models DESSTINEE (Bobmann and Staffell, 2015) and HEB (Güneralp et al., 2017). Finally, embedding derived future configurations of the energy system in a macroeconomic framework, using the WEGDYN model, allows for an economy-wide assessment including indicators such as GDP, welfare[6] and employment effects.

[6] Welfare is computed as Hicksian equivalent variation reflecting consumption possibilities of private and public households per region. In other words, it quantifies the willingness to pay for marketed goods and services at hypothetically unchanged relative prices that results in the same level of welfare.

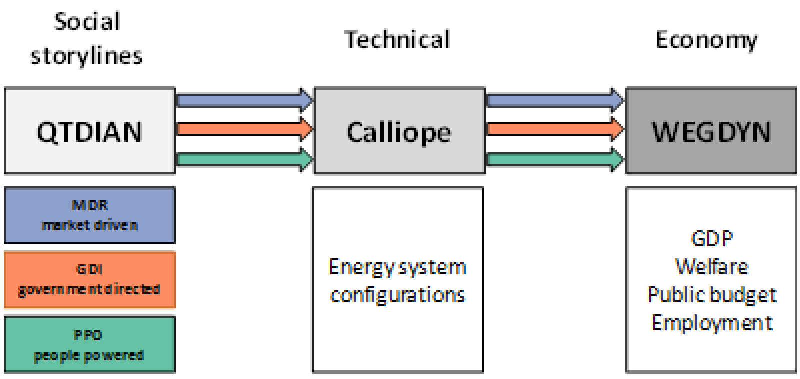


Figure 11. QTDIAN-Calliope-WEGDYN **(**QCW) model ensemble flow chart.

The combined application of this model ensemble is in the spirit of SENTINEL's aspiration to use models for generating alternatives in a modular, flexible, detailed and transparent manner. However, answering the specified RQs of the European CS with the proposed set of soft-linked modelling tools, we expect also problems in terms of resolution, convergence and uncertainty propagation. In the following, we consider each of these issues in turn. The mentioned research clusters at the beginning of this section are addressed using the soft-linked WEGDYN model, which is why we mainly report and explain WEGDYN input and output data.

The *QTDIAN* storylines cover three governance logics (**Figure 11**). In brief, the MDR storyline shapes the energy system in a cost-effective manner with a European expansion viewpoint, strong corporate ownership but high local opposition. The GDI storyline endorses an "energy efficiency first" philosophy with many large private and public utilities and local opposition to otherwise high public support in a national expansion setting. With a focus on citizen and community ownership, the PPO storyline emphasises local needs and capacities leading to a much more decentralized energy system with strong regional expansion of renewable energy. All three storylines are applied to the same mitigation target, which corresponds to the EU "**Climate Neutrality**" scenario outlined in Stavrakas et al. (2021), with production-based emissions reduced to less than 2,000 $MtCO_2$ by 2030 and less than 200 $MtCO_2$ by 2050. These numbers are consistent with the 55% reduction target of 2030 and the 2050 carbon-neutrality pledge of the EU (**Table 4**).

The storyline implementation in Calliope concerns nine parameters covering the technology mix for renewable electricity and heat generation, the conversion, storage, and transmission of energy, as well as phase-out of fossil and nuclear energy. The MDR system prioritises least-costs applying no limit on hourly production transmitted to or from neighbouring countries, no limit on new transmission and nuclear capacity (but limited to current nuclear using countries), a high-capacity maximum for batteries, and a full technically feasible land availability for renewables. The GDI system aims at balancing (de)central electricity generation, while limiting hourly transmission to neighbours by no more than 15% of current production and a limit to new transmission lines. Official public schedules limit the share of nuclear in the energy mix, the maximum battery capacity is mediocre and there is prohibited use of protected land and forest for onshore wind power and photovoltaics (PV). The PPO system prioritises rooftop PV while also limiting transmission to only current capacities.

Nuclear power is not part of the energy mix anymore and the maximum of battery capacities is low. Offshore wind power and open-field PV are subject to limited land availability.

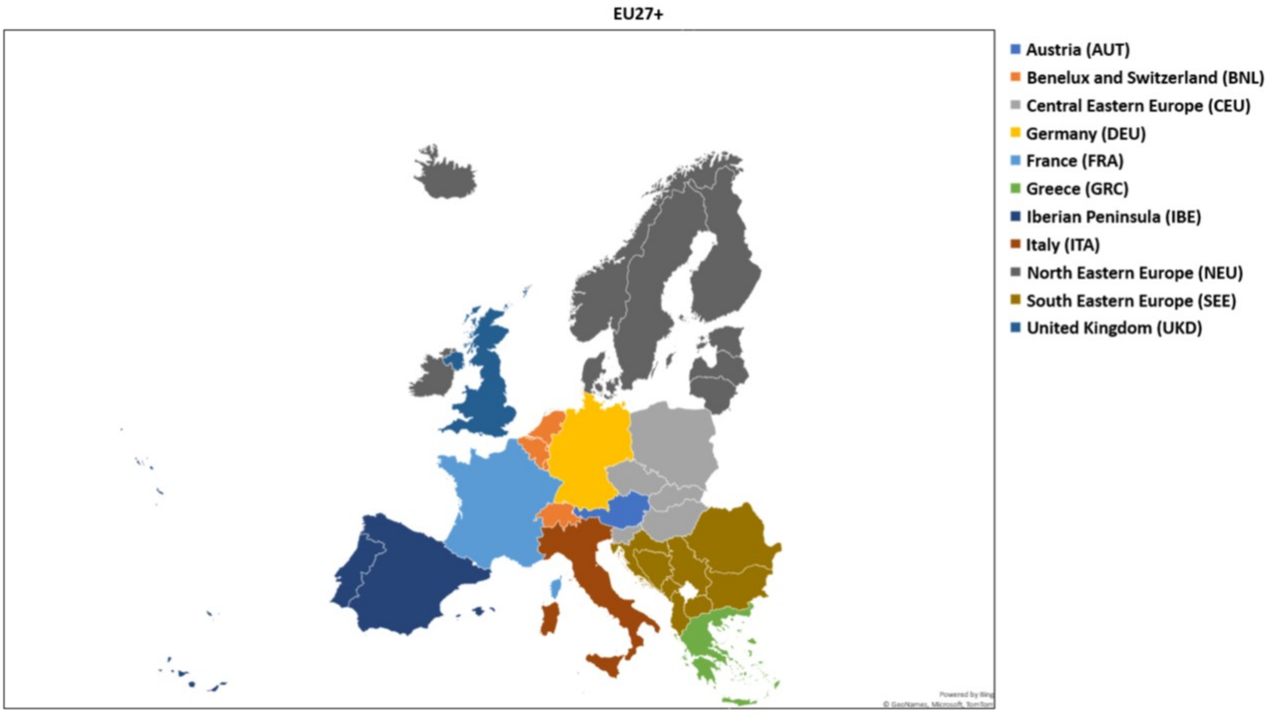


Figure 12. WEGDYN resolution for the EU27+ European regions.

The outputs of Calliope, enriched by the three storylines, are inputs to WEGDYN. Processing input data requires matching the high technology resolution of Calliope with the coarse sector representation in WEGDYN, and Calliope country resolution with WEGDYN regional aggregates. **Appendix B** – Supplementary Tables and Figures provides respective technology-sector correspondences in **Table B.5** (with a respective categorisation of generation and integration costs) and the country-region correspondence in **Table B.6**. The resolution for European regions is shown in **Figure 12**. The soft-linking itself concerns supply and demand side adjustments in the WEGDYN model to mimic the restructured energy system. The former includes the cost-quantity pairs of (i) generation, (ii) conversion and storage, and (iii) transmission. The demand side calibration between models is explained later in this section.

For electricity generation, we scale the share of physical outputs (based on Calliope derived TWhs) and productivity changes (based on Calliope derived LCOEs) of the WEGDYN electricity sector, which distinguishes various subsectors (five fossil-based, five renewable, one nuclear and one transmission and distribution). The respective energy-mix-shift (EMS) parameter depending on storyline (stl), time step (tst), region (reg) and technology (tec) reads as in **Equation 1**. WEGDYN parameters are indicated by upper bars with monetary output levels (Y) and levelized cost of electricity in the benchmark year. This parameter is multiplied with the benchmark monetary output of each WEGDYN electricity generation technology per region. For energy conversion and storage (battery, syngas and biofuels), we add respective integration costs as additional (Leontief-nested) cost input in affected WEGDYN sectors (e.g., additional cost of biofuels in supply of "refinery products"). Additional costs of transmission lines are equally split between importers and exporters and modelled as expenditure-neutral shift in the structure of the import basket of the importing region.

$$EMS(stl,tst,reg,tec) = \frac{\sum_{tec}\bar{Y}(0,reg,tec)}{\bar{Y}(0,reg,tec)} * \frac{TWh(stl,tst,reg,tec)}{\sum_{tec}TWh(stl,tst,reg,tec)} * \frac{LCOE(stl,tst,reg,tec)}{\overline{LCOE}(0,reg)} \quad (1)$$

The EU27+ electricity mix and LCOE components across storylines are shown in **Figure 13** and represent Calliope outputs processed for implementation in WEGDYN. We observe three developments at the level of EU27+ regions. First, generation of mostly renewables-based technologies increases strongly, with MDR at the slowest and PPO at the fastest pace. Second, LCOEs of the MDR storyline are less driven by generation costs due to higher transmission, while the opposite applies for PPO. The GDI storyline requires larger expenditures for storage and conversion due to a relatively centralized supply structure balancing hourly and seasonal demand patterns. Third, the GDI system is around 4% costlier in 2030 compared to the MDR system, while PPO is slightly cheaper by around -1%. By 2050, implemented energy demand in Calliope assumes that harder-to-abate sectors fully decarbonize (steel, cement, chemicals) requiring additional costly generation, storage and conversion to serve their demands, which leads to costlier GDI and PPO systems of around 10% and 26% compared to MDR.

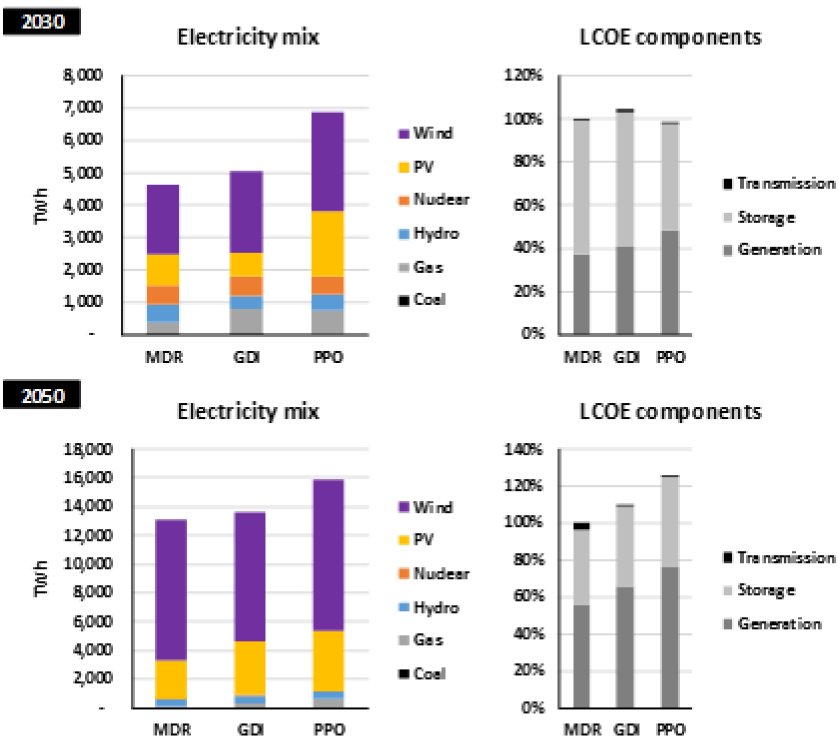


Figure 13. EU27+ electricity mix and Levelized Costs of Energy (LCOE) components across storylines for 2030 (top) and 2050 (bottom); note that gas-fired generation by 2050 is based on green hydrogen (H_2).

These near-optimal configurations of energy supply depend on specific assumptions for the development of climate-neutral service and thus energy demands of industry, transport and heating as detailed in Pickering et al. (2021). In terms of emission reductions, and taking supply and demand adjustments together, energy-related emission cuts amount to 63% by 2030 and 20% for non-energy-related in the MDR and GDI storylines resulting in a 55% system-wide reduction consistent with the European CS. The PPO storyline achieves larger system-wide reductions with 65% by 2030 (74% for energy- and 34% for non-energy-related emissions) due to the underlying governance logic with stronger diffusion of particularly roof-top PV. The energy demand side specified for Calliope modelling is transferred to the WEGDYN demand representation following two steps. First, changes in physical demand flows per storyline (stl), time step (tst), region (reg), economic sector (ecs) and energy carrier (nrg) are converted to monetary metrics using benchmark year energy expenses ($\overline{D}$) in € (from Aguiat et al. (2016)) per TWh (from Eurostat (Eurostat, 2014)) as specified in **Equation 2**:

$$D(stl, tst, reg, ecs, nrg) = \frac{TWh(stl, tst, reg, ecs, nrg)}{\overline{TWh}(0, reg, ecs, nrg)} * \overline{D}(0, reg, ecs, nrg) \qquad (2)$$

Second, and based on monetized energy demands, we update the share of energy demands relative to the benchmark (**Equation 3**), which is the new energy input quantity in respective production and consumption functions of WEGDYN. This adjustment implies that technological progress and behavioural changes are depicted as switching to new energy-using production and consumption functions.

$$EDM(stl, tst, reg, ecs, nrg) = \frac{D(stl, tst, reg, ecs, nrg)}{\sum_{nrg} D\,(stl, tst, reg, ecs, nrg)} * \frac{\sum_{nrg} \overline{D}(0, reg, ecs, nrg)}{\overline{D}(0, reg, ecs, nrg)} \qquad (3)$$

The EU27+ energy demand structure assumed for Calliope and processed for inclusion in WEGDYN is shown in **Figure 14**, which points to strong electrification of the economy. Note that by 2050, refinery products and gases are assumed to be produced synthetically and industrial processes (steel, chemicals) are assumed to be based on green hydrogen (H_2) and thus be climate neutral. To reflect this change also in WEGDYN, respective emission factors are adjusted accordingly.

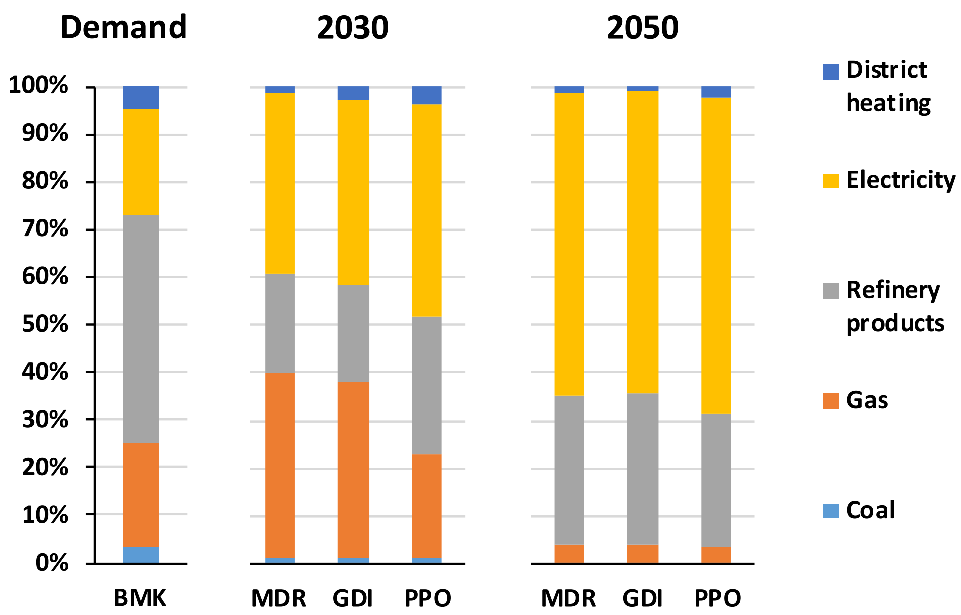


Figure 14. Structure of EU27+ energy system demand in the benchmark (bmk) year 2011 of WEGDYN and across storylines for 2030 and 2050; note that gas and refinery product demand by 2050 are green hydrogen and climate neutral synthetic sources.

Calliope-EMMA

Hourly demand profiles are implemented on the basis of Calliope simulations. This allows to account for cross-sectoral interactions that would not be captured otherwise, such as electricity demand caused by Electric Vehicles (EV) whose interaction with the electricity sector is modelled endogenously in Calliope. This does not only impact the yearly electricity demand, but also the hourly profiles. Because power-to-hydrogen is part of the EMMA model, the electricity consumed to produce H_2 in Calliope is excluded from the linkage and recalculated endogenously. This linkage and its motivation are further described in (Bachner et al., 2021).

EnergyPLAN-HEB-DESSTINEE

Hourly demand profiles for heat and electricity are implemented based on HEB's and DESSTINEE's simulations. Annual heat demands are taken from HEB's 2050 estimates from the "**Moderate Efficiency**" scenario (**Section 3.1.2.5**), while the electricity demand profiles, and transport fuel baskets are gathered from DESSTINEE. When consumption or demand shares were not available, the total annual estimates from these models were used and rescaled based on the shares already present in the EnergyPLAN scenarios.

Calliope-ENBIOS

With all of the external reference data in place, the key system definition inputs to the ENBIOS module (for each modelled scenario to be evaluated) is supplied by outputs from the Calliope model, according to the linkages shown in **Figure 15**. Indeed, the configuration of the assumed energy system (i.e., the included energy processes) within ENBIOS has been developed to align with the structure of outputs coming from the version of the Euro-Calliope model used within SENTINEL. Data from a total of 29 individual energy carrier production processes are taken from Calliope, assigned to 11 electricity, three heat and five fuel production processes at so-called 'structural processors', the nodes that represent the highest resolution in the defined hierarchical system within ENBIOS. Again, emissions from fuel combustion processes (i.e., those outside of electricity and heat processes) is calculated separately, accounting for 15 additional connections at five dedicated fuel combustion processors. Annual energy production totals are imported at all processors, while infrastructure capacities are also imported for electricity and heat processors to enable labour calculations to be undertaken. A full listing is provided in **B** – Supplementary Tables and Figures

Table B.1.

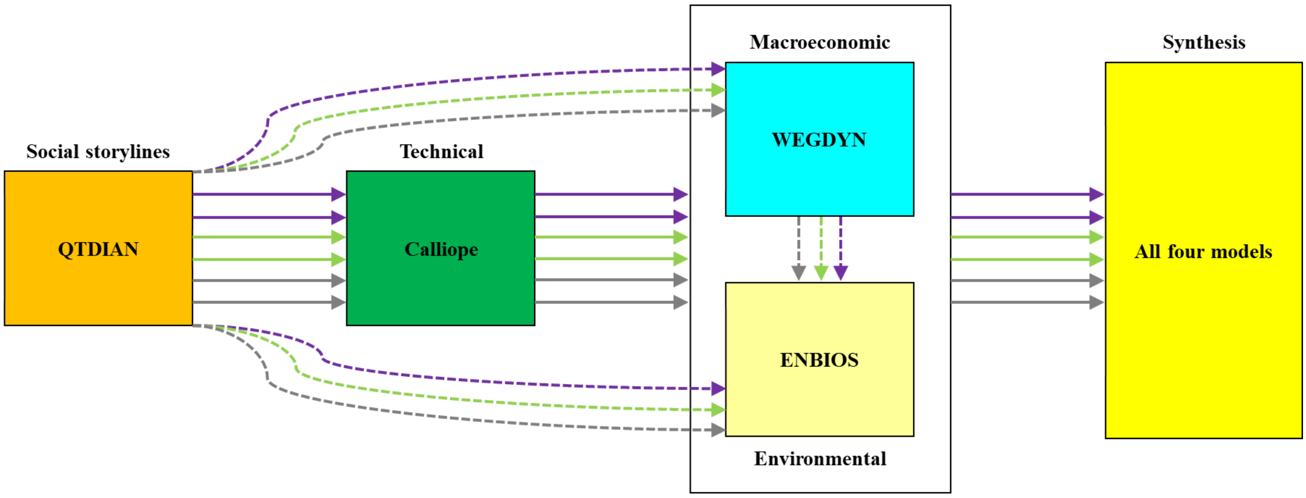


Figure 15. Linkages between the QTDIAN, Calliope, WEGDYN and ENBIOS models. Solid lines represent existing linkages, while dotted lines represent potential linkages for future simulations.

3.1.3. Transforming the power sector: increasing ambitions for Greenhouse Gas (GHG) emissions reduction & Renewable Energy Sources (RES) targets

*3.1.3.1. **EU-C1:** The role of flexibility in decarbonised economies*

Contributing models: EnergyPLAN and EMMA

Research Questions' Overview

On the path towards carbon neutrality, the share of intermittent renewable sources will increase whilst conventional emitting dispatchable units will leave the electricity system (either MDR or by regulatory interventions). This raises the question about the role of technologies that can provide flexibility in a decarbonized system, such as storages and dispatchable technologies (such as H_2-fired plants, and Carbon Capture and Sequestration (CCS) complemented units and natural gas as a bridge technology). Thus, the theme of flexibility connects RQs 7, 11 and 12 as presented below. The focus is on comparison between the "**Current**

Trends" and the "**Carbon Neutrality**" scenarios of the European CS (see **Table 4** and Deliverable 7.1 (Stavrakas et al., 2021)), and the years 2030 and 2050.

- **RQ7:** What would be the evolution of natural gas power dispatch in the coming years? What shall be an annual increase of efficiency for the gas-fired power plants? Shall they implement CCS?
- **RQ11:** What power sector flexibility mechanisms should be in the focus of energy planning/ modelling as renewables increasingly become the dominant component of the power system?
- **RQ12:** Regarding the different energy storage carriers, what will be the necessary energy capacities of large-scale storage (e.g., batteries, hydro, heat storage, etc.), synthetic fuels, and H_2 by 2030 and 2050?

Results and Discussion

Cross-sectoral interactions in Europe (EnergyPLAN results)

Cross-sectoral integration will play a significant role in the path towards climate neutrality. Namely, coupling the energy demands and infrastructure across multiple sectors such as heating, transport and industry with the intermittent renewable energy production from the power sector will allow for further flexibility across the whole energy system and reduce the need for increased capacities of expensive electricity batteries (**RQ11**).

The electrification of the heating sector can be achieved via the use of individual heat pumps at the building level, as is expected under a "**Current Trends**" scenario. However, under a "**Climate Neutrality**" scenario, district heating (DH) can also be a potential option to bridge the power and heat sectors by integrating the heat supplied from large-scale heat pumps, thermal storages and thermal grids, all of which provide an alternative to balance and store intermittent renewable energy production. Moreover, DH systems can also integrate the use of industrial excess heat, as well as making use of the recoverable heat from combined heat and power plants. The diversity in heat supply can provide further balancing options since heat production can be efficiently obtained in hours when intermittent renewable resources are not readily available.

Other cross-sectoral interactions can also be found when looking at the transport sector and industry sectors. The electrification of the road transport and industrial processes indeed provides a first level of integration. However, where electrification is not an option the use of e-fuels could play an important role, which allows for the use of existing fuel infrastructure, transport modes, and fuel storages, as well as the use of additional intermittent renewable production.

These cross-sectoral synergies are key considerations for a transition towards a smart energy system and a "**Climate Neutrality**" scenario by 2050. From the scenario modelling in EnergyPLAN, no additional large-scale electricity battery storage capacities will be needed when comparing our "**Climate Neutrality**" scenario with the "**Current Trends**" scenario in 2050 (**RQ12**). However, approximately 0.76 TWh additional thermal energy storage could be needed to supplement the DH supply. This would be equivalent to about 8 hours of storage of the average hourly DH demand. Moreover, the increase in H_2 demand – both as transport fuel and as intermediate fuel for e-fuel pathways – will require significant amounts of H_2 storage. In the modelling results, this represents an increase of over a factor of 16 relative to the "**Current Trends**" scenario, or an increase from 3.85 TWh/year to 62.95 TWh/year of H_2 storage. On the other hand, the increase in H_2 production via electrolysis also serves as an additional heat supply source, with the recoverable excess heat from the electrolysis process feeding into the DH supply.

Regional electricity sector deep-dive-Germany (EMMA results)

The share of natural gas (**RQ7**) is expected to decrease with tightening CO_2 caps. Nevertheless, CO_2 budgets are not fully utilized in the 2030 scenarios, nor in the 2050 current trends scenario. These scenarios are characterized by a carbon reduction between 47-64%. The observation that modelled emissions are lower than the CO_2 budget is caused by the decreasing investment costs of VRES (**Table 5**) paired with the increasing gas price (Duić et al., 2017).

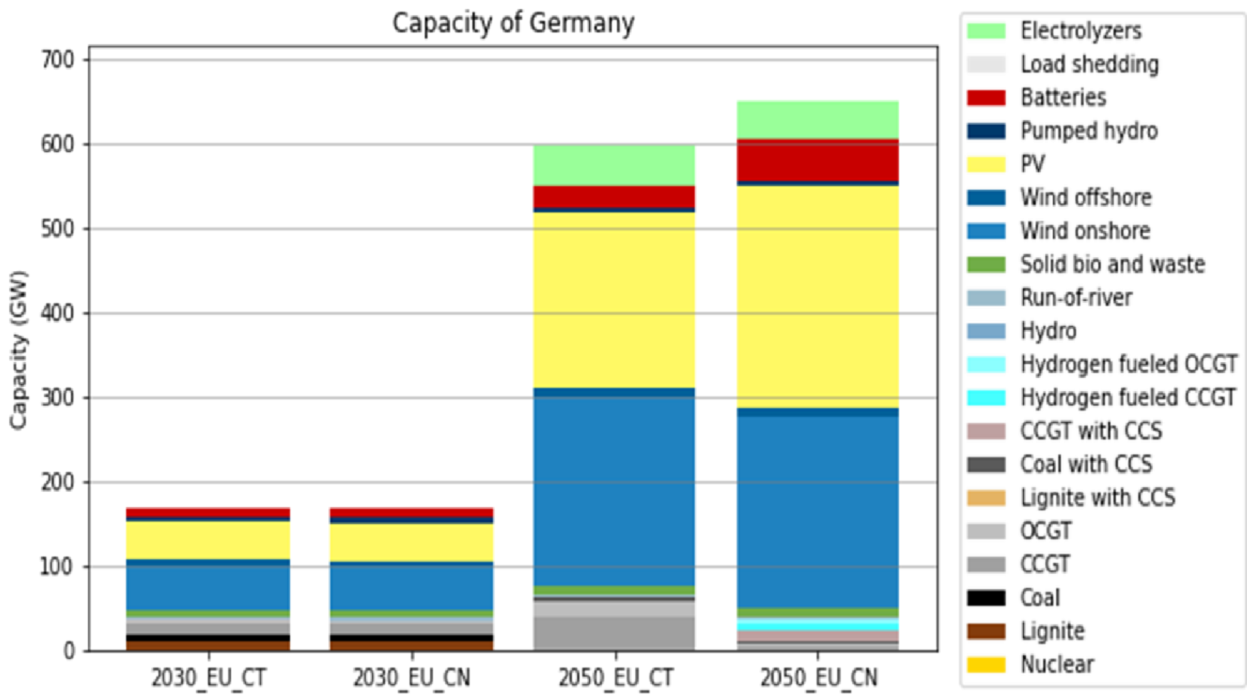


Figure 16. Installed capacity in Germany by scenario simulated by EMMA. "**2030_EU_CT**": 2030 Current Trends scenario; "**2030_EU_CN**": 2030 Carbon Neutrality scenario; "**2050_EU_CT**": 2050 Current Trends scenario; "**2050_EU_CN**": 2050 Carbon Neutrality scenario.

The share of natural gas-fired capacities (**Figure 16**) decreases in the 2050 "**Carbon Neutrality**" scenario and compared to the 2050 "**Current Trends**" scenario, this share reduces from 10% to 3%. Furthermore, more than half of the remaining gas capacities get equipped with CCS. The coexistence of natural gas with CCS and hydrogen is driven by the trade-off between investment and variable costs. The role of natural gas plants (abated and unabated) as a mid- to peak-load supplier persists, as the load factor of the most efficient Combined

Cycle Gas Turbines (CCGT) units ranges from 31.6 % to 63.6 % in all scenarios. Nevertheless, this role is less pronounced when ambitious decarbonization targets are set (i.e., 2050 "**Carbon Neutrality**" scenario).

The flexibility of the supply mix (**RQ11**) depends on the following scenario assumptions:

- **2030 scenarios:** On the supply side, flexibility is mainly provided by fossil-fuelled power plants and complemented by batteries (on top of the fixed capacity of pumped hydro storage).
- **2050 "Current Trends" scenario**: Fossil fuels still play an important role on the supply side. In addition, the installed capacities of batteries and, to a larger extent, electrolysers increase notably. This is caused by an increasing exogenous H_2 demand.
- **2050 "Carbon Neutrality" scenario**: The capacity of batteries doubles compared to the 2050 Current Trends scenario. This increase in battery capacity between these two scenarios is almost proportional to the increase in installed PV capacities. In fact, batteries can smoothen the daily fluctuations of PV generation. H_2 is used to fire CCGT and Open Cycle Gas Turbines (OCGT). Hence, H_2 complements batteries (and pumped hydro storage) as a long-term (i.e., seasonal) storage option.

With respect to the different energy storage carriers (**RQ12**), both batteries and H_2 are installed in the 2050 "**Carbon Neutrality**" scenario. This is a consequence of the assumed characteristics of these storage technologies. The round-trip efficiency of batteries is assumed to be significantly higher than the one of H_2 electrolysis combined with the CCGT (92% compared to 47.5% respectively). In contrast, the investment costs of batteries for each MWh are high compared to cost of storing H_2. As a result, batteries are an attractive short-term storage option (daily fluctuations), while H_2 storage becomes attractive for longer-term storage.

Model limitations: (i) Only H_2 is modelled, no other synthetic fuels. (ii) Besides load shedding at the price of 1000 €/MWh, power demand is inelastic. (iii) Hydroelectric power is available throughout all scenarios, but its capacity is assumed to remain constant. (iv) A fixed H_2 import price (150 €/MWh) is assumed and foreign H_2 sources (in terms of geography and in terms of technology) are not differentiated. (v) H_2 transportation and storage facilities are not modelled explicitly but assumed to sum up to 20 €/MWh. (v) Carbon absorption technologies are far from mature. We assume that carbon can be abated at the price of 1000 €/MWh.

3.1.4. Sector coupling: implementing smart energy systems and accelerating the shift to sustainable mobility

*3.1.4.1. **EU-C2:** The EU electricity grid - what is optimal or what is wanted?*

Contributing models: EnergyPLAN, Calliope and QTDIAN

Research Questions' Overview

Increasing the transmission capacities is one main way to integrate fluctuating renewables in the power system. The EC has stated that *"the power sector's shift away from fossil fuels and towards renewables [...] requires significant investment in transmission and distribution systems"* (European Commission et al., 2021).

The Ten-Year Network Development Plan (TYNDP) 2020 expects that over 300 transmission projects will be commissioned by 2040 with a length of about 45000 km (ENTSO-e, 2021). Most of the TYNDP projects fall into the time-period from 2021-2025. But the question stated in RQ20 remains:

- **RQ20:** How many additional kilometres of electricity grids in the EU are needed to foster electrification and realise climate neutrality by 2050? By how many kilometres could this amount be reduced by implementing smart and integrated renewable energy systems?

On top of that, sector coupling as well as heating and cooling are gaining increasing interest among model users (Stavrakas et al., 2021), while much of the modelling focus is still on electricity (Gaschnig et al., 2020). A redesign of the heating sector poses a major challenge in the decarbonisation process of the European energy system considering the historical path dependency of fossil fuel infrastructure, especially natural gas (Bertelsen and Mathiesen, 2020). The composition of the European heat supply relies, to a large extent, on individual supply options (Fleiter et al., 2017), however, studies have shown a great potential for DH to take a larger role in the decarbonisation of the heating sector, while allowing increased shares of VRES, diversified supply sources and storage options in a smart energy system (Connolly et al., 2014; Lund et al., 2016, 2014; Möller and Lund, 2010). Therefore, the following RQ is raised:

- **RQ23:** How should the heating and cooling sector be structured across different European countries to accommodate smart energy systems?

Results and Discussion

There is no simple answer to the question of how many additional kilometres of electricity grids are needed. The EU Reference Scenario 2020 assumes that improvements in grid infrastructure take place and that the TYNDP is completed. The PRIMES and its sub-models assume that the infrastructure plans of the European Network of Transmission System Operators for Electricity (ENTSO-E), European Network of Transmission System Operators for Gas (ENTSOG) and the Trans-European Transport Network are completed as intended (European Commission et al., 2021). This is an assumption used in many other modelling studies.

Rodríguez et al. (2014) explored the residual load and excess power generation with a 100% penetration of VRES to quantify the benefit of power transmission between countries. They find a capacity layout five times as large as today's. Furthermore, Tröndle et al. (2020) found that the cheapest, continental-wide electricity supply would require a large grid expansion to twice that of the grid as today. However, they also show that if the transmission grid is used for a continental-scale balancing of net self-sufficient regional supply, it requires much less transmission capacity − roughly the size of today's transmission system, but with twice the cross-border capacities. Most cost-optimised renewable power scenarios thus, critically hinge on the realisation and feasibility of massive grid expansion.

QTDIAN-Calliope Results (RQ20)

Model runs with the model Euro-Calliope show that the least cost, market-based storyline would require a 6x expansion of grid capacity from 2030 to 2050 within the EU28 and 3x expansion between EU28 countries and neighbouring non-EU28 countries (CH, Balkans, ISL, NOR). Meanwhile, under the PPO storyline, no European grid expansion would be possible between 2030 and 2050. This implies that there are options to reduce the transmission infrastructure whilst still achieving carbon-neutrality in energy system designs. **Figure 17** shows the distribution of capacity allocation and its impact on net electricity imports in European countries. In the MDR storyline, we see that the UK and Hungary are the two largest net electricity exporters, with an electricity network focussed on bringing this electricity from the Europe periphery into the centre. In the PPO storyline, there is relatively very little dependence on the grid infrastructure, so spatial impacts are difficult to discern. Nevertheless, most countries continue being net-importers/exporters in the two storylines. Germany is still the biggest net importer (~10% of that seen in MDR). In contrast, Italy is a net exporter in the PPO storyline compared to a net importer in the MDR storyline.

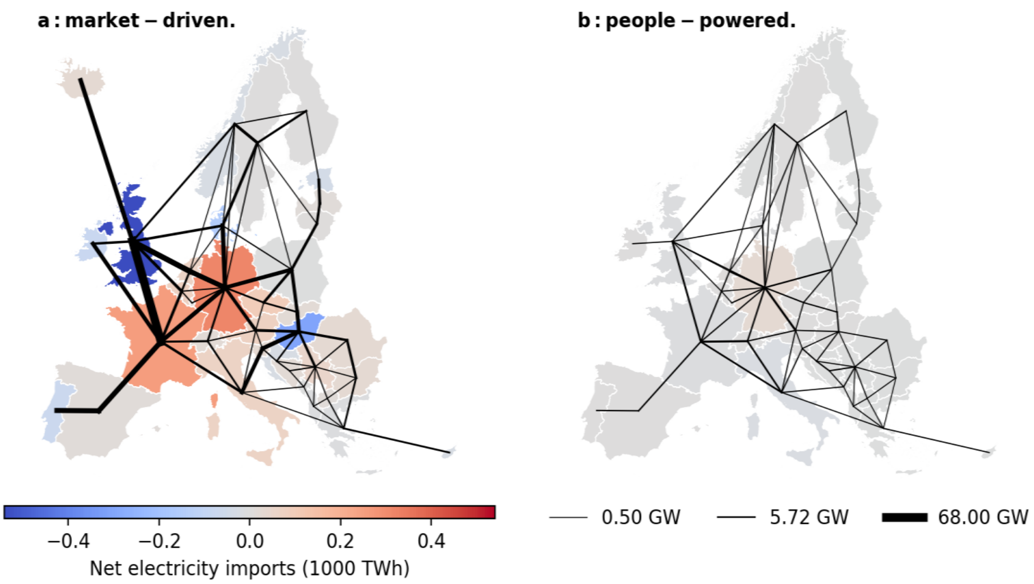


Figure 17. Comparison of QTDIAN storyline-specific 2050 grid transfer capacities between countries in Europe. Results are derived from Euro-Calliope energy system optimisation model runs for each storyline, with a target of European-wide carbon neutrality (see (Pickering et al., 2021; Süsser et al., 2021c)).

However, in reality, new installations of overhead transmission lines across Europe have met local opposition, causing delays (Pall et al., 2019; Perras, 2014). The implementation of electricity grids has been slow and thus it might not be a question of how much electricity grids are needed but of how much is socially feasible? According to the TYNDP 2020, 17% of TYNDP transmission investments are delayed − 65 out of 321 projects − and further 13% have been rescheduled (ENTSO-e, 2021). This has not changed significantly over time: TYNDP 2012 already reported that a third of projects were delayed due to “social resistance and longer than initially expected permitting procedures” (ENTSO-e, 2012). Cohen et al. (2016) found that it is important to communicate positive effects of transmission lines, such as long-term carbon reduction potential or economic benefit, to reduce opposition. Addressing opposition to transmission grids seems to be essential to ensure that planned electricity grids can become reality.

EnergyPLAN results (RQ23)

Alongside any potential changes towards new heat supply options, improvements in the future energy efficiency standards and subsequent energy savings are necessary (Lund et al., 2018). To this end, the modelling results from HEB and DESSTINEE were incorporated in the energy system scenarios as basis of projected demand developments. The demand scenarios included a "Frozen Efficiency" and a "Moderate Efficiency" scenario, which were included in the "**Current Trends**" and the "**Climate Neutrality**" scenario, respectively.

From the EnergyPLAN modelling results, the heating supply mix is shown in **Figure 18**. Here, the total heat supply in the European (EU27+UK) energy system shown includes both individual small-scale heating technologies, and large-scale units used in DH. As seen in the figure, the projected heat demands under a "**Frozen Efficiency**" demand development – implemented in the "**Current Trends**" scenario – present some heat saving compared to today, which translates in a much lower fuel consumption. However, a much larger demand reduction of roughly half is expected when considering "**Moderate Efficiency**" projections in **the** "**Climate Neutrality**" scenario. Additionally, in the "**Reference**" and "**Current Trends**" 2050 scenarios, a large portion of the heat supply consists of individual fuel boilers, predominantly consuming natural gas. While in the "**Climate Neutrality**" scenario modelled in EnergyPLAN, individual heating is mostly done via individual heat pumps.

Relative to the total heat supply, large-scale heat pumps and the use of industrial excess heat are expected to play a larger role under the "**Climate Neutrality**" scenario when introducing DH grids. In the case of the first, large-scale heat pumps provided additional flexibility to the energy system by integrating the electricity supply from renewables to be coupled to thermal storages found in DH. For the latter, the use of industrial excess heat in DH would allow re-using otherwise wasted energy from industrial process and infrastructure already in place. In addition to these, large-scale solar thermal can also be incorporated in the energy system to supply seasonal baseload heat demands, and Combined Heat and Power plants can also play a role in the heat supply in hours when VRES are not readily available.

By incorporating diverse and highly efficient heat supply options under the "**Climate Neutrality**" scenario, the European energy system can reap the benefits of the synergies across different energy sectors and can also have a flexible supply that is less reliant on fossil fuels and fuel imports, thus increasing the security of energy supply in Europe.

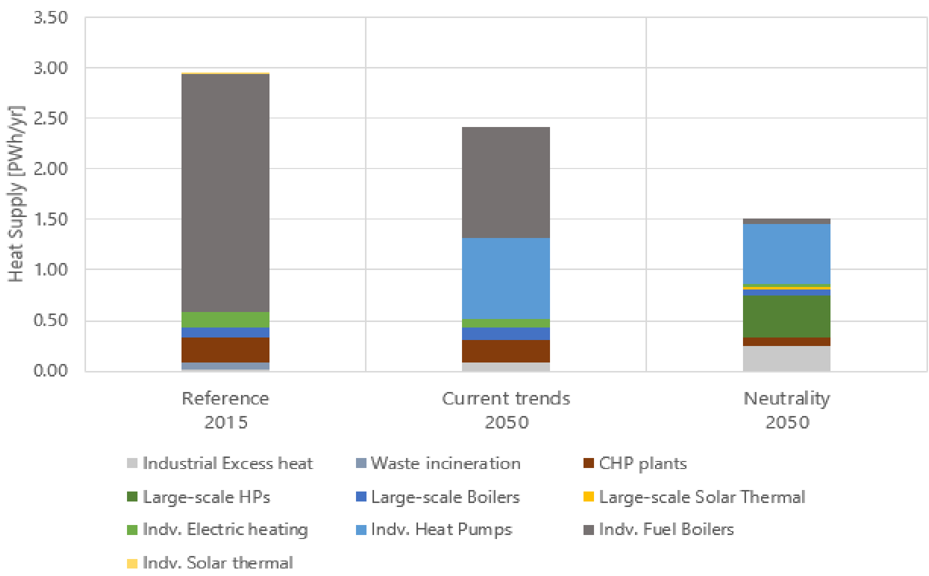


Figure 18. Heat supply mix across the energy system scenarios for the EU27+UK system, modelled in EnergyPLAN.

*3.1.4.2. **EU-C3:** Cost-effectiveness of the energy transition*

Contributing models: EnergyPLAN, QTDIAN, Calliope and WEGDYN

Research Questions' Overview

A climate neutrality pathway is connected to diverse sectoral and geographical implications, particularly if distinct social preferences and constraints are considered. The QCW model ensemble (see **Section 3.1.2.9**) defines such storylines, which lead to different configurations of the EU27+ energy system. Embedding them in a macroeconomic framework, including the broad climate policy instrument of carbon pricing, allows exploring answers to the following RQ:

- **RQ22:** How will the energy transition costs be distributed across different sectors and geographical settings? What will be the impact of system integration on the attempt to lower the strain on the electricity grids?

Furthermore, new infrastructures can facilitate the process of achieving a decarbonised European energy system. Such an infrastructure in a climate neutral EU system can be the introduction of new DH grids. DH enables the use of diverse heat supply sources and the integration of large-scale thermal storages. Seen from a system perspective, this could prove to be a cost-effective solution as waste heat from electricity production and industrial processes can be reutilized, as well as due to the cheaper costs of thermal storage compared to electricity storage. Within the EnergyPLAN model, the introduction of DH in the "**Climate Neutrality**" scenario allows answering the following RQ:

- **RQ24:** What would be the total cost of introducing DH and implementation of heat pumps, waste heat, and thermal storage in the EU by 2050?

Results and Discussion

WEGDYN results (RQ22)

The emission allowance market in the WEGDYN model fixes the supply of and confronts demand for allowances connected to the storyline-specific configuration of the energy system, in line with the emission targets specified in **Table 4**. This leads to carbon prices as shown in **Figure 19** and the same aggregate EU27+ emission reductions as already shown in **Figure 7**[7]**.** For 2030, the **GDI** storyline implies higher allowance prices due to a larger remaining share of fossil-based energy supply relative to **MDR**. The **PPO** storyline implies lower allowance prices relative to **MDR** due to stronger renewables penetration driven by the underlying governance logic. In the climate-neutral state of 2050, remaining demand is smaller than available certificates and respective allowance prices are zero.

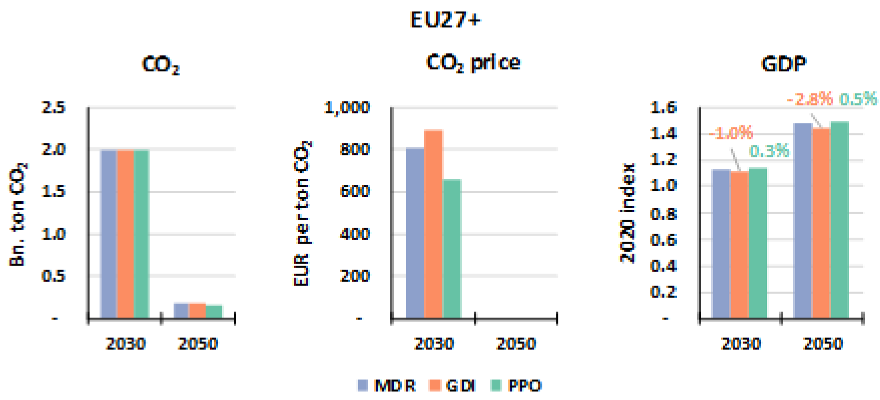


Figure 19. Carbon Dioxide (CO_2) emissions (left), allowance prices (middle) and Gross Domestic Product (GDP) effects (right) with labels indicating percentage-point deviations relative to Market-driven (MDR) storyline (blue bars) across further storylines.

At the aggregate EU27+ level, GDP rises compared to 2020 in all storylines (**Figure 19**). Compared to **MDR** the **GDI** storyline implies lower GDP and **PPO** achieves slightly larger GDP for both 2030 and 2050. Explaining these differences, **Figure 20** decomposes GDP into private and public consumption, investment and current account effects. In 2030, we see that the net-negative GDP effect for **GDI** (compared to MDR) is driven by lower private consumption and investments dominating the positive government consumption effect, which originates from higher public revenues due to higher allowance prices. There is a net-positive GDP effect for **PPO** in 2030 originating from different channels. The cut in government consumption (due to lower allowance prices and thus public revenues) dominates the otherwise positive effect on private consumption and investments. By 2050, all components of GDP show negative effects in the **GDI** storyline compared to MDR. In the **PPO** storyline, positive current consumption effects dominate small negative economy-wide investment. In the **GDI** storyline, public consumption turns negative because of strong cuts in tax income (see **Figure 63** of cluster **EU-C20** (**Section 3.1.8.2**). In the **PPO** storyline, we observe positive private income

[7] Regional and sectoral differences in emission reductions are reported in **Figure B.1** and **Figure B.2** in **Appendix B**. The implied regional excess supply or demand for emission allowances are shown in **Figure B.3**.

effects, particularly for skilled and unskilled labour driving private consumption (see **Figure 65** in cluster **EU-C20** (**Section 3.1.8.2**). This positive income effect stems from the capital-intensive energy supply in PPO with its larger share and level of renewables-based production. Consequentially, the rental rate of capital rises relative to nominal wages and energy-using sectors substitute capital for labour. In a situation of a slack labour market, this implies more employment and an expanding economy. Employment effects are reported and discussed in detail in cluster **EU-C19** (**Section 3.1.8.1**).

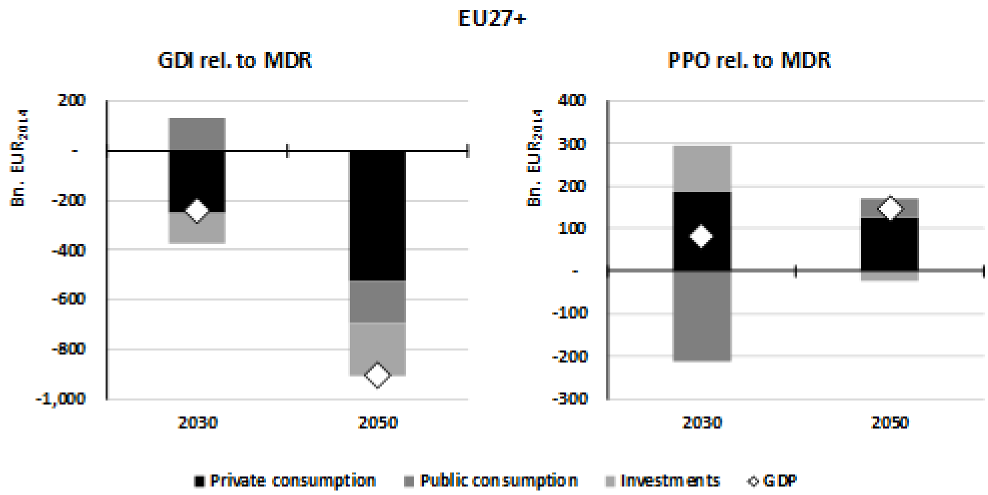


Figure 20. Gross Domestic Product (GDP) decomposition of Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

The regional variation in GDP effects is shown in **Figure 21**. For GDI, we observe lower GDP relative to MDR for all regions but for Greece (GRC) in 2030 and France (FRA) in both time periods. For GRC, positive public income effects due to higher allowance prices are comparably large relative to the size of the Greek economy. Productivity gains through lower LCOE is the main source of slightly lower rates of unemployment in FRA driving this result. Largest regional GDP discrepancies emerge in PPO mainly due to restricted transmission, which leads to less favourable GDP effects for the continental periphery (inter alia SEE, IBE and GRC). A “deep dive” into economic effects for Greece is provided in the respective CS section of this deliverable. Note that GDP is a proxy measure of economy-wide income and expenditures but does not reflect purchasing power, which is why we report relevant welfare impacts in **Figure 67** in cluster **EU-C20 (Section 3.1.8.2**).

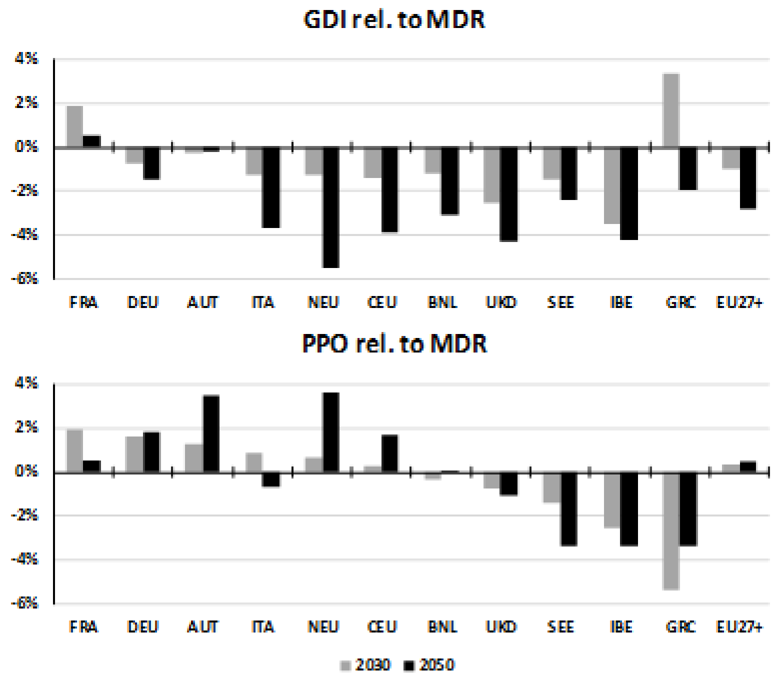


Figure 21. Regional Gross Domestic Product effects of Government-directed (GDI, top) and People Powered (PPO, bottom) storylines relative to the Market-driven (MDR) storyline; AUT: Austria; BNL: Benelux and Switzerland; CEU: Central & Eastern Europe; DEU: Germany; FRA: France; GRC: Greece; IBE: Iberian Peninsula; ITA: Italy; NEU: North-Eastern Europe; SEE: South-Eastern Europe; UKD: United Kingdom. Further details in **Table B.6**.

Price and turnover effects per economic sector are shown in **Figure 22**. Largest productivity changes in terms of price reactions are visible for the "electricity" sector (ELY) in the GDI and PPO storylines compared to MDR. For GDI, largest turnover gains emerge for the sectors "gas distribution and hot water supply" (GDT) as well as "crude oil" (OIL) and largest turnover losses for "coal supply" (COA). For PPO, the positive turnover effect for ELY in 2030 is a result of small productivity gains in the energy system configuration, which also drive economy-wide activity inducing positive turnover effects for sectors OIL and P_C in 2030. Largest turnover losses in PPO concern the sectors GDT and COA. Note that the products of the OIL sector are not only relevant for purposes of energy-use but are essential non-energy inputs in the chemical, plastics and pharmaceuticals industry.

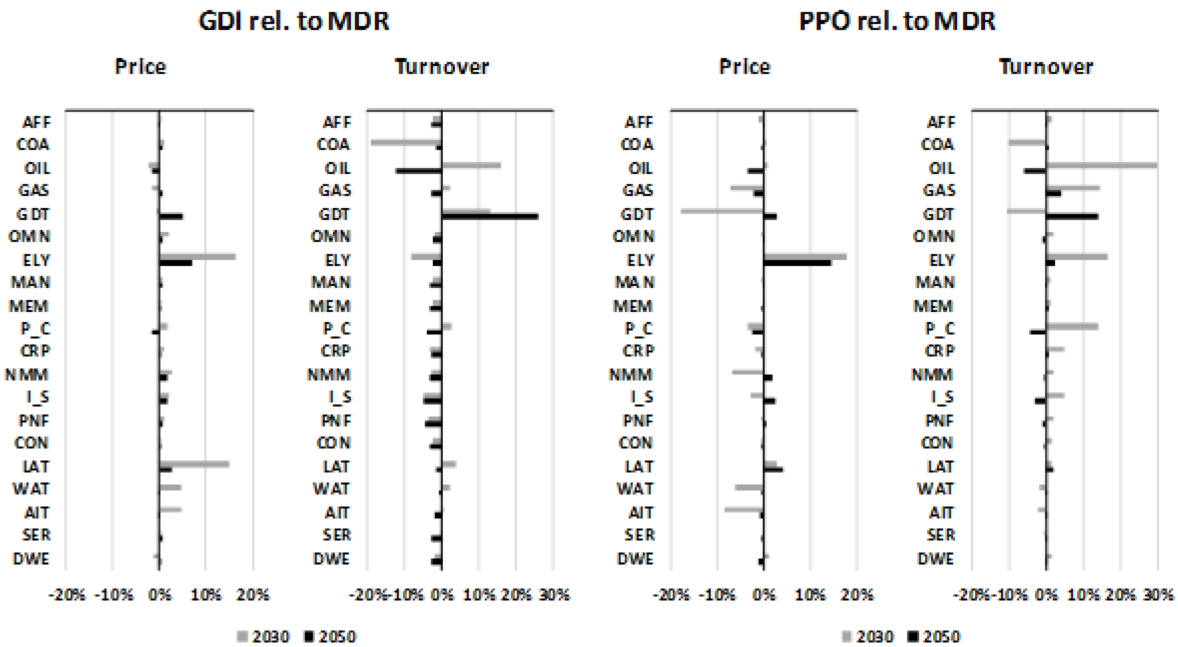


Figure 22. EU27+ price and turnover effects per economic sector of the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline; AFF: Agriculture, Forestry and Fishery; COA: Coal; OIL: Crude Oil ; GAS: Natural Gas; GDT: Gas distribution and hot water supply; OMN: Other mining; ELY: Electricity; MAN: Manufacturing; MEM: Machinery, equipment, other; P_C: Refined oil products ; CRP: Chemical, rubber, plastic products; NMM: Manufacture of other non-metallic mineral products; I_S: Manufacture of basic iron and steel and casting; PNF: Manufacture of precious and non-ferrous metals, and fabricated metal products; CON: Construction; LAT: Transport – Land; WAT: Transport –Water; AIT: Transport –Air; SER: Other services; DWE: Dwellings and real estate. Further details in **Table B.7**.

EnergyPLAN results (RQ24)

The introduction of DH will require investment in new large-scale conversion technologies, thermal storages, as well as thermal grid infrastructure. From the former, the investment costs in DH grids and substations will represent the largest share in costs. However, this will be comparable to the investment costs in individual heating, mainly individual heat pumps. A comparison of the annualised costs in heating supply is present in **Figure 23**.

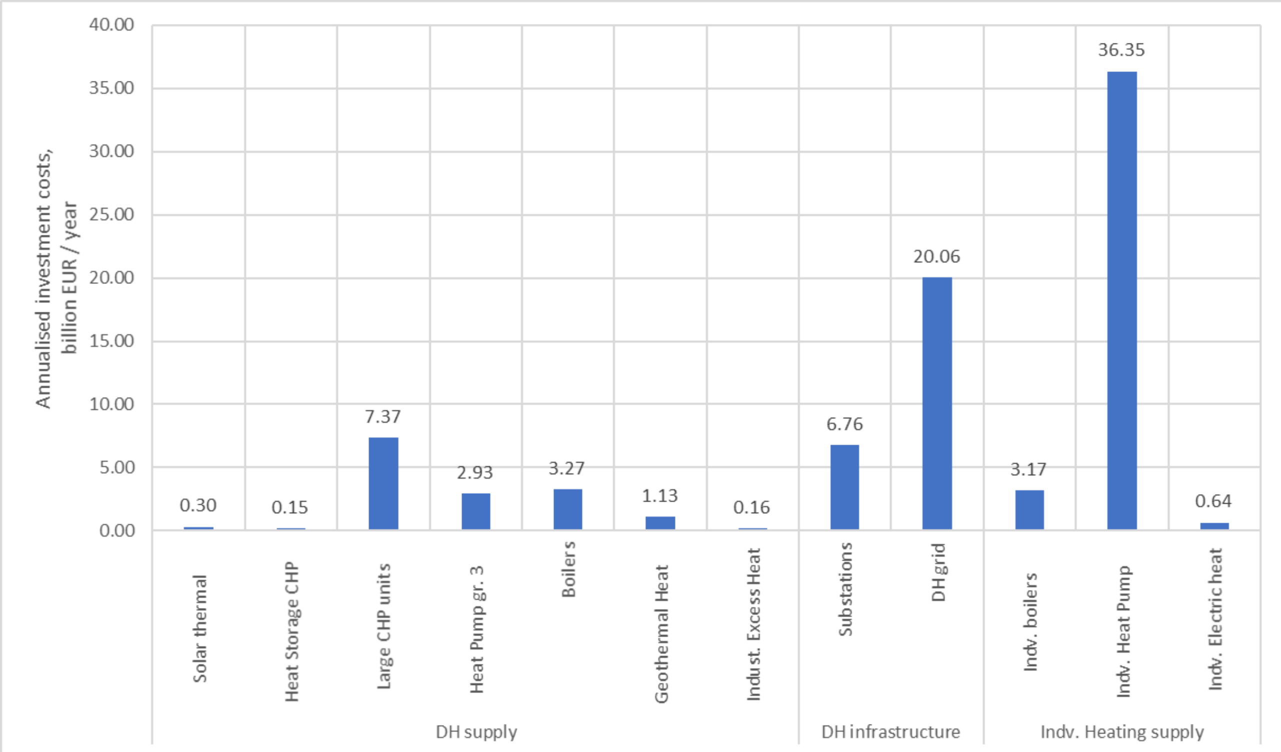


Figure 23. Annualised investment costs of heating technologies and infrastructure in billion EUR/year.

*3.1.4.3. **EU-C4**: Industrial Decarbonisation*

Contributing models: DESSTINEE, EnergyPLAN, Calliope, and IMAGE

Research Questions' Overview

This following set of RQs aims to understand key transformations which are foreseen to occur in the industrial sector to reduce the carbon footprint of light and heavy industries.

- **RQ26:** What are the potentials for H_2 and DH usage in industry?
- **RQ28:** How can low carbon fuel contribute to decreasing the carbon footprint of the industrial sector? Particularly, what is the role that electrification will play?

Calliope, DESSTINEE, and EnergyPLAN used the increase of sectorial value added (from the EU Reference Scenario (European Commission et al., 2021)) to project the sectorial outputs or service energy demand. IMAGE uses a combination of bottom-up and top-down approaches to estimate its industrial projections, and energy use is calibrated to IEA balances (IEA, 2017) or more detailed data if available. Specifically, steel, cement, paper, chemicals, and food industrial sectors use bottom-up calculations and are supplemented by a top-down method, mainly for light-industry, using the industrial value added as driver for energy use. Considering the approaches, summarised in **Section 3.1.2.3**, the different models have simulated/defined the fuel baskets for large energy-consuming industrial sectors – such as ‘Steel and metallic’, ‘Cement and minerals’, ‘Chemicals’, and ‘Paper and Pulp’ manufacturing facilities. Some less energy-intensive sectors, such as ‘Food Production’ or other types of light industries, are considered in detail by some of the models, though most of the models group these sectors under a single ‘Light Industry’ category.

Results and Discussion

Figure 24 displays the fuel basket for the industrial sector derived from the four models, showing the role that the different energy feedstocks will play in view of decarbonising the secondary sector. Further sectoral insights are the main subject of the cluster **EU-C9** (**Section 3.1.5.1**).

As a general pattern, the models project an increase in the power consumption within industries across the scenarios and the time horizons. The different models also project a partial substitution of natural gas and coal by synthetic gases, such as ‘power to gas’ and H_2. Reported total figures for FEC within the industrial sector range between 10 and 12 EJ for 2030 (in a scenario compatible with 55% overall reduction in comparison with 1990) and between 8 and 12 EJ by 2050 (with the exception of Calliope) considering the emission cuts to fulfil climate neutrality. Higher energy inputs simulated by Calliope are a consequence of different assumptions for accounting of feedstock for chemical industries, the latter being included in the figures for total sectoral energy consumption. Furthermore, efficiencies for manufacturing processes within industries are assumed to keep constant in Calliope.

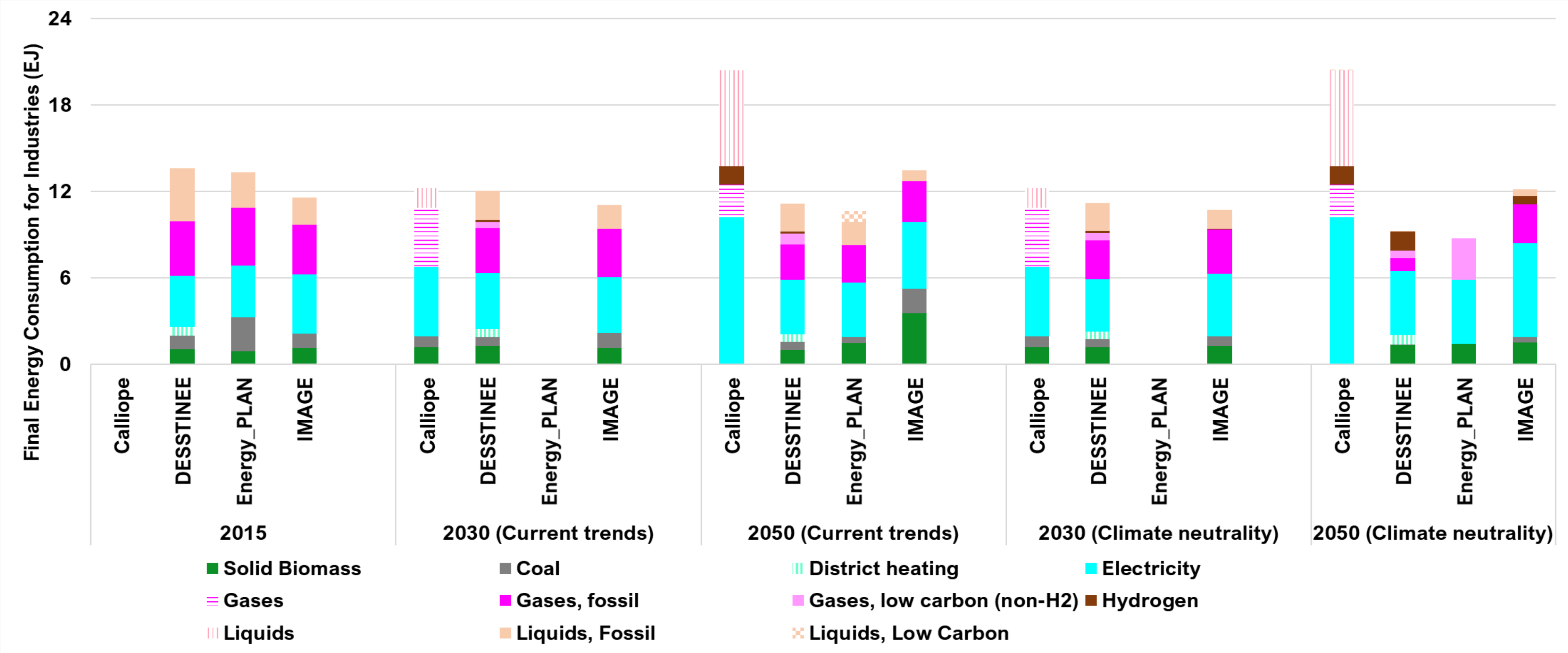


Figure 24. Final energy consumption for Industries, according to fuel type, reported by the four energy models. ‘Gases’ and ‘Liquids’ account for all gaseous and liquid fuels (some models only report at this level) respectively, ‘Gases, fossil’ and ‘Liquids, fossil’ groups all fossil gaseous and liquids fuels (for models presenting results at this level), ‘Gases, low carbon (non-H_2)’ and ‘Liquids, low carbon’ consider gaseous/liquid biofuels and ‘Power-to-X’ solutions.

3.1.4.4. ***EU-C5***: *Heat pump deployment*

Contributing models: DESSTINEE, EnergyPLAN, and IMAGE

Research Questions' Overview

As mentioned in Deliverable 7.1 (Stavrakas et al., 2021), heating strategies for Europe should be established and the potential for DH and heat pumps should be investigated. Therefore, the following RQ is tackled.

- **RQ27:** What should be the adoption rate of heat pumps in European households instead of ineffective less efficient heaters by 2030 and 2050 to decarbonise residential buildings?

Results and Discussion

Using the thermal energy service demand projected by HEB, EnergyPLAN and Calliope we modelled the FEC for buildings accounting for the least-cost options to meet overall emission reduction targets for 2050.

DESSTINEE estimated the thermal energy service demand using data by nationally adapting (based on current trends) continent-wide building renovation rates from officially released scenarios (European Commission, 2020c; Runge-Metzger, 2018) and income-based correlations for building floor area increase (as default methodology). In addition, three alternative scenarios were defined ("**DESSTINEE_gov**", "**DESSTINEE_market**", and "**DESSTINEE_power**") based on QTDIAN outputs for behavioural patterns in terms of building occupancy and area growth. QTDIAN methodology is further described in Deliverable 2.3 (Süsser et al., 2021a). Continent-wide shares for electrification of heating from the EC official scenarios (European Commission, 2020c; Runge-Metzger, 2018) were nationally adapted assuming that current differences in electricity usage patterns among countries would persist in the future. Past trends for the penetration of heat pumps, reported in the JRC-IDEES database (Mantzos et al., 2017), were extrapolated to allocate the fraction of electric heat being delivered by heat pumps.

The IMAGE model includes a detailed residential building sector and a less detailed service sector. The residential sector uses demand variables, such as floor space and Heating Degree Days (HDD), to determine output variables such as final energy demand and corresponding emissions. In the IMAGE energy model, called TIMER, the multinomial logit function is used to mimic investment decisions in options/technologies for the buildings insulation/renovation, technology used for heating, the appliances, etc. The service building sector uses a top-down approach using the sectorial value added. However, this approach is enriched by additional factors affecting energy demand, such as the improvement in the buildings' envelope.

Figure 25 displays the total FEC for heating in buildings, accounting both for residential and commercial facilities. Given that not all the models distinguish between residential and commercial buildings, this section discusses the trends for the whole building sector.

Electricity is expected to become the most used fuel for heating purposes in 2050, both for the "**Current Trends**" and the "**Climate Neutrality**" scenarios. This is a consequence of the wide adoption of heat pumps, which, according to **Figure 26,** deliver the largest number of buildings' thermal requirements. By 2050, DESSTINEE and EnergyPLAN project that heat pumps will deliver 42% and 60% of the thermal energy service in buildings respectively, when assuming fulfilment of climate neutrality pledges. As a consequence, heat pumps will produce between 4.2 and 5.8 EJ of thermal energy service demand, whilst consuming between 1.2 and 1.6 EJ of electricity. Scenarios conducted by DESSTINEE project that country-level shares of heat delivered by heat pumps will vary between 5% and 66% by 2030 ("**Climate Neutrality**" scenarios) and between 15% and 84% by 2050. This is a consequence of the current wide span for heating electrification rates which is assumed to continue in the future despite overall continent-wide increases.

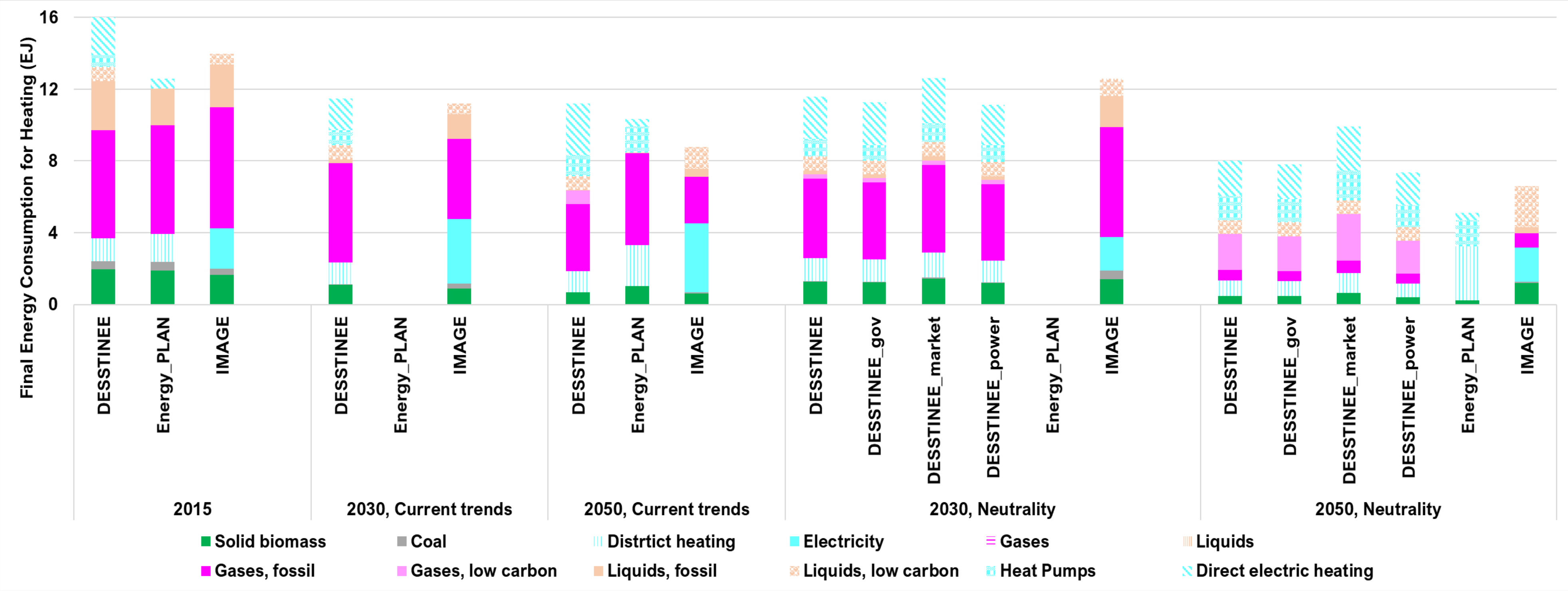


Figure 25. Final energy consumption for heating according to fuel type, reported by the four energy models. 'Gases' and 'Liquids' account for all gaseous and liquid fuels (some models only report at this level) respectively, 'Gases, fossil' and 'Liquids, fossil' groups all fossil gaseous and liquids fuels (for models presenting results at this level), 'Gases, low and 'Liquids, low carbon' consider gaseous/liquid biofuels, H_2 and 'Power-to-X' solutions. 'Heat pumps' refers to the power consumption by heat pumps whilst 'Direct electric heating accounts for all other non-heat pump technologies to supply heat using electricity**.**

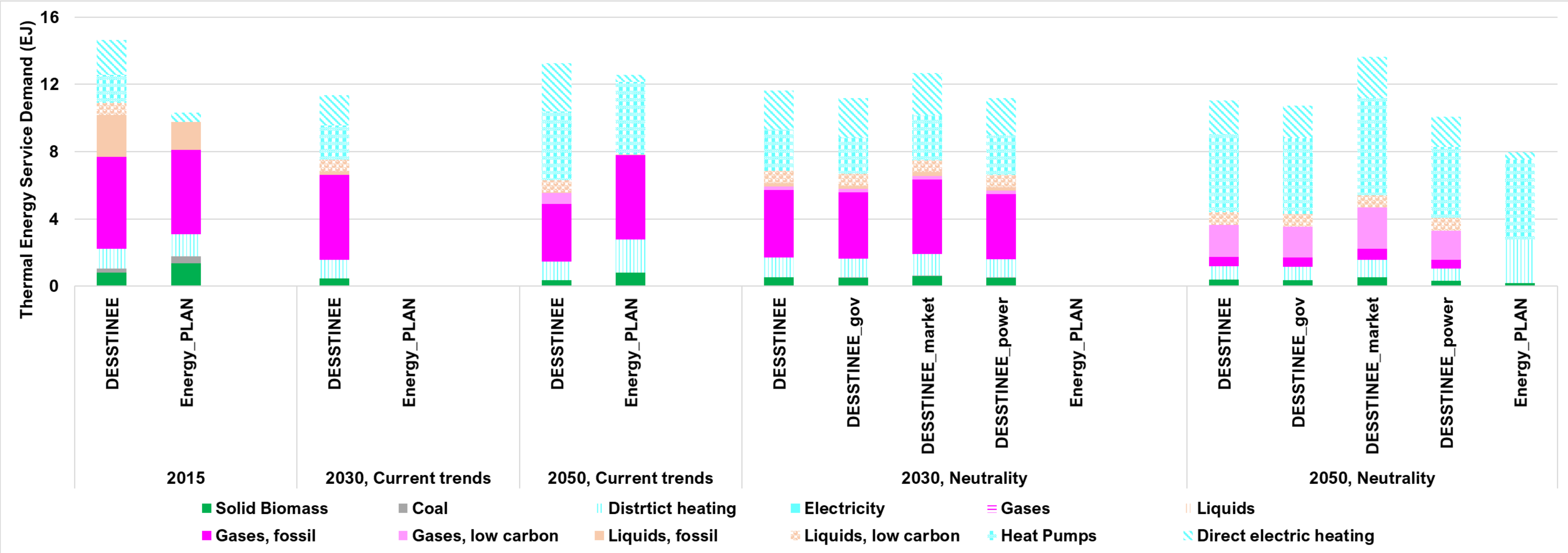


Figure 26. Thermal Energy Service Demand in buildings, according to fuel type, reported by the models. 'Gases' and 'Liquids' account for all gaseous and liquid fuels (some models only report at this level) respectively, 'Gases, fossil' and 'Liquids, fossil' groups all fossil gaseous and liquids fuels (for models presenting results at this level), 'Gases, low and 'Liquids, low carbon' consider gaseous/liquid biofuels, H_2 and 'Power-to-X' solutions. 'Heat pumps' refers to the power consumption by heat pumps whilst 'Direct electric heating accounts for all other non-heat pump technologies to supply heat using electricity.

3.1.4.5. ***EU-C6***: *Electrification of passenger road transport*

Contributing models: DESSTINEE and IMAGE

Research Questions' Overview

Electrification of road transport, particularly of passenger cars, is considered crucial to reducing transport-related emissions. EVs constitutes both battery electric vehicle (BEV) – operated only with electricity, and hybrid EVs – which use both electricity and liquid fuels. The following RQs are tackled:

- **RQ30:** What should be the share of EVs and plug-in hybrid EVs (PHEVs) in the total car fleet by 2030 and 2050?
- **RQ32:** What should be the pace of exchanging the existing car fleet with EVs by 2030 and 2050 to achieve 90% reduction in transport emissions by 2050? What are the other options to decarbonise the transport sector, except for introduction of EVs?

Results and Discussion

FEC and associated emissions from road transport are modelled in DESSTINEE using assumptions for the shares of travel demand corresponding to each type of fuelled unit within a vehicle category. These shares are considered to be equal to the fleet composition, since occupancy and yearly mileage for the different types are equal within a category, and are defined at the national level whilst respecting continent-wide emission cuts for the transport sector (European Commission, 2020c; Runge-Metzger, 2018). In the case of EVs, the correlation between the ratio of country-level and the EU-wide share of electric cars and the ratio of national and continental GDP per capita was used to model the national uptake. This mathematical relationship was based on current data, and assumed to be valid for the different time horizons here considered, employing figures for continental shares from the official scenarios (European Commission, 2020c; Runge-Metzger, 2018) to estimate national values.

The starting point of the transport model in IMAGE/TIMER are the travel time budget and travel money budget. These budgets assume that on average daily travel time only slightly increases with income, and money spent on travel increases more with income. Due to income increases in a region, faster transport modes (e.g., walking, cycling, driving) are chosen, and therefore larger distances are covered. The latter determines the service demand in terms of tonnes-km and passenger-km. For each transport mode, the multinomial logit determines the investment decisions in available vehicle types (e.g., diesel, electric cars, etc.).

Regarding the share of EVs and hybrids in the total car fleet by 2030 and 2050 (**RQ30**), **Table 15** presents the intervals for their shares as reported by DESSTINEE and IMAGE. The observed differences in 2030 are mostly a consequence of the assumptions on phasing out trends for internal combustion engines (ICEs). When analysing 2050, the differences mostly derive from considering different paces for the deployment of H_2 /fuel-cell technologies. DESSTINEE, based on the official high-level continental projections (European Commission, 2020c; Runge-Metzger, 2018), assumes that around one-fifth of the passenger car fleet will be made up of fuel cell EVs (climate neutrality).

Table 15. Continent-wide shares for battery and hybrid electric vehicles in the passenger car fleet, expressed in % of total vehicle stock (IMAGE) and in % of total travelled distance[8] (DESSTINEE).

	2030		**2050**	
	Current trends	Neutrality	Current trends	Neutrality
BEV in the passenger car fleet	10 – 26%	13 – 27%	50 – 52%	74 – 95%
Hybrids in the passenger car fleet	4 – 25%	7 – 41%	4 – 28%	0.2 – 4%

National ranges, defined using DESSTINEE, corresponding to the "**Climate Neutrality**" scenarios for 2030 and 2050 are presented below.

Table 16. Country-level shares of travelled distance by battery electric vehicles and hybrid units on total travelled distance by cars, expressed in %. Bounds among the 28 countries of the bloc, modelled using DESSTINEE.

	2030 (Neutrality)	**2050 (Neutrality)**
BEV in the passenger car fleet	5 – 20%	59 – 81%
Hybrids in the passenger car fleet	1– 13%	Lower than 3%

Regarding **RQ32**, **Figure 27** displays emission reductions for passenger cars across the different scenarios and time horizons. Reductions are defined in comparison with 2015 values estimated by each modelling tool. We can observe that the proposed fleet for the 2050 "**Climate Neutrality**" scenario enables decreases which are larger than 90%.

[8] The remainder percentage consists of fuel cell units; It is assumed that the share of travelled distance is equal to the shares of vehicles.

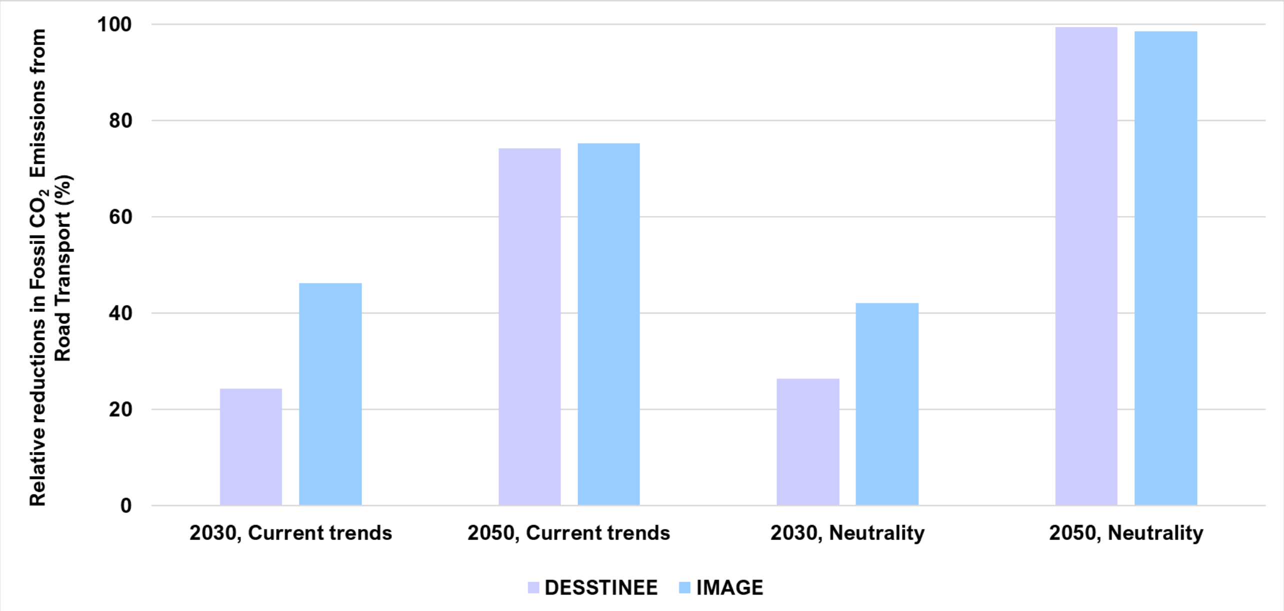


Figure 27. Reductions in direct fossil Carbon Dioxide (CO_2) emissions from passenger cars projected by DESSTINEE and IMAGE at EU27+UK level.

3.1.4.6. ***EU-C7****: Emission and fuel economy standards*

Contributing models: DESSTINEE

Research Questions' Overview

Post-2020 emission and fuel economy standards are envisaged to contribute to the decarbonisation of ICE vehicles. Particularly, aiming to reduce the fuel usage per travelled kilometre. The following RQs are tackled:

- **RQ33:** What should be the post 2020 CO_2 emission standards for fossil-fuelled vehicles?
- **RQ34:** What should be the increase in efficiency (fuel consumed per km) for different types of vehicles by 2030 and 2050?

Results and Discussion

In DESSTINEE, emission and fuel economy standards are considered for the calculation of the average fuel economy indicators per vehicle category. Current age profile for the different vehicle types, based on EUROSTAT data (Eurostat, 2021a), is extrapolated to the time horizon of the scenarios, building an age-weighted average fuel economy indicator for each vehicle type (accounting for different assumptions in terms of standards for new vehicles). Existing legislation is assumed to be compelled for 2030 and fuel economy indicators are modelled, for the years comprising between nowadays and that time frame, following a linear interpolation. In the case of 2050, previously conducted studies (Stewart and Stokeld, 2017) were consulted to define seed values for an iterative calculation process, enabling the definition of standards for the new vehicles whilst fulfilling the residual emissions for fossil-fuelled vehicles.

Table 17 and **Table 18** respectively display the age-weighted fuel economy indicators and emissions per travelled distance for the vehicle categories considered in DESSTINEE. Whilst the figures modelled for 2050 represent a significant change in comparison with nowadays, the yearly increase in efficiency would be close to 1.4%. This improvement rate is compatible with the trends observed in the last three decades, showing that these ambitious targets could be feasible (Lapillonne et al., 2021).

Table 17. Fuel economy indicators (expressed in MJ/km) for different vehicle categories, scenarios, and time horizons modelled by DESSTINEE.

	Small cars				Large cars				Light duty commercial vehicles				Buses and trucks			
MJ/km	Gasoline	Diesel	BEV	FC	Gasoline	Diesel	BEV	FC	Gasoline	Diesel	BEV	FC	Gasoline	Diesel	BEV	FC
2015	2.0	1.4	0.5	1.0	2.2	1.8	0.5	1.0	3.8	3.0	0.6	0.9	16	11.3	4.2	9
2030, current trends	1.5	1.2	0.44	0.8	1.7	1.5	0.44	0.8	3.4	2.6	0.6	0.8	13.6	9.6	4.2	9
2050, current trends	1.0	0.7	0.4	0.8	1.1	0.9	0.4	0.8	2.3	1.8	0.5	0.8	8	5.7	3.7	7.4
2030, Neutrality	1.4	1.1	0.44	0.9	1.6	1.4	0.44	0.9	3.4	2.6	0.55	0.7	12.8	9.6	4.5	9
2050, Neutrality	1.0	0.7	0.4	0.8	1.1	0.9	0.4	0.8	2.3	1.8	0.5	0.8	8	5.7	3.7	7.4

Table 18. Emissions (expressed in gCO_2/km) for different vehicle categories, scenarios, and time horizons modelled by DESSTINEE.

	Small cars				Large cars				Light duty commercial vehicles				Buses and trucks			
gCO_2 /km	Gasoline	Diesel	BEV	FC	Gasoline	Diesel	BEV	FC	Gasoline	Diesel	BEV	FC	Gasoline	Diesel	BEV	FC
2015	136	104	-	-	153	133	-	-	263	222	-	-	1109	837	-	-
2030, current trends	103	89	-	-	118	111	-	-	235	193	-	-	942	711	-	-
2050, current trends	68	52	-	-	76	65	-	-	159	133	-	-	554	422	-	-
2030, Neutrality	97	82	-	-	111	104	-	-	235	193	-	-	887	711	-	-
2050, Neutrality	68	52	-	-	76	65	-	-	159	133	-	-	554	422	-	-

*3.1.4.7. **EU-C8**: Decarbonisation of road transport freight and other transport modes*

Contributing models: DESSTINEE

Research Questions' Overview

Due to load and long-distance travel demand, the decarbonisation of the freight road and other transportation modes (excluding rail) may be unsuitable for batteries, as in the case of passenger cars. Alternative solutions need to be considered, involving the use of H_2 and other low-carbon fuels (power to gas and power to liquid carriers and rich biofueled blends). In this respect, the following RQs are addressed:

- **RQ36:** What role will electricity play in the decarbonisation of freight road transport?
- **RQ37:** How can H_2 contribute to decarbonising freight road transport?
- **RQ38:** Can we distinguish different strategies according to vehicle type?
- **RQ40:** How can we reduce emissions from navigation and aviation?

Results and Discussion

In the case of DEESTINEE, a similar approach to the procedures described in cluster **EU-C6** (**Section 3.1.4.5**) was applied for the light duty and the heavy duty or truck categories. To answer this set of RQs, modelling results associated with the latter were considered. Continent-wide predictions for the truck fleet were nationally adapted on the basis of income-based correlations for the case of EVs whilst current country-level patterns for biofuel consumption were considered for the downscaling for the EU27+UK covering scenarios.

For H_2 ('green'), two calculation routes were considered given the possible production pathways for this fuel. One of these routes consists of nationally downscaling total travelled distance on the basis of the ratio of country-level EVs and total continental figures. This is because a share of the H_2 will be synthesised using excess electricity thus one could assume that the larger penetration of EVs indicates larger electricity production. H_2 can also be obtained thanks to the gasification of woody biomass thus the ratio of country-level biomass and the total continental production figures were also employed to disaggregate EU27+UK covering projections for travelled distance using H_2 from officially released decarbonisation scenarios (European Commission, 2020c; Runge-Metzger, 2018). The shares of travelled distance using H_2 on national total travel distance by trucks (modelled by the EU Reference Scenario (European Commission et al., 2021)) were estimated as the average of the fractions defined using the two possible 'H_2 routes'.

For the four scenarios, **Figure 28** displays the resulting fuel shares for travelled distance by trucks (at EU level) modelled by DESSTINEE whilst **Table 19** reports the bounds for each of these categories at the national level across the 28 countries (for the "**Climate Neutrality**" scenarios).

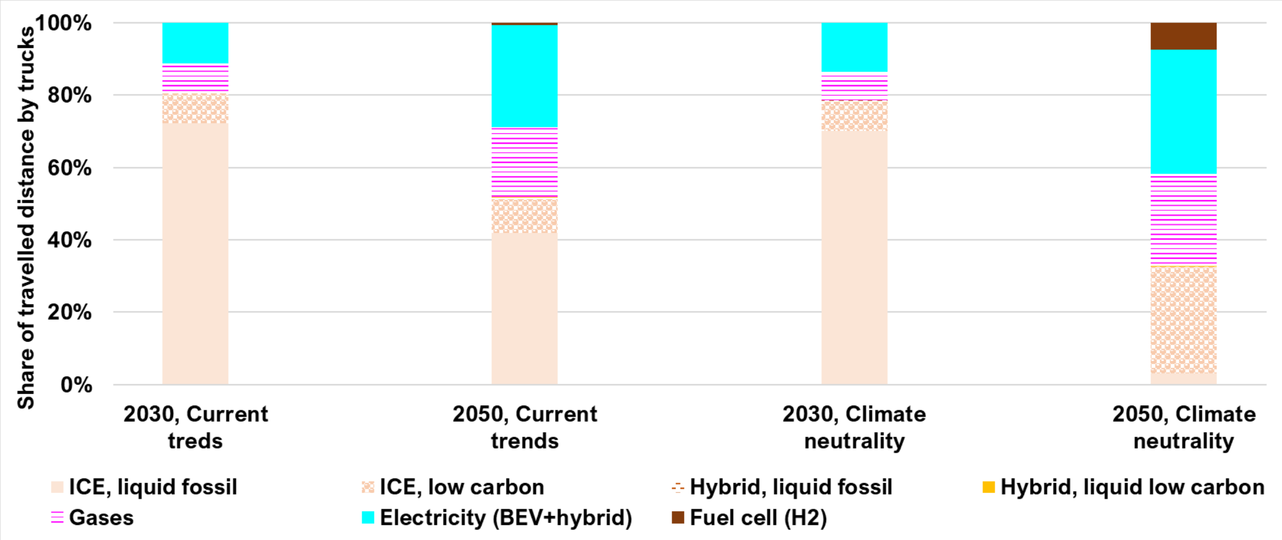


Figure 28. Shares of travelled distance for different fuelled truck types, modelled by DESSTINEE. 'ICE' accounts for internal combustion engine units, operated with 'liquid fossil' or 'low carbon' (bioliquids and Power-to-X solutions).

Table 19. Bounds of shares for travel distance, by fuel type, in total travel demand by trucks across the 28 countries (modelled by DESSTINEE).

Share in total country-level travelled distance for trucks	2030, Climate Neutrality	2050, Climate Neutrality
ICE, liquid fossil	47 – 85%	2 – 5%
ICE, liquid low carbon	2 – 18%	2 – 5%
Hybrid, liquid fossil	Lower than 8%	Lower than 0.6%
Hybrid, liquid low carbon	Lower than 2%	Lower than 6%
Gases	5 – 9%	14 – 34%
Electricity (BEV+ hybrid)	2 – 4%	8 – 56%
Fuel cell (H_2)	-	1 – 22%

As we can observe, a steady decrease in the shares of travelled distance by fossil fuels is expected in view of reaching emission reduction targets. On the contrary, the travelled distance by the natural gas-fuelled vehicles is projected to significantly increase alike the role of EVs (accounting for battery and hybrids). It must be noted that the truck subcategory includes vehicles with a wide span of loads, used in different settings and to transport goods from different industrial and retail activities. This is translated in the bounds presented in the table above. In some countries, vehicles with lower weight and travelling shorter distances could be more widespread, enabling further electrification of the fleet.

Regarding navigation and aviation, a significant substitution of fossil liquids by low carbon vectors, mostly 'power to liquids' and biofuels, is also required if emission cuts compatible with the overall neutrality targets are to be met in 2030 and 2050, as displayed in **Figure 29**.

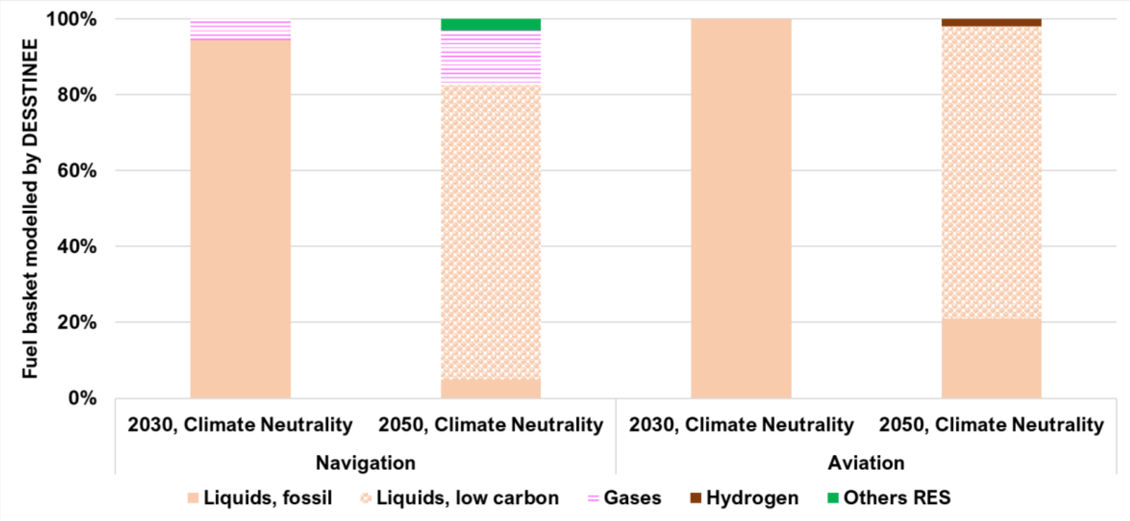


Figure 29. Shares in fuel basket for navigation and aviation. "Other RES" consider renewables on board, especially for navigation.

3.1.5. Decarbonisation of industry and Carbon Capture Utilisation and Storage & Bioenergy with Carbon Capture and Storage

*3.1.5.1. **EU-C9**: Sectorial analysis of industrial decarbonisation*

Contributing models: DESSTINEE, Calliope, and IMAGE

Research Questions' Overview

The analysis for this cluster focused on the so-called 'Heavy Industries'. In particular, we aim to respond to the following RQs by studying the changes, expected to take place, in the 'Steel and metallic', 'Cement', and 'Chemical' industries. The followed model methodology aligns with the procedures described in cluster **EU-C4** (**Section 3.1.4.3**).

- **RQ41:** What will be the levels of electrification of different industrial subsectors by 2030 and 2050 and what role would H_2 and biomass play in decarbonisation of these subsectors?
- **RQ43:** How and at what level could different industrial subsectors be decarbonised by 2030 and 2050? What should be the pace of electrification of heat production in different industrial subsectors?
- **RQ46:** In which industrial sectors could Carbon Capture Utilisation and Storage (CCUS) be an efficient emissions mitigation technology?

Results and Discussion

Figure 30, **Figure 31**, and **Figure 32** display the fuel basket for the three key heavy industries considered in the analysis. In the case of steel, Calliope and DESSTINEE focus on decarbonisation pathways based on phasing out coal and partial substitution by electricity and low carbon gases across the different scenarios. IMAGE proposes emission reduction pathways, with the exception of the 2050 "**Climate Neutrality**" scenario, in which coal feedstock facilities are equipped with carbon capture technologies, particularly by 2050 under the assumption of the "**Current Trends**" scenario. Nevertheless, to meet the more stringent emission caps for climate neutrality in 2050, IMAGE also assumes that coal needs to be significantly phased out within the steel industry. This is possible thanks to the high uptake of electric arc based technologies for steel manufacturing, which relies on electricity and recycled steel rich metallic waste. This avoids the production of pig iron (BEIS, 2015). Other novel production methods also consist of replacing coal by H_2 as reduction agent.

Solutions proposed for the decarbonisation of cement are mostly based on the concept of 'Calcium looping technologies' (IEA, 2020a), for which alternative fuels are being considered for the operation of the kiln and the calciner. H_2 (or low carbon gases) and biomass have the potential to replace coal in the kiln whilst the calciner can be operated using these fuels or thermal plasma torches relying on electricity (BEIS, 2019).

The fuel baskets for the 'Chemical Industries' show the largest differences among the models, and this is a consequence of the assumptions on the production rates and processes of different bulk chemicals, considered within this wide category. Furthermore, some models like Calliope also tend to include fuel usage for feedstock as part of the FEC, leading to a larger proportion of liquid carriers in the sectorial fuel basket. Nevertheless, like the other heavy industries, there is a tendency for biomass, electricity and H_2 to substitute coal and, partially liquid fossil fuels.

All scenarios agree that the residual fossil fuel usage within the different industrial sectors will be in plants equipped with CO_2 capture units whilst a fraction of CO_2 emissions from biomass feedstock facilities will need to be captured (leading to 'negative emissions') in view of allowing EU27+UK-wide fossil CO_2 emissions to be in the range of 50-60 Mt $CO_{2,eq}$ in a climate neutral 2050.

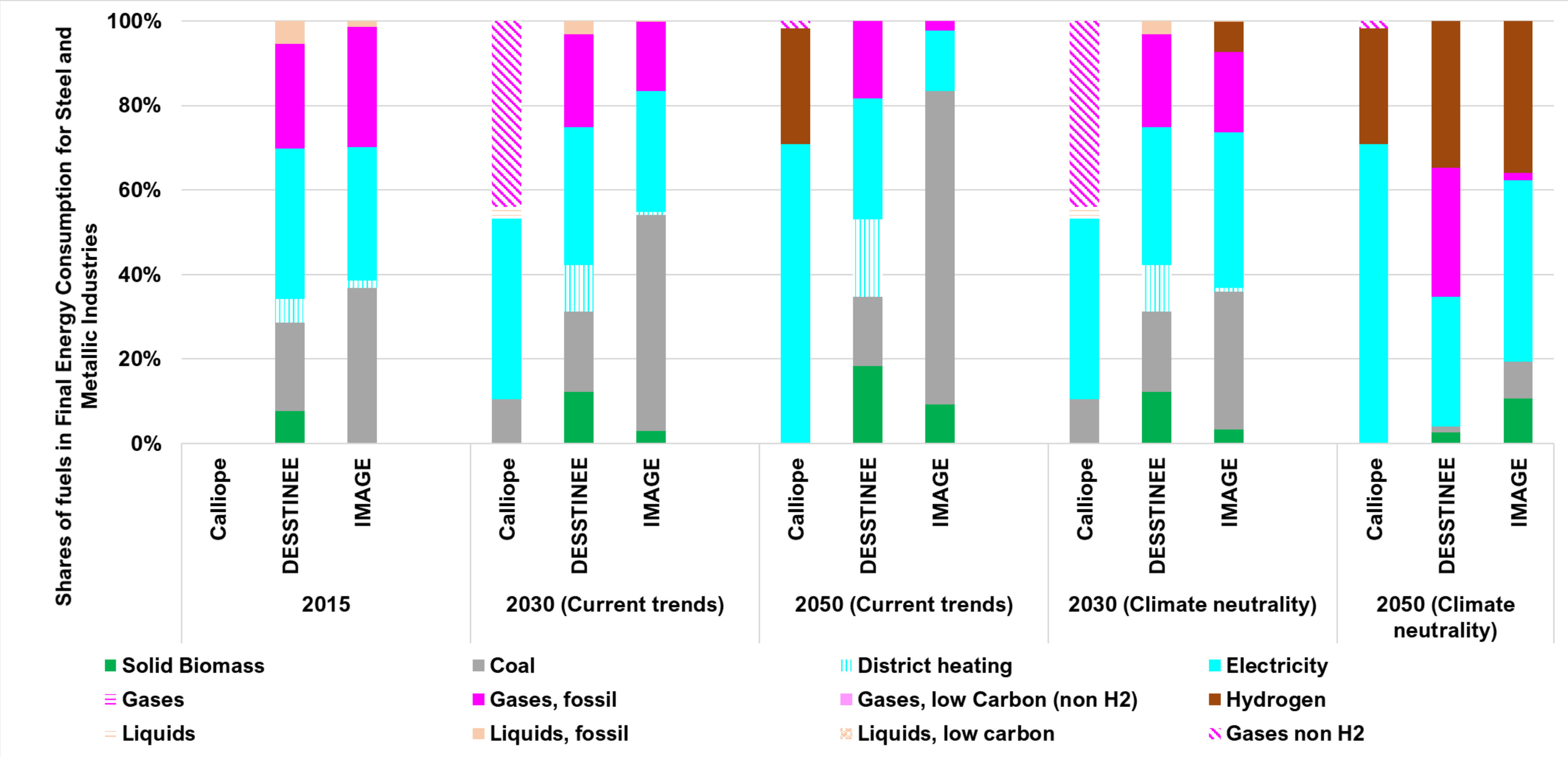


Figure 30. Shares of fuels in final energy consumption for Steel and Metallic Industries. 'Gases' and 'Liquids' account for all gaseous and liquid fuels (some models only report at this level) respectively, 'Gases, fossil' and 'Liquids, fossil' groups all fossil gaseous and liquids fuels (for models presenting results 'at this level), 'Gases, low carbon (non-H_2)' and 'Liquids, low carbon' consider gaseous/liquid biofuels and 'Power-to-X' solutions. 'Gases non H_2' groups all gaseous energy vectors with the exception of hydrogen.

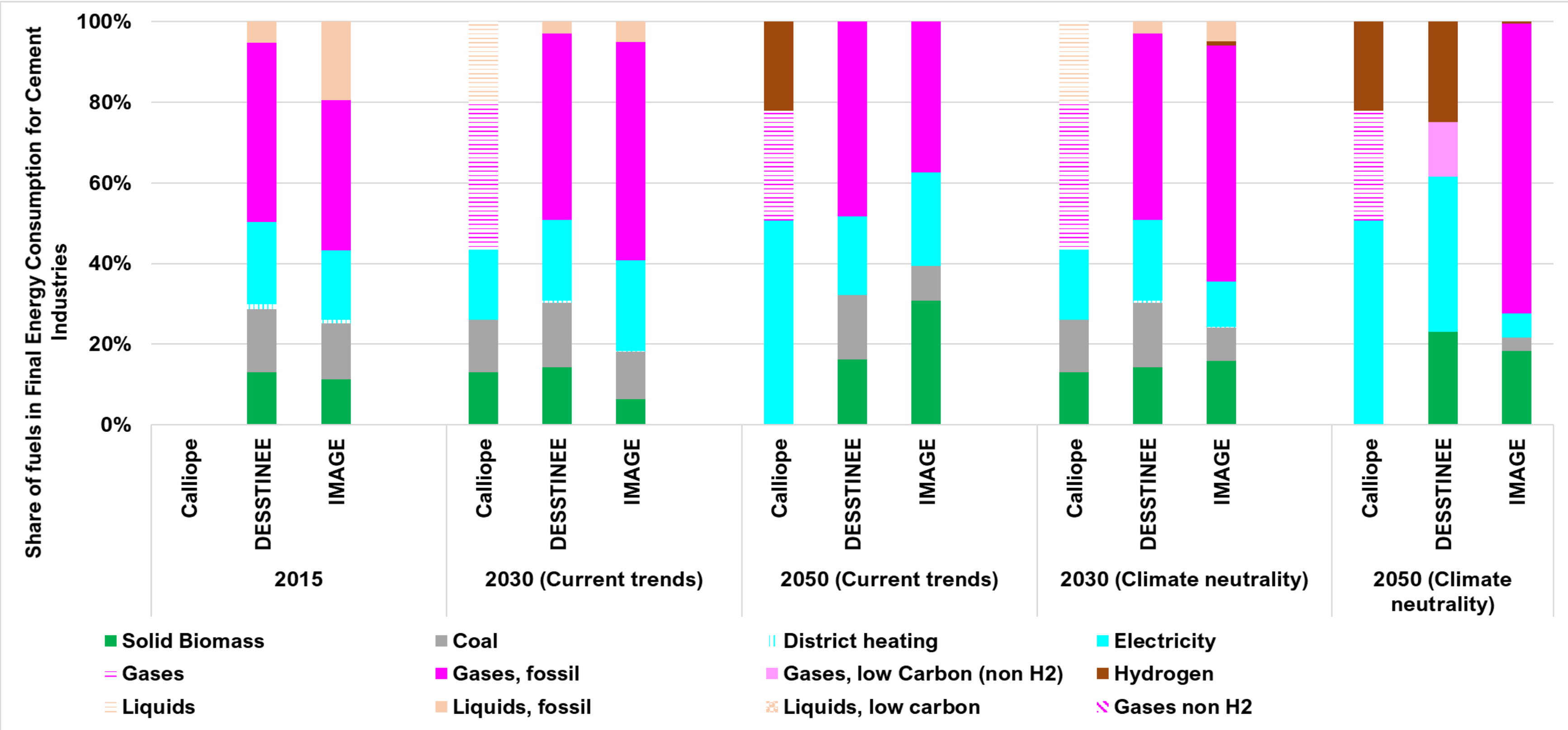


Figure 31. Shares of fuels in final energy consumption for Cement Industries. 'Gases' and 'Liquids' account for all gaseous and liquid fuels (some models only report at this level) respectively, 'Gases, fossil' and 'Liquids, fossil' groups all fossil gaseous and liquids fuels (for models presenting results 'at this level), 'Gases, low carbon (non-H_2)' and 'Liquids, low carbon' consider gaseous/liquid biofuels and 'Power-to-X' solutions. 'Gases non H_2' groups all gaseous energy vectors with the exception of hydrogen.

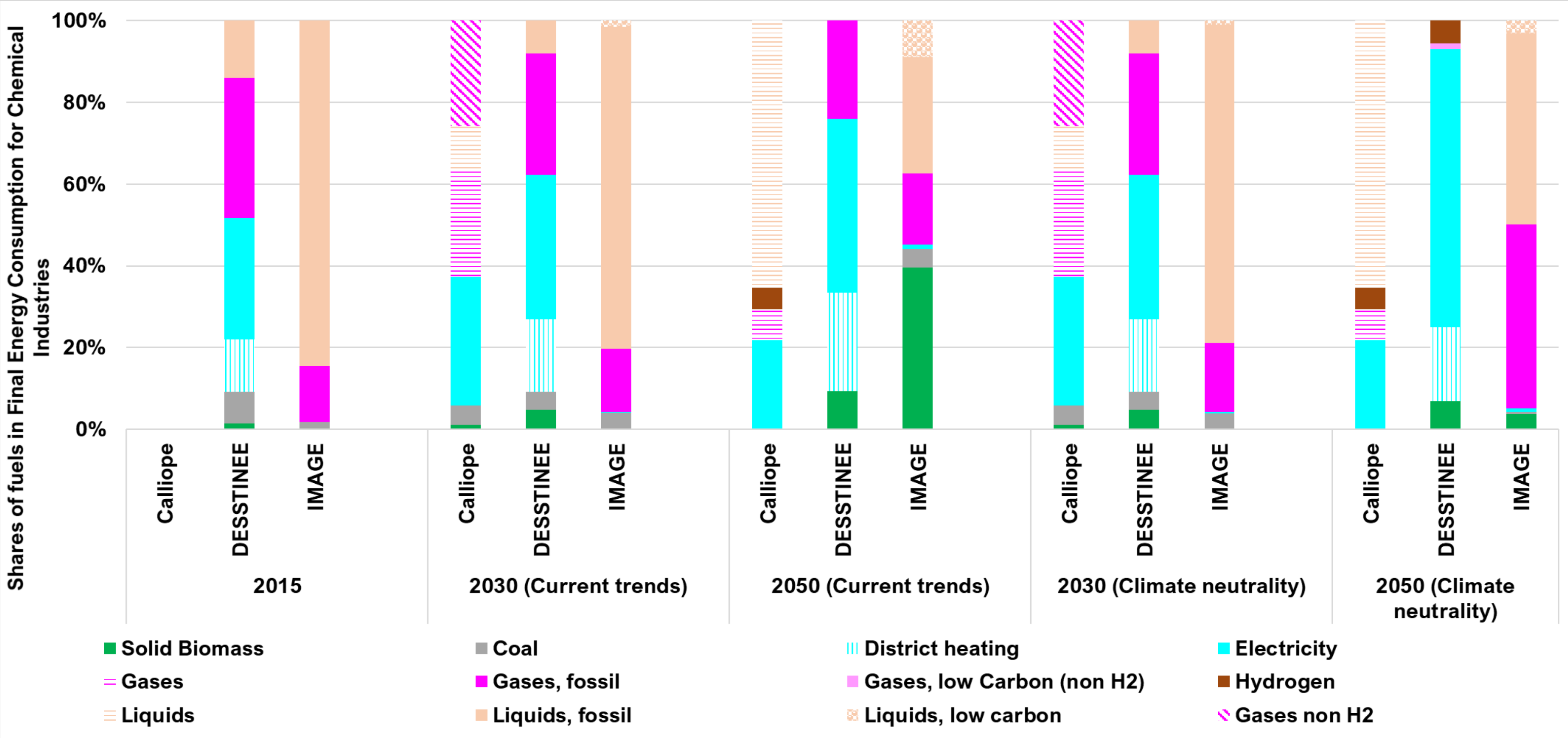


Figure 32. Shares of fuels in final energy consumption for Chemical Industries**.** **'**Gases' and 'Liquids' account for all gaseous and liquid fuels (some models only report at this level) respectively, 'Gases, fossil' and 'Liquids, fossil' groups all fossil gaseous and liquids fuels (for models presenting results 'at this level), 'Gases, low carbon (non-H_2)' and 'Liquids, low carbon' consider gaseous/liquid biofuels and 'Power-to-X' solutions. 'Gases non H_2' groups all gaseous energy vectors with the exception of hydrogen.

3.1.5.2. ***EU-C10****: Fossil fuel use reduction and the effect on production*

Contributing models: IMAGE

Research Questions' Overview

According to stakeholders interviewed during the preparation of Deliverable 7.1 (Stavrakas et al., 2021), as industry will gradually be using less fossil fuels, the operation of refineries is expected to be affected. This effect will also be amplified by the electrification of the transport sector. In this respect, we answer the following RQ:

- **RQ42:** How would fossil fuel production be affected due to the decarbonisation of industry as well as the electrification of the transport sector?

Results and Discussion

We use the IMAGE model and the outcome for the SENTINEL scenarios. IMAGE is a relatively detailed integrated assessment model, including different sectors relevant for fossil fuel production and fossil fuel use. We consider energy production in the energy supply sector, energy and non-energy use for cement, steel, chemicals and other industry sectors, and consumer travel and freight in the transport sector. For this purpose, we apply three scenarios: "**Current trends**", "**Neutrality 1.5°C**", and "**Neutrality 2.0°C**" scenarios.

Figure 33 shows fossil fuels production decreasing by 39% by 2030 relative to 2015 in the "**Current Trends**" scenario, mainly through reductions in the ETS sectors and CO_2 performances standards for cars. By 2050, the reduction in fossil fuel production in the "**Neutrality 1.5°C**" and "**Neutrality 2.0°C**" scenarios is respectively 46% and 48% with relevance to the 2015 levels, while it increases by 17% in the "**Current Trends**" scenario. The reductions in both the "**Neutrality**" scenarios are strongly affected by increasing carbon prices, which drive the increase of fossil fuel prices (**Figure 34** and **Figure 35**).

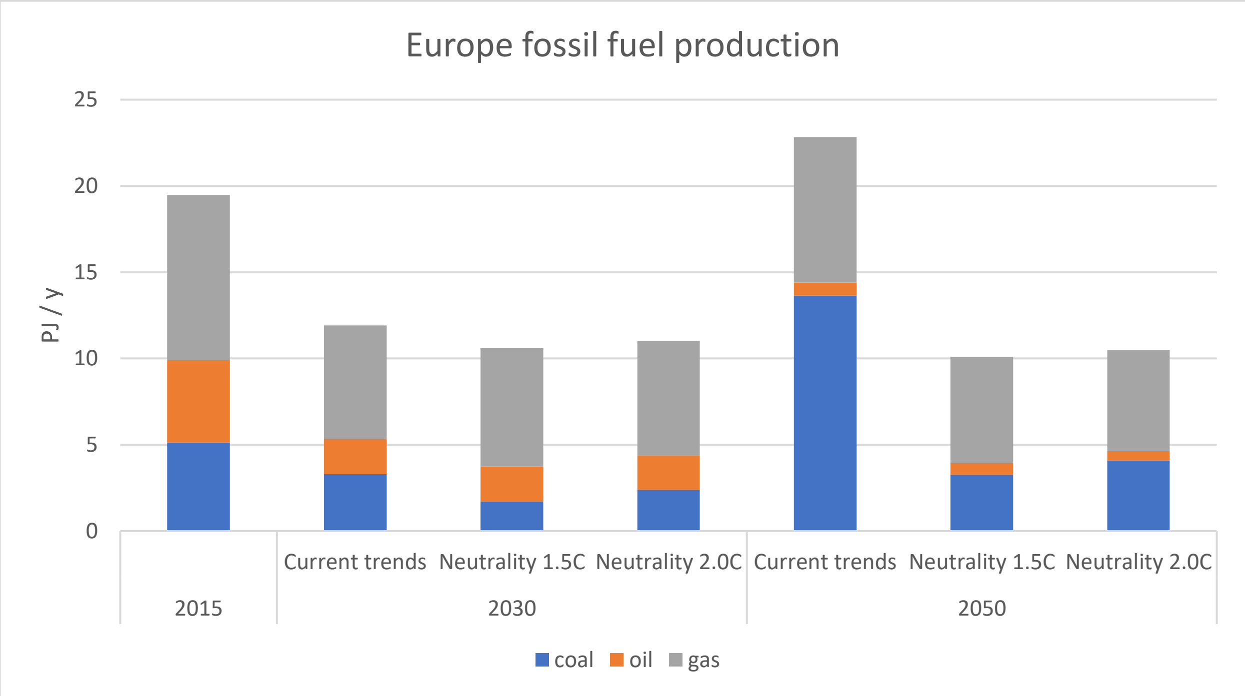


Figure 33. Fossil fuel production in Europe in 2030 and 2050 (IMAGE).

Without additional climate policy, fossil fuel production will grow in the "**Current Trends**" scenario from 19.5 to 22.8 PJ/y between 2015 and 2050, mainly driven by the increase in coal production from 5.1 to 13.6 PJ/y (**Figure 33**).

Fossil fuel prices are higher in the "**Neutrality**" scenario than in the "**Current Trends**" scenario. The results show that fossil fuels production will decline significantly in 2050, to 10.1 PJ/y in the "**Neutrality 1.5°C**" scenario and 10.5 PJ/y in the "**Neutrality 2.0°C**" scenario. Furthermore, gas production dominates fossil fuel production in the "**Neutrality 1.5°C**" scenario in 2050 due to its lower emissions factor and relatively low gas prices (**Figure 34**, fuel prices are weighed by fuel productions in Western Europe and Central Europe). The coal price under the "**Neutrality 2.0°C**" scenario in 2050 is lower than "**Neutrality 1.5°C**" scenario, so the coal production is also somewhat higher than the 2050 "**Neutrality 1.5°C**", as is for the gas production and total fossil fuel production.

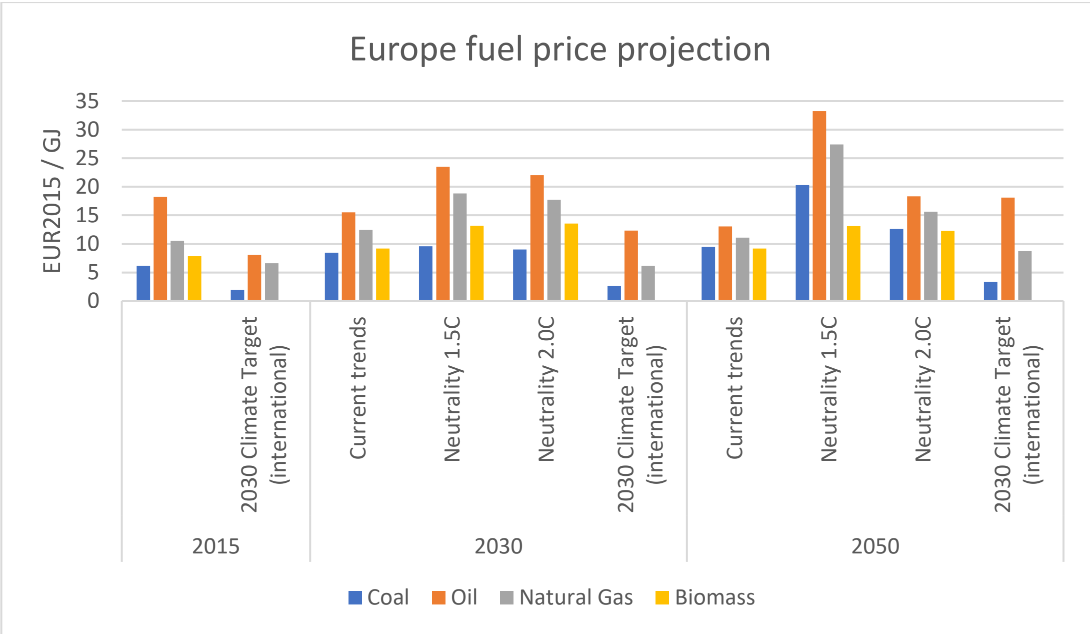


Figure 34. Fossil fuel and biomass fuel prices projection for Europe, weighed by Western Europe and Central Europe fossil fuel productions (IMAGE).

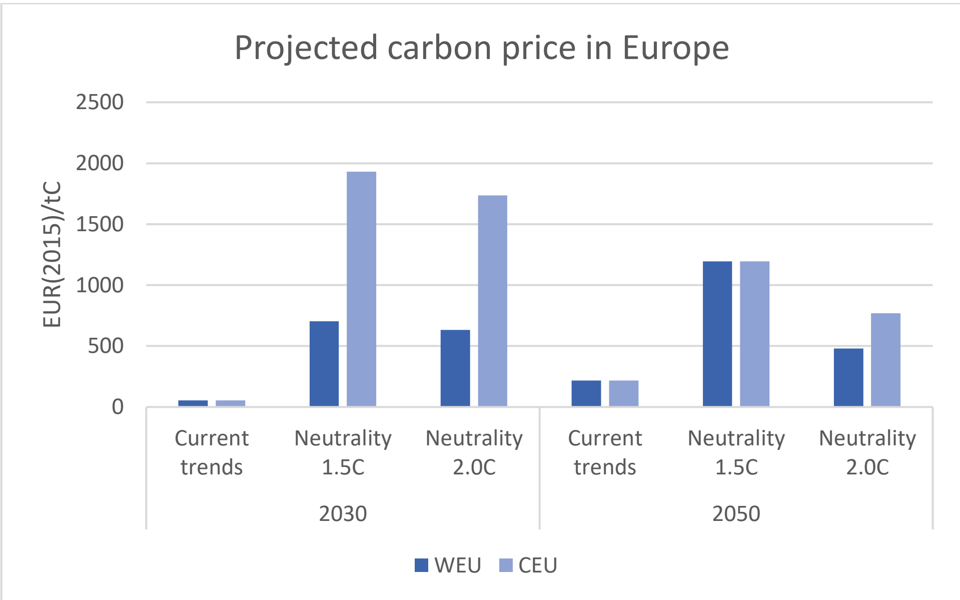


Figure 35. Projected carbon prices for Western Europe (WEU) and Central Europe (CEU) (IMAGE). Carbon price in the IMAGE model functions as a shadow price of climate policy.

The industry and transport sector are especially affected by higher fuel prices. This drives several fuel switching and efficiency measures, resulting in less liquids fuel use in the "**Neutrality**" scenarios (**Figure 36**). Especially, the switch to electric and H_2 cars results in high-efficiency savings in the transport sector.

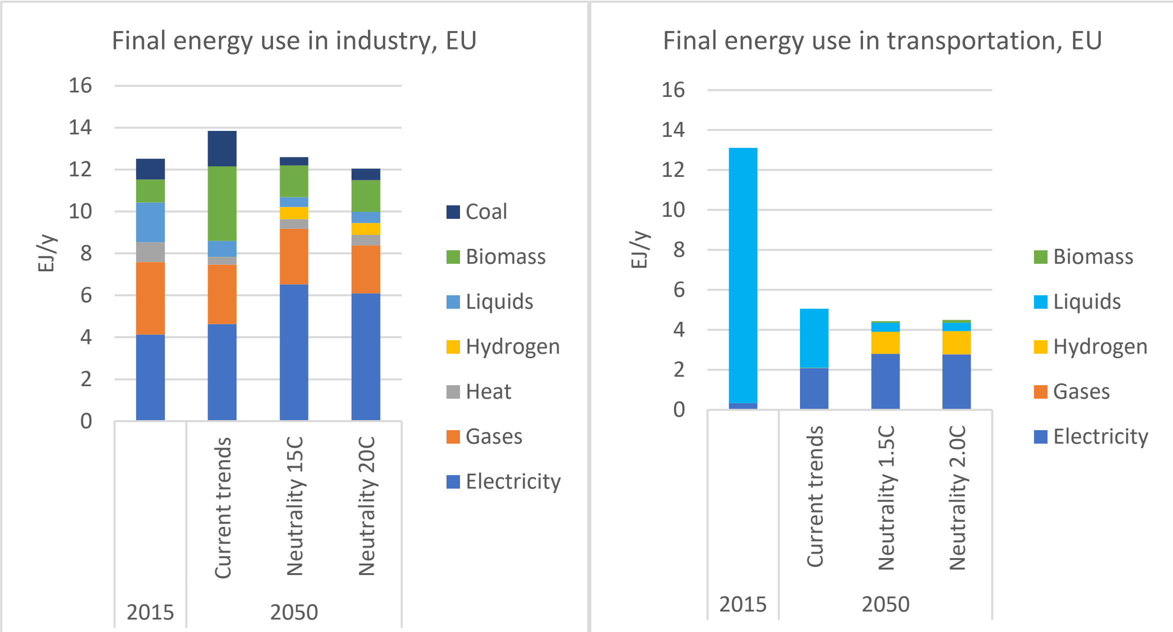


Figure 36. Final fuel use in industry and transport sectors in the EU, 2015 and 2050. Projected by IMAGE.

3.1.6. Modelling energy demand of the building sector - Transition towards zero carbon society

3.1.6.1. ***EU-C11****: Energy demand evolution in the building sector*

Contributing models: HEB

Research Questions' Overview

Stakeholders have stated that the level of energy demand in EU countries is affected by a multitude of region-specific factors, such as the weather, the traditional architecture, the potential for RES-powered heating, the degree of electrification, as well as developments in population and urbanisation, and consumer behaviour (Stavrakas et al., 2021). In this respect, the following RQs are raised:

- **RQ52:** How would energy demand evolve under the effect of various region-specific factors in European countries by 2030 and 2050? How would these factors affect energy-related behavioural patterns and use?

Results and Discussion

HEB scenarios have different assumptions and some of them, such as GDP growth rate, population rate, retrofit rate, and share of advanced buildings, has country specific data. Thus, the final service energy demand data varies as per the scenarios for each of the EU member state. The total demand of the building sector for EU-27 (and UK) is expected to decrease by 73% by 2050 compared to 2022 under the "**Deep-efficiency**" scenario (see **Section 3.1.2.5**). Whereas the "**Frozen**" scenario indicates slight (5%) increase by the middle of the 21st century. Overall, the largest reduction can be achieved by balancing the local consumption with onsite clear energy production. More precisely, considering rooftop PV electricity production, the total building-related energy demand is estimated to be shrank by around 85% as compared to the 2022 level.

Analysing the results for different major EU member states it can be concluded that there are only minor differences between the countries in energy demand reduction within a given scenario. In the "**Frozen**" scenario, if the current policies persist, the values are anticipated to increase by over 5% by 2050. The largest enhancements are found for Middle-East European countries (e.g., Hungary and Poland). On the other hand, Germany and Italy are predicted to be capable of reducing its demand despite the increasing floor space in these countries. In the "**Moderate-efficiency**" scenario, the improvement in the energy efficiency of buildings is even more observable, with reductions around 50-60%. By introducing more ambitious policies in the "**Deep-efficiency**" scenarios, the estimated reduction in the building-related energy demand can be larger than 70%. As the modelling results suggest, three quarters of the demand of 2022 can be saved in such countries as France, Germany and the UK. In these countries, the rapid transformation of building stock (i.e., high share of advanced buildings) may be a key to achieve the presented numbers. By complementing these policies with the promotion of solar technology (i.e., **Net Zero scenario**), the expected reduction could be as high as 85-87% by 2050. The slight differences in the country-level values are the manifestation of the differences in the solar potential and expected composure of the building stock. As **Table 20** highlights, the demand reduction is expected to be accelerated after 2030, which is due the assumption that the advanced buildings will be more frequent towards the middle of the century. It is also a conclusion that there is a need to follow the most ambitious paths as soon as possible, otherwise enormous interventions are needed later to reach the desired climate neutrality by 2050.

Table 20. Energy demand evolution under region specific assumptions.

Scenario	Baseline	Moderate			Deep			Net Zero			Frozen		
	2022 PJ	**2050 PJ**	**Δ% to 2022**	**Δ% to 2030**	**2050 PJ**	**Δ% to 2022**	**Δ% to 2030**	**2050 PJ**	**Δ% to 2022**	**Δ% to 2030**	**2050 PJ**	**Δ% to 2022**	**Δ% to 2030**
France	1623.6	660.8	-59%	-6%	408.2	-75%	-9%	211.0	-87%	-10%	1770.4	9%	3%
Germany	2444.0	953.8	-61%	-8%	626.4	-74%	-10%	371.9	-85%	-11%	2389.8	0%	-2%
Hungary	257.6	120.2	-53%	-1%	71.6	-72%	-4%	43.0	-83%	-5%	327.6	27%	10%
Italy	1308.5	527.8	-60%	-11%	365.2	-72%	-13%	209.8	-84%	-14%	1154.4	-12%	-3%
UK	1885.8	799.9	-58%	-6%	495.0	-74%	-9%	250.2	-87%	-10%	2066.8	10%	2%
Netherlands	413.3	194.9	-53%	-5%	133.8	-68%	-7%	69.8	-83%	-9%	451.5	9%	4%
Poland	927.0	401.2	-57%	-3%	236.4	-74%	-6%	137.4	-85%	-7%	1013.5	9%	6%
Spain	542.2	268.2	-51%	-6%	196.9	-64%	-8%	88.6	-84%	-10%	579.1	7%	3%
EU27 + UK	***12355.6***	***5196.6***	***-58%***	***-6%***	***3329.3***	***-73%***	***-9%***	***1854.2***	***-85%***	***-10%***	***12977.0***	***5%***	***2%***

3.1.6.2. ***EU-C12****: Role of energy efficiency improvements, energy-saving potential, and cost-effectiveness of energy-efficiency measures in Europe.*

Contributing models: DREEM and IMAGE

Research Questions' Overview

According to the EC, the uptake of energy efficient equipment following the EU energy labelling and eco-design legislation can significantly contribute to the reduction of total energy demand (European Commission, 2018a). Especially for buildings in Europe, the sector is responsible for approximately 40% of energy consumption and 36% of $CO_{2,eq}$. emissions (Ascione et al., 2019). Furthermore, about 35% of the residential building stock is over 50 years old and more than 75% is considered energy inefficient (Camarasa et al., 2019). Within this context, renovation of existing residential buildings can lead to significant energy savings and play a key role in the clean energy transition, especially towards the 2050 zero carbon-emission target set by the EC (CE Delft, 2020). However, the energy performance of the building stock is improving very slowly, with only 1% of the building stock being retrofitted annually (Streicher et al., 2020).

The energy consumption of the residential built environment varies substantially across EU member states depending on the availability of heating fuels, government policies, and the different climatic conditions that have a major influence on heating and cooling demand. As a result, the energy-saving potential of EEMs differs among Member States and country-specific evaluations are necessary to develop effective renovation packages (Filippidou and Jimenez Navarro, 2019). Overall, the diversity of the EU building stock requires tailored renovation strategies that consider aspects such as climatic conditions, energy uses, and, ultimately, the age of the building stock itself across Europe. Additionally, deep energy retrofit measures in buildings require very high initial investment costs and their benefits only accrue slowly over time (Tzani et al., 2022). It is, therefore, crucial to identify retrofit measures that are not only beneficial for the environment but will also incentivise the owner of the buildings and will ensure effective private and public budget spending (Ekström et al., 2018).

Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021) :

- **RQ56:** Which sectors have the highest potential for EEMs to reduce CO_2 emission, and which EEMs have the highest potential to reduce energy consumption and, thus, to contribute to higher energy savings? How would the emergence of new technologies/appliances impact the energy consumption trends?

Results and Discussion

IMAGE results

A decomposition analysis of the "**Current Trends**" and "**Neutrality**" scenarios for three sectors gives insights into the impact of EEMs compared to the impact of other decarbonisation measures. For this purpose, we have used the Kaya identity to extract the factors driving GHG emissions (see **Table 21** and **Table B.8, Table B.9** and **Table B.10** in **Appendix B)**. There are in general six factors in the Kaya equation (Kaya et al., 1997): population change (P), activity level (A) (electricity production/ industrial production/ travel distance per capita/ residential energy use per square metre), structural change (S), energy efficiency (E), carbon intensity (I), and carbon capture and storage (C) (only for power generation and industry). See **Appendix B** for the details. The sectors we analyse are (i) power generation, (ii) industry, (iii) passenger transport, and (iv) residential.

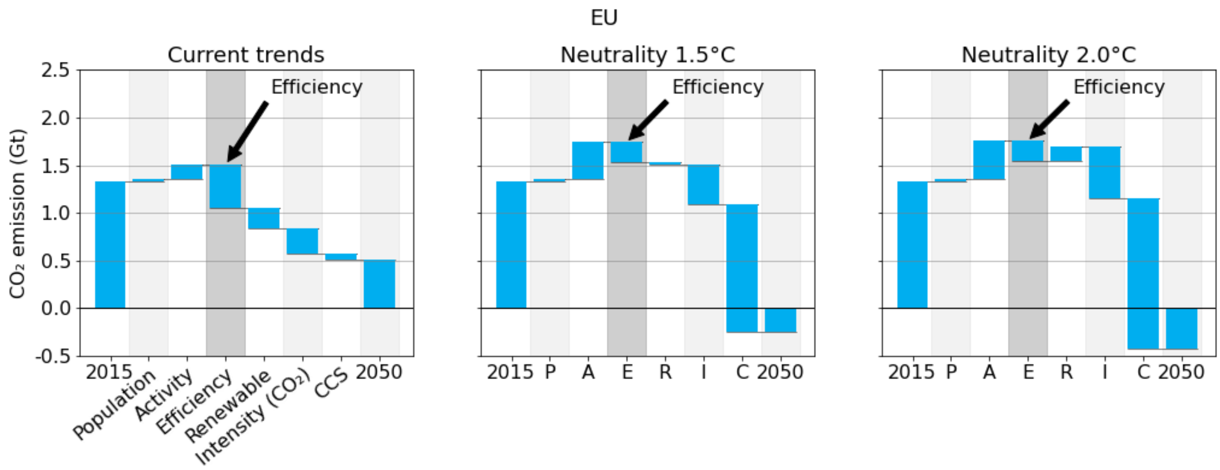
The structural change is defined differently for each sector. This is represented by the renewable energy share from the Kaya equation for power generation. In the industry sector, it is the change in the share of different industrial sectors and in passenger transport, it is the switch between different transportation modes. In residential, it is different energy services within buildings.

Table 21. The Kaya equation of Carbon Dioxide (CO_2) emissions for sectoral decomposition analysis.

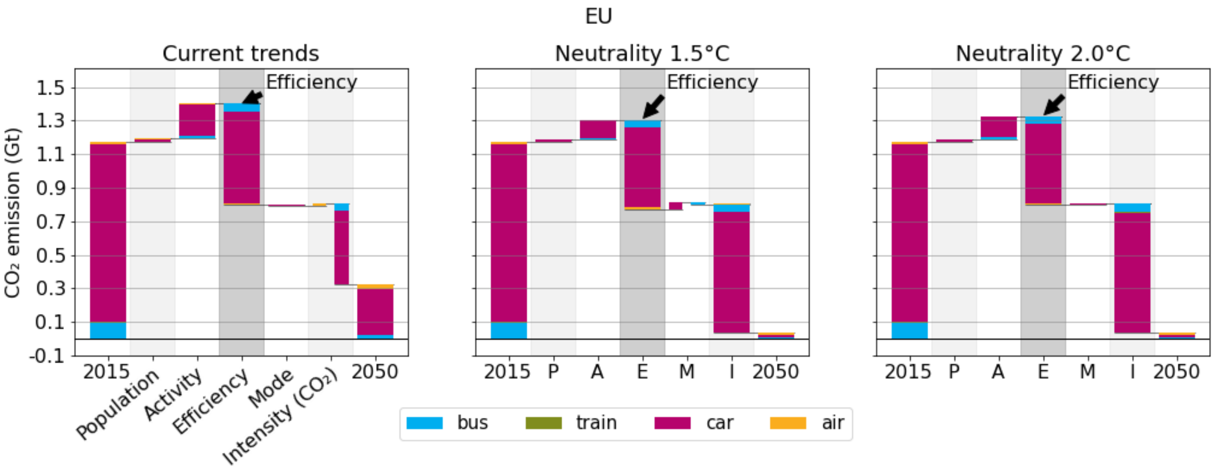
CO_2 *emissions*	=									
Population	×	$\frac{Activity}{population}$	×	*Structural change* (%)	×	$\frac{Energy\ use}{Activity}$	×	$\frac{CO_2 + CCS}{Energy\ use}$	−	CCS
Population		Activity level		Structure/ mode change		Efficiency		Carbon intensity		CCS

Figure 37 shows that the efficiency improvement has the highest impact in the passenger transport, mainly caused by a shift to electric cars. For the passenger transport sector, the energy efficiency already has a significant impact in the "**Current Trends**" scenario, leading to 0.61 Gt CO_2 reduction from 2015 to 2050 due to current implemented CO_2 standards for cars and trucks. It can have 0.55 Gt and 0.56 Gt CO_2 reduction in the "**Neutrality 1.5°C**" and "**Neutrality 2.0°C**" scenarios.

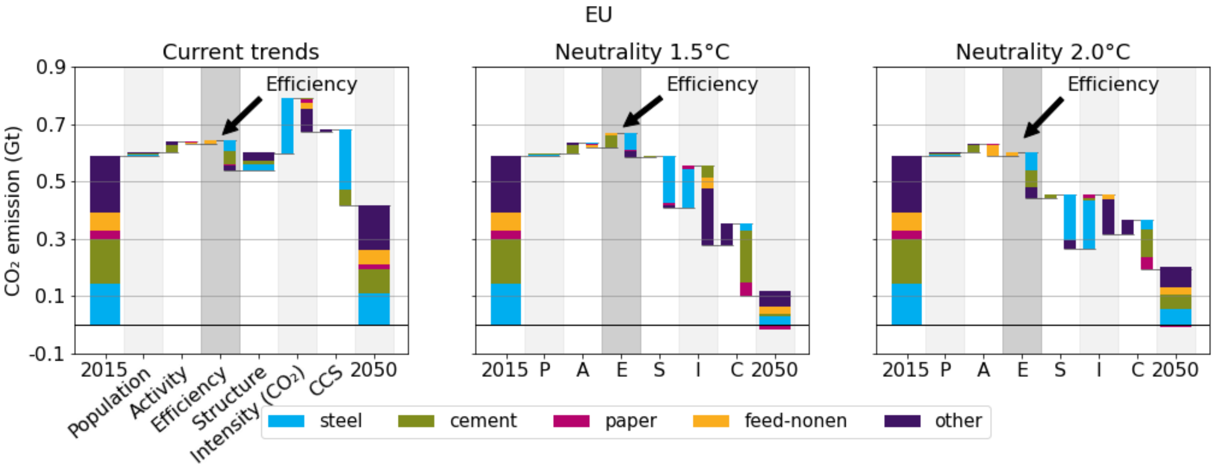
Power generation



Passenger transport



Industry sector



Residential sector

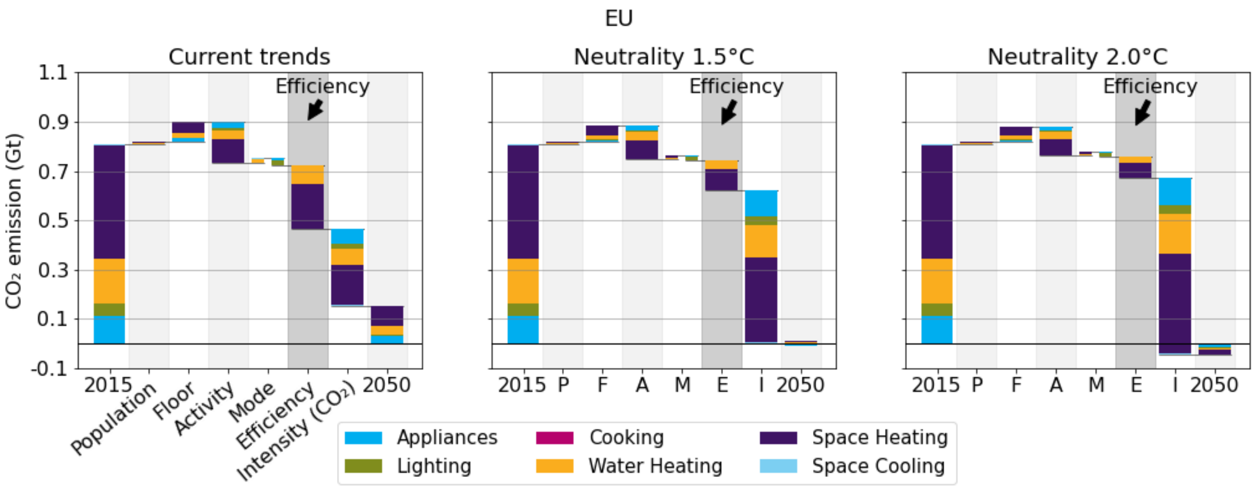


Figure 37. Kaya decomposition analysis for power generation, industry, passenger transport and residential sector. A: activity, E: energy efficiency, R: renewable share, M: mode shift, S: structural change, F: floor space per capita, I: CO_2 intensity, C: CCS.

In the power generation sector, energy efficiency is important for reducing CO_2 emissions in the "**Current Trends**" scenario (0.46 Gt CO_2 emission reduction in 2050 from 2015). However, with the increased carbon price in the "**Neutrality**" scenarios, reducing CO_2 intensity in energy use and carbon capture and storage becomes more important measures to reach the net-zero emissions in 2050. One important explanation of the impact of energy efficiency in the "**Current Trends**" scenario can be efficiency improvements incorporated through the near-zero buildings targets from the EU EPBD, and the CO_2 performance standards in the transport sector.

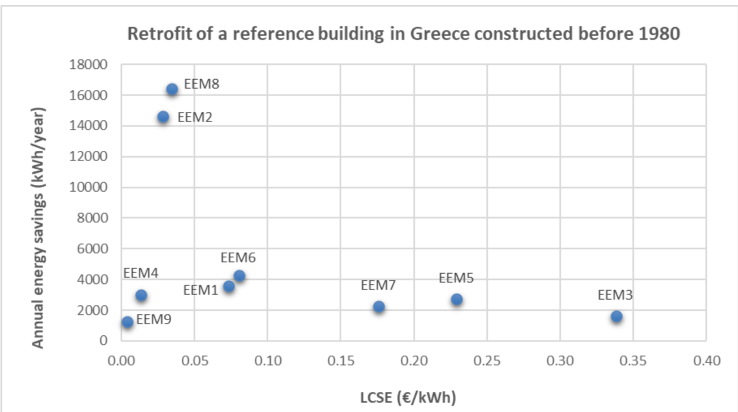
For the industry sector, the highest potential of efficiency improvements in the Neutrality scenarios come from the steel sector. Total energy efficiency improvements can lead to 0.04 Gt CO_2 reduction in the "**Neutrality 1.5°C**" and 0.09 Gt CO_2 reduction in "**Neutrality 2.0°C**" scenarios, from 2015 to 2050. In the "**Current Trends**" scenario, energy efficiency improvements in the steel and cement are the result of the ETS instrument and have roughly equal impact.

In the residential sector, energy efficiency of space heating and water heating improve in the "**Neutrality**" scenarios by 2050 compared to the "**Current Trends**" scenario, which leads to 0.09-0.12 Gt more CO_2 reduction than the "**Current Trends**" scenario. Although for both space heating and water heating, the ambitious policies in the "**Current Trends**" scenario already cause 0.26 Gt CO_2 reduction from efficiency improvement by 2050.

DREEM results

In order to answer **RQ56**, we estimated the annual energy savings per EEM for all the countries modelled with DREEM and we estimated the LCSE as shown in **Section 3.1.2.7**. Results for each country are presented below.

Greece



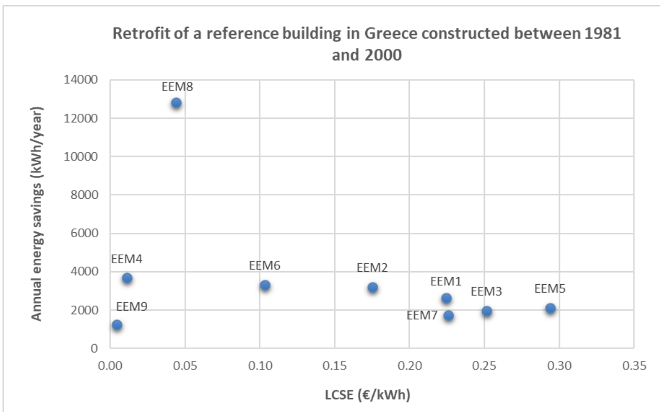


Figure 38. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Greece.

Italy

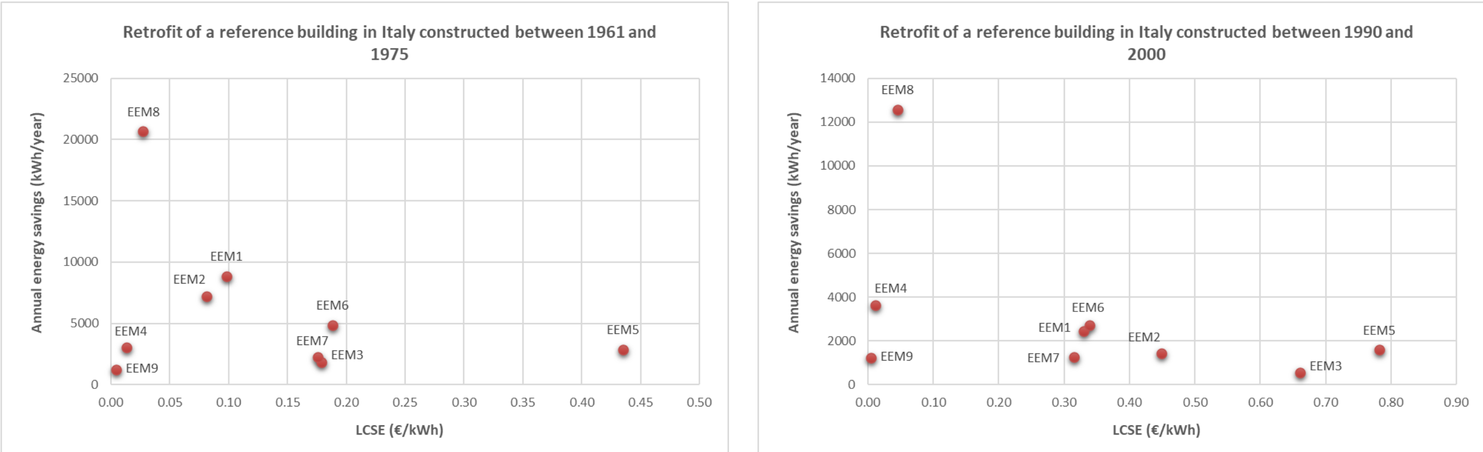


Figure 39. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Italy.

Spain

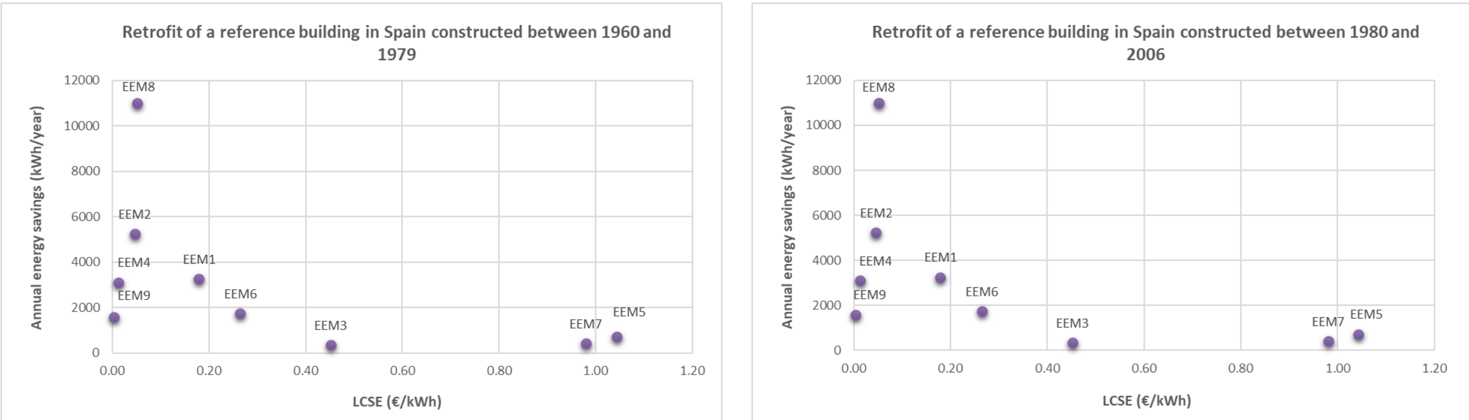


Figure 40. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Spain.

Croatia

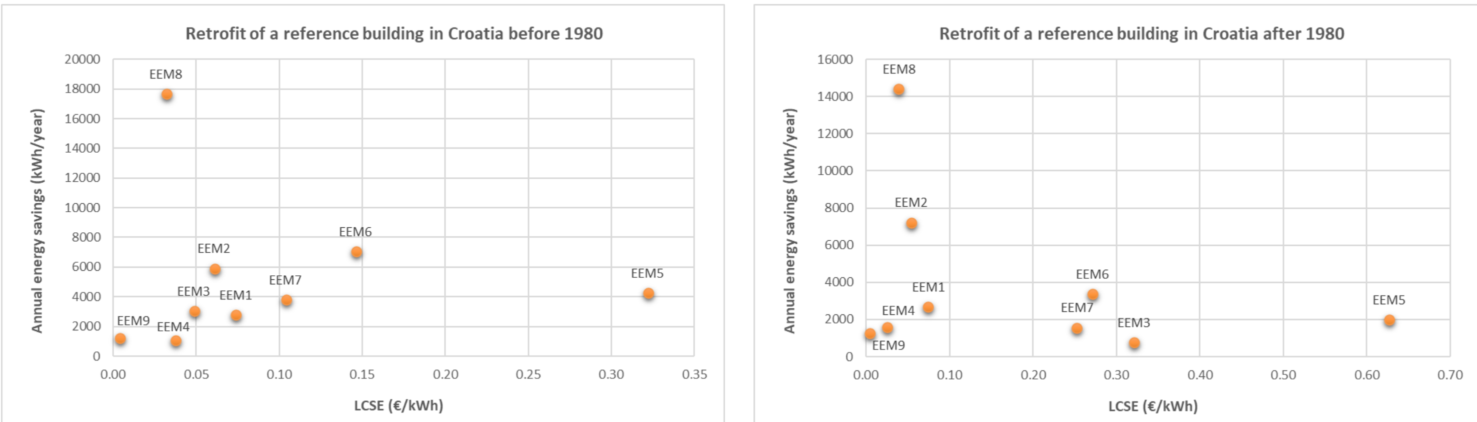


Figure 41. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Croatia.

Romania

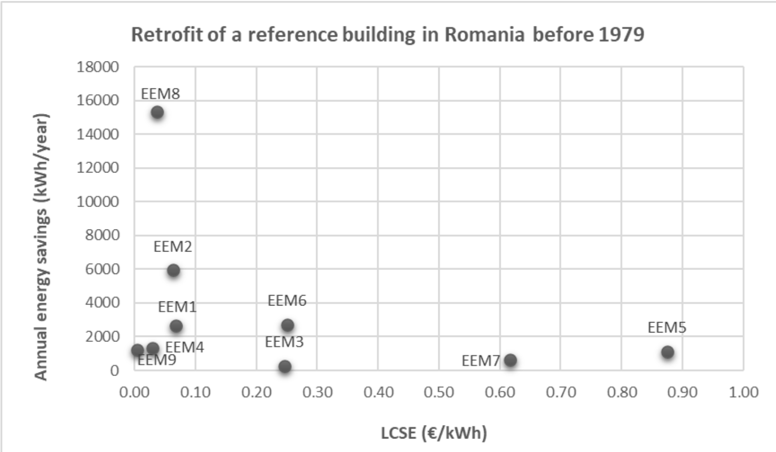


Figure 42. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Romania.

Latvia

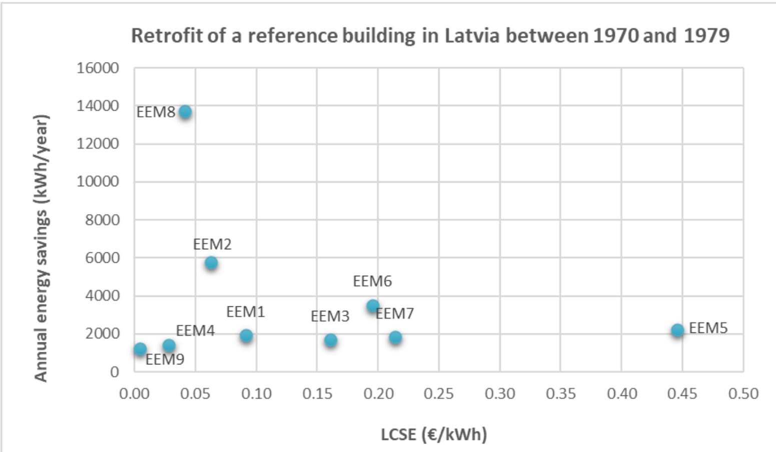


Figure 43. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Latvia.

France

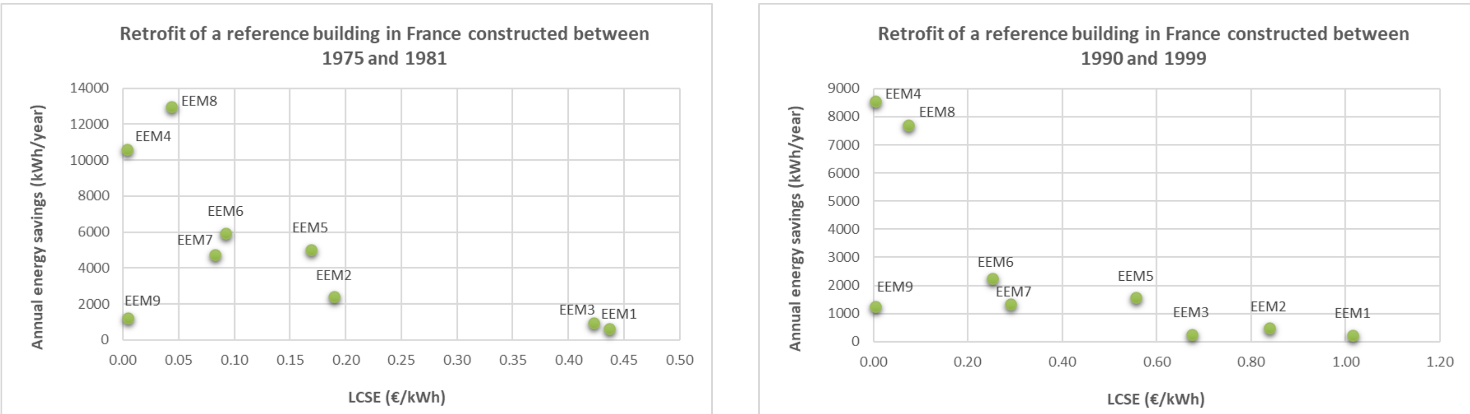
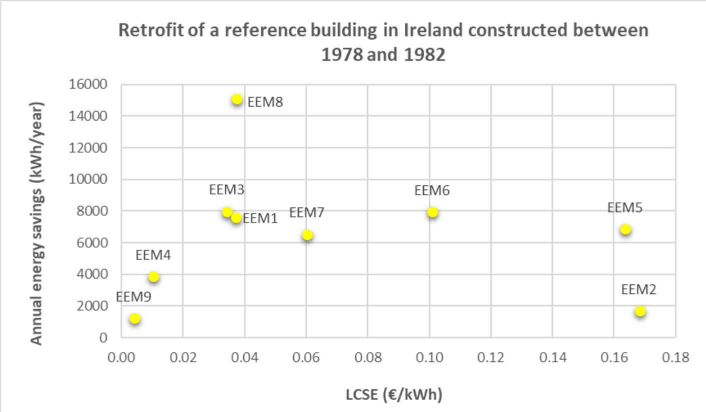


Figure 44. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in France.

Ireland



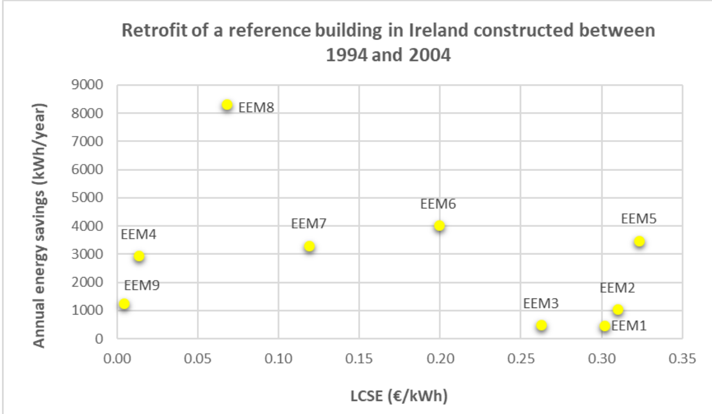


Figure 45. Energy-saving potential and cost-effectiveness of the energy efficiency measures under study in the residential sector in Ireland.

Overall, modelling results from DREEM are summarised in the tables below:

Table 22. Energy-saving potential and Levelized Cost of Saved Energy (LCSE) of the energy-efficiency measures under study in the different countries for residential buildings in Category I.

	Greece		Italy		Spain		Croatia		Romania		Latvia		France		Ireland	
Energy Efficiency Measures explored	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)
EEM1	0.0732	3586.9	0.0981	8871.5	0.1791	3243.9	0.0740	2771.8	0.0675	2688.6	0.0914	1922	0.4371	640.4	0.0371	7599.9
EEM2	0.0283	14626.2	0.0811	7241.1	0.0461	5226.8	0.0612	5917.5	0.0631	5948.2	0.0627	5765	0.1897	2400.2	0.1683	1699.7
EEM3	0.3383	1617.6	0.1788	1863.6	0.4521	342.1	0.0489	3035.6	0.2470	289.0	0.1607	1702.9	0.4231	928	0.0342	7992.7
EEM4	0.0134	3009.1	0.0132	3042.9	0.0129	3103.1	0.0376	1068	0.0302	1332.0	0.0282	1423.1	0.0038	10593	0.0104	3867.5
EEM5	0.2292	2727.1	0.4352	2872.9	1.0431	719.1	0.3223	4267.1	0.8758	1142.0	0.4454	2245.3	0.1686	5042.7	0.1637	6872.6
EEM6	0.0804	4275.1	0.1885	4863.1	0.2647	1731.7	0.1463	7048	0.2506	2743.4	0.1954	3518.9	0.0924	5951.6	0.1009	7945.9
EEM7	0.1759	2243.7	0.1754	2250.2	0.9801	402.7	0.1041	3792.9	0.6166	640.1	0.2138	1845.9	0.0830	4757.9	0.0604	6536.2
EEM8	0.0344	16435.5	0.0273	20678.9	0.0514	11003.7	0.0320	17673.1	0.0369	15321.1	0.0412	13724.1	0.0435	12996.1	0.0374	15129.5
EEM9	0.0041	1245.8	0.0041	1246	0.0033	1579.3	0.0041	1242.3	0.0041	1246.0	0.0041	1245.7	0.0041	1244.9	0.0041	1246.1

Table 23. Energy-saving potential and Levelized Cost of Saved Energy (LCSE) of the energy-efficiency measures under study in the different countries for residential buildings in Category II.

	Greece		Italy		Spain		Croatia		France		Ireland	
Energy Efficiency Measures explored	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)	LCSE (€/kWh)	Annual energy savings (kWh/year)
EEM1	0.2243	2651	0.3298	2434.8	0.1791	3243.9	0.0746	2680.2	1.0152	232	0.3017	479.9
EEM2	0.1750	3226	0.4488	1433.7	0.0461	5226.8	0.0541	7228.4	0.8384	480.3	0.3101	1043.5
EEM3	0.2515	1987.1	0.6606	540.3	0.4521	342.1	0.3211	770.6	0.6742	264.7	0.2625	498.6
EEM4	0.0109	3680.1	0.0110	3644.1	0.0129	3103.1	0.0252	1594.4	0.0047	8552	0.0136	2945.8
EEM5	0.2940	2126.4	0.7822	1598.2	1.0431	719.1	0.6270	1993.9	0.5570	1571.2	0.3231	3482.6
EEM6	0.1031	3332.9	0.3389	2704.4	0.2647	1731.7	0.2716	3374.6	0.2531	2263.2	0.1992	4026.3
EEM7	0.2258	1748.2	0.3154	1251.4	0.9801	402.7	0.2528	1561.3	0.2914	1354.4	0.1192	3312.3
EEM8	0.0441	12813.4	0.0450	12570.4	0.0514	11003.7	0.0392	14419.6	0.0734	7701.1	0.0679	8321
EEM9	0.0041	1247.8	0.0041	1245.8	0.0033	1579.3	0.0041	1246.3	0.0041	1246.1	0.0041	1246.3

The results of the simulations and the techno-economic analysis performed are presented in **Figure 38-Figure 45** and reported in **Table 22** and **Table 23**. The energy-saving potential of the different EEMs and the LCSE indicator differ between the countries under study but also between the buildings in **Category I** and **Category II** of the same country. As expected, the energy-saving potential of the EEMs is commonly higher for buildings in **Category I**, due to the low energy performance of these buildings since most of them lack sufficient thermal insulation of the building envelope. The replacement of an old heating system with an energy-efficient HVAC system (**EEM8**) is one of the most cost-effective measures for all countries and both categories of buildings mainly due to the high energy-saving potential of this measure. The greatest value of annual energy savings achieved through **EEM8** is shown in Italy for buildings that belong in **Category I** (20678 kWh/ year) and in Croatia for buildings that belong in **Category II** (14419 kWh/year). The only case where **EEM8** has not the highest value of annual energy savings is in France for buildings in **Category II**, where the installation of a smart thermostat (**EEM4**) is more effective with a value of 8552 kWh/ year. On the contrary, the replacement of the traditional heating system with a more energy-efficient diesel boiler is shown to be the least cost-effective energy-efficient measure due to its cost of replacement and the low values of expected annual savings in most cases (Italy, Spain, Croatia, Latvia, Romania, Greece – **Category II**, Ireland – **Category II**). France is the only exception, where the insulation of exterior walls is the least cost-efficient measure for both categories of buildings mainly due to the high investment cost of installation. In Greece, in **Category I**, the least cost-efficient measure is the replacement of windows with double-glazed efficient ones (**EEM3**), while in Ireland, in **Category I**, the least cost-efficient measure is the installation of roof insulation (**EEM2**). Overall **EEM1**, **EEM2,** and **EEM3** are the ones that usually rank low in terms of cost-effectiveness in many cases (Greece, Italy, France, Ireland), mainly because of the high investment cost of these measures.

Figure 46 shows the energy-saving potential and cost-effectiveness of the installation of a smart thermostat (**EEM4**) for residential buildings in **Category I** in the different countries under study.

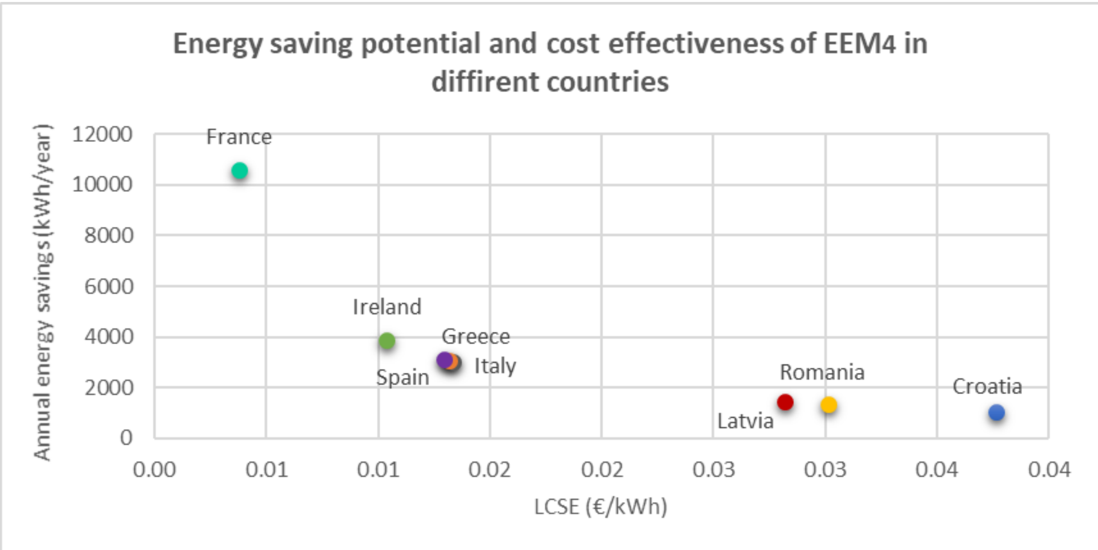


Figure 46. Energy-saving potential and cost-effectiveness of a smart thermostat installation (EEM4) for buildings in Category I in the different countries under study.

The smart thermostat is set by maximising heating and cooling efficiency based on optimised temperature set-points. In **Figure 46**, we observe the similarities in Mediterranean (Greece, Spain and Italy) countries where the measure achieves similar annual energy savings (approx. 3000 kWh/ year) and LCSE values (approx. 0.015 €/kWh).

*3.1.6.3. **EU-C13**: Electric vehicle charging and peaks*

Contributing models: DESSTINEE

Research Questions' Overview

Electrification of road transport is key to enabling emission reductions for this final energy use. However, this will also lead to a significant increase in the country and block level power demand. Therefore, the following RQ emerges:

- **RQ67:** How would EVs charging patterns influence the energy demand peaks? Particularly, what is the influence of 'home charging' regimes?

Results and Discussion

DESSTINEE projects that yearly power consumption for road transport, associated with the 2050 "**Climate Neutrality**" scenario, will represent 15% of the EU27+UK-wide electricity consumption, ranging between 9% and 22% across the 28 countries of the block. In addition, it is expected that power consumption within other final energy uses will also increase, becoming as well more time-dependent like supply availability given the higher renewable shares for power supply. Consequently, being able to understand the impact of different EV charging regimes on hourly demand is crucial to inform and advise relevant stakeholders on the most suitable design and operation of the power market.

Based on the yearly estimated figures, using DESSTINEE, hourly demand at the country-level was quantified for the different scenarios (**Table 4**). According to the final energy use, different distribution profiles for power consumption (across the days and hours) have been incorporated as 'default' in the model. Sources for these distributions and validations/comparisons with other similar tools are discussed elsewhere (see (Bobmann and Staffell, 2015; Chatterjee et al., 2021)). In the case of road transport, for every hour of the day, the charging profile is the blending of three possible regimes, namely: 'Work', 'Home', and 'Smart'. Under 'Work', it is assumed that EVs will be charged in parallel with occupants being at their respective employment. 'Home' considers charging in households and 'Smart' that the units are plugged when the electricity prices (or demand) is low. To answer **RQ67**, the hourly distribution for Germany was used, as this is the largest power consuming country in the block, considering an average winter day in 2015 and 2050 ("**Climate Neutrality**" scenarios).

The contributions of power consumption, from different final energy uses, to the total hourly electricity demand in Germany are plotted in **Figure 47**. We can observe that the 'Road transport' contribution to hourly power demand becomes dominant from approximately 6 pm onwards in the profile corresponding to "**2050 Neutrality**", mimicking the rise of electricity consumption in residential appliances. This reflects larger shares of the 'Home' regime in the charging blending, adding 30 GW to the evening peak in comparison with 2015. The effects of 'Smart' charging are noticeable during the first hours of the day, when the power consumption for 'Road transport' is the second largest in the "**2050 Neutrality**" profile. A plateau in the power usage from

‘Road transport’ is appreciated between 7 and 11 am, aligned with peak traffic hours and consumers using their vehicles.

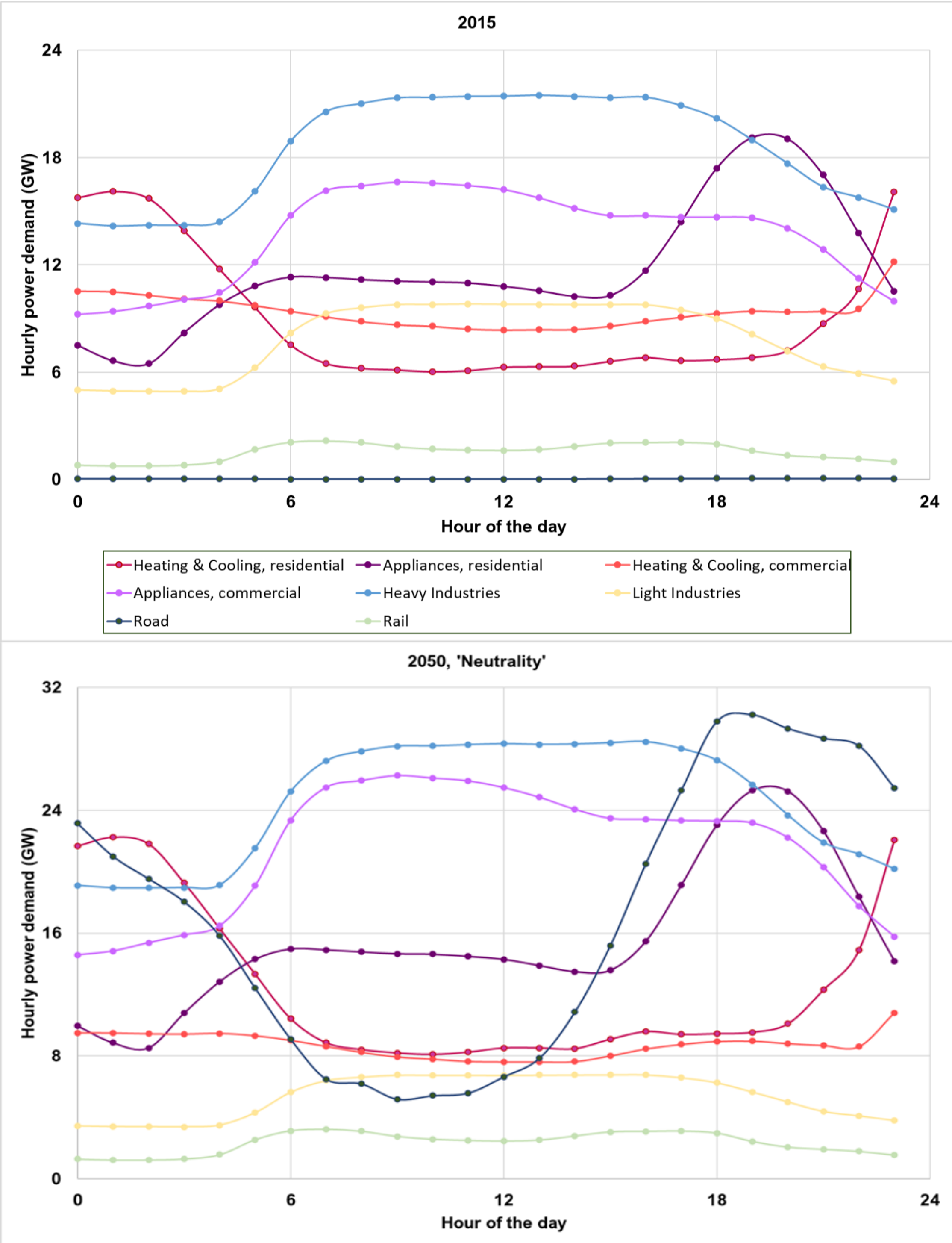


Figure 47. Hourly power demand on an average winter day in Germany and contribution of different final energy uses in 2015 and in 2050, under the “**Climate Neutrality**” scenario.

3.1.7. Environmental aspects & implications, including the circular economy

*3.1.7.1. **EU-C14**: The impact of EU climate policy on pollutants*

Contributing models: IMAGE

Research Questions' Overview

Many air pollutants originate from fossil fuel combustion, and often have a short-term effect on global temperature (Harmsen, et al., 2020). Note that that the impact of reducing some pollutants, such as black carbon (BC) and SO_2, is opposite (in terms of temperature) to that of GHG reductions. This cluster sheds light to the following RQ:

RQ72: What kind of pollutants and at what levels would be produced by different energy technologies and sectors in 2050?

Results and Discussion

The IMAGE model is an integrated assessment model that describes key processes in the interaction of human development and the natural environment for which climate change is the main component, but also covering interlinked dimensions such as air quality (Stehfest et al., 2014). Many air pollutants originate from fossil fuel combustion, and often have a short-term effect on global temperature (Harmsen, et al., 2020). Note that that the impact of reducing some pollutants, such as BC and SO_2, is opposite (in terms of temperature) to that of GHG reductions. We consider the following pollutants: VOCs (volatile organic compounds), CO, SO_2, NOx, organic carbon (OC) and BC, for which emission estimates are available from the IMAGE model. For this purpose, we focus on three scenarios: “**Current Trends**”, “**Neutrality 1.5°C**”, and “**Neutrality 2.0°C**”. The bunkers emission includes emissions from passenger air travel, freight air transport, and freight marine transport, which is the result of European citizens’ travel demand and freight transport due to their consumption.

In general, pollutant emissions decrease relative to 2015, even in the “**Current Trends**” scenario. VOC emissions by 2050 in the “**Current Trends**” scenario mainly come from fuel used for international aviation and shipping (bunkers) (73%), followed by the domestic transport (16%) and residential sector (5%) (**Figure 48**). The total VOC emissions are 1.45 Tg/y. The effect of climate policy on VOC emissions gives a mixed picture. In the “**Neutrality**” scenarios, VOC emissions from bunkers and domestic transport in 2050 are lower compared to the “**Current Trends**” scenario, but the residential VOC emissions are higher. This opposite impact is the result of how the two scenario types were developed. The “**Current Trends**” scenario incorporates specific policies, in this case aimed at the residential sector, while the “**Neutrality**” scenarios are driven by a carbon price with more dynamic effects. In other words, the strict buildings energy transition policies in the “**Current Trends**” scenario achieved a lower energy use in buildings compared to the “**Neutrality**” scenarios. However, total VOC emissions are still slightly lower in the “**Neutrality**” scenarios (1.29 Tg/y in “**Neutrality 1.5ºC**” and 1.44 Tg/y in “**Neutrality 2.0ºC**”).

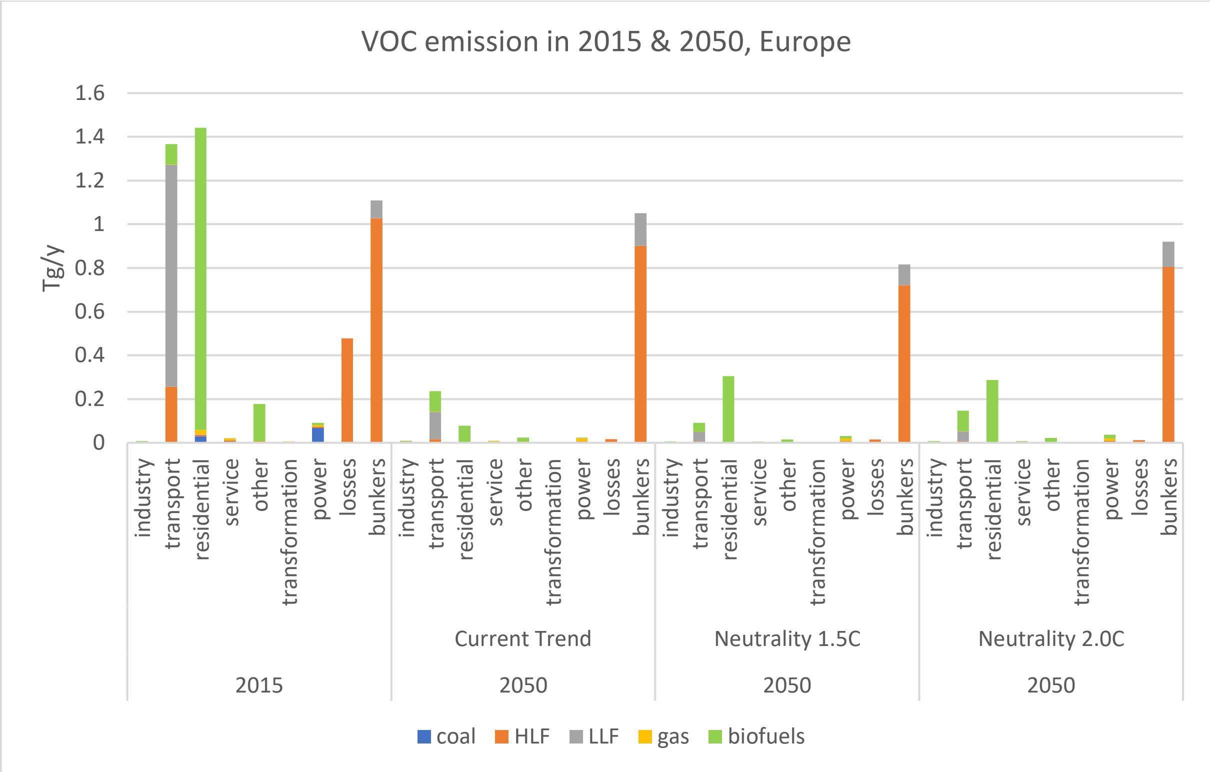


Figure 48. The sectoral Volatile Organic Compound (VOC) emission in 2015 and 2050 of the Europe region (including Western Europe and Central Europe). HLF: heavy liquid fuel (diesel, residual fuel oil and crude oil), LLF: light liquid fuel (liquefied petroleum gas and gasoline), biofuels: including modern biofuels and traditional biofuels. Bunkers include passenger air travel, freight air transport, and freight marine transport.

CO emissions are substantially reduced in all scenarios by 2050 compared to 2015 (**Figure 49**). The "**Current Trends**" scenario projects less CO emissions than the "**Neutrality**" scenarios. This is the result of higher biofuel consumption in the residential sector for "**Neutrality**" scenarios, as the "**Current Trends**" scenario includes stricter energy transition policies in the building sector.

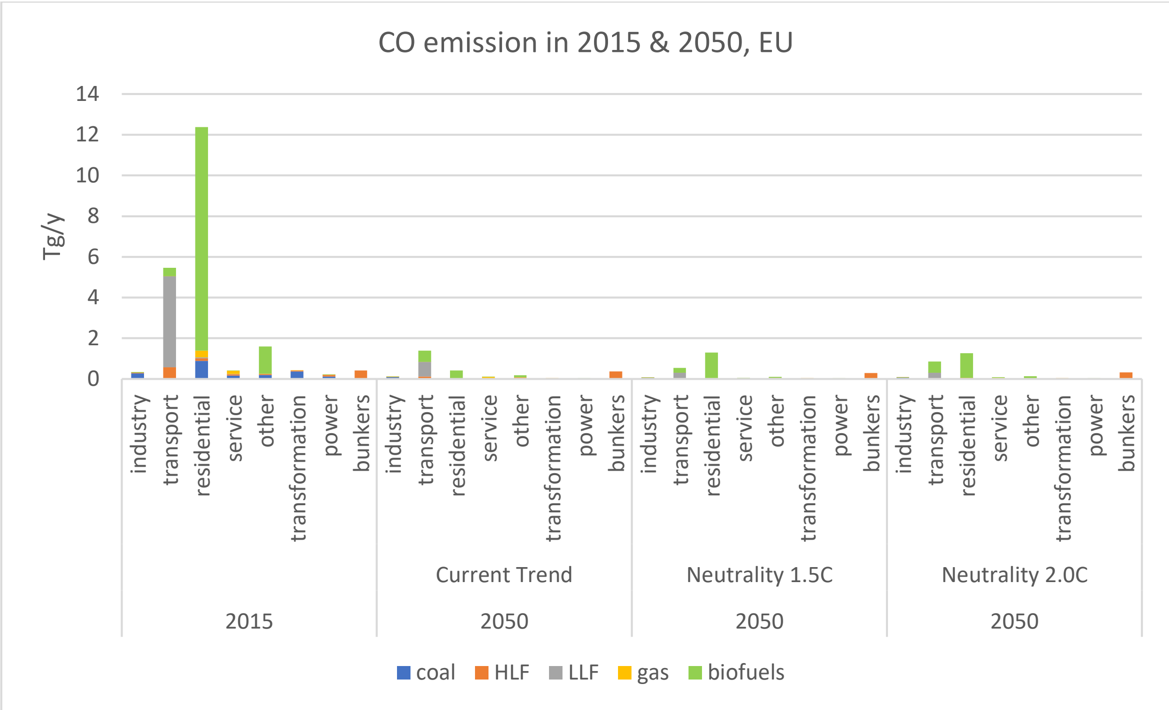


Figure 49. The sectoral Carbon Monoxide (CO) emission in 2015 and 2050 of Europe region (including Western Europe and Central Europe).

The main source of SO_2 emissions shifts from power generation in 2015 to bunkers by 2050 (**Figure 50**). The SO_2 emissions reduce significantly in all three scenarios by 2050, from 15.7 Tg/y in 2015 to around 0.7-0.9 Tg/y in 2050. The differences between the "**Current Trends**" and the "**Neutrality**" scenarios are minor; however, the "**Neutrality**" scenarios have slightly lower emissions from bunkers and power generation and a bit higher emission from the residential sector.

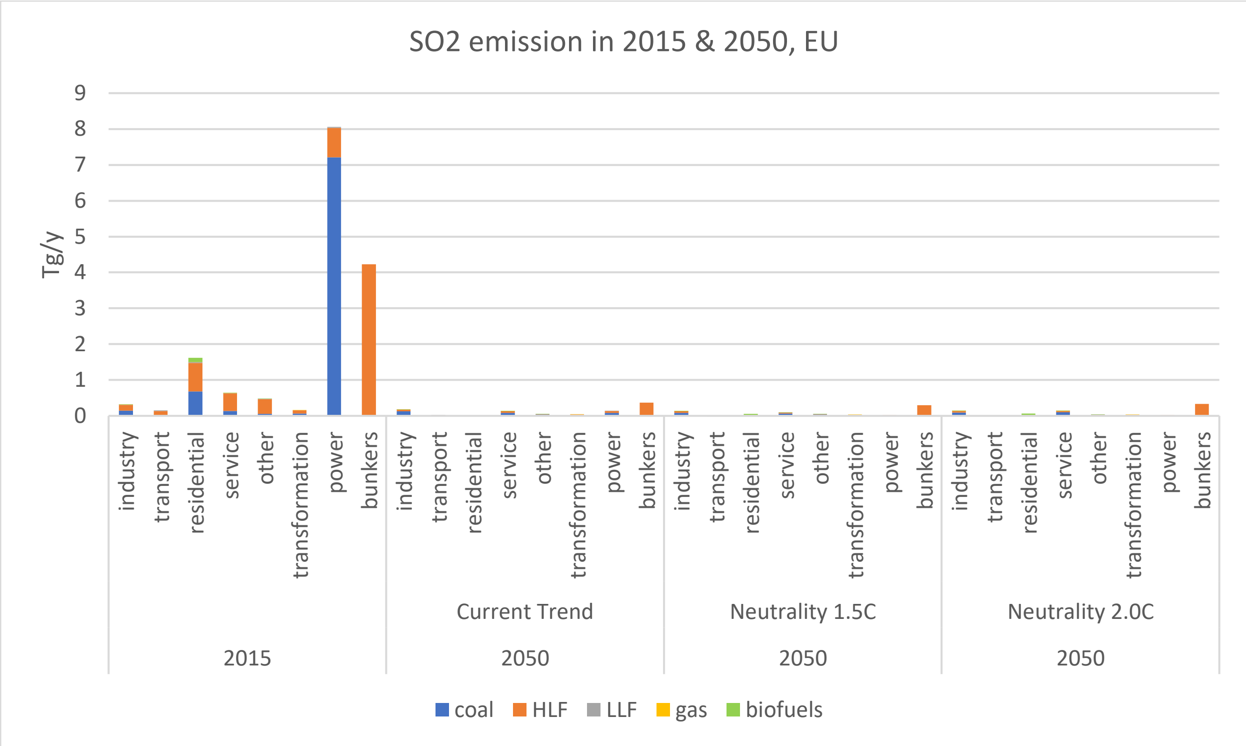


Figure 50. The sectoral Sulfur Dioxide (SO_2) emission in 2015 and 2050 in Europe (including Western Europe and Central Europe).

In 2015, main NOx emission sources are bunkers and transportation (1.8 Tg N/y and 1.2 Tg N/y, **Figure 51**), followed by power generation (0.6 Tg N/y). The total emissions are 4.0 Tg N/y. In the "**Current Trends**" scenario, NOx emissions reduce to 2.2 Tg N/y in 2050; and to 1.7 Tg N/y and 1.9 Tg N/y in the "**Neutrality 1.5°C**" and "**Neutrality 2.0°C**" scenarios, respectively. Nevertheless, NO_x emissions from bunkers remain high in all three scenarios by 2050, and the main reduction occurs in the transport and power generation sectors.

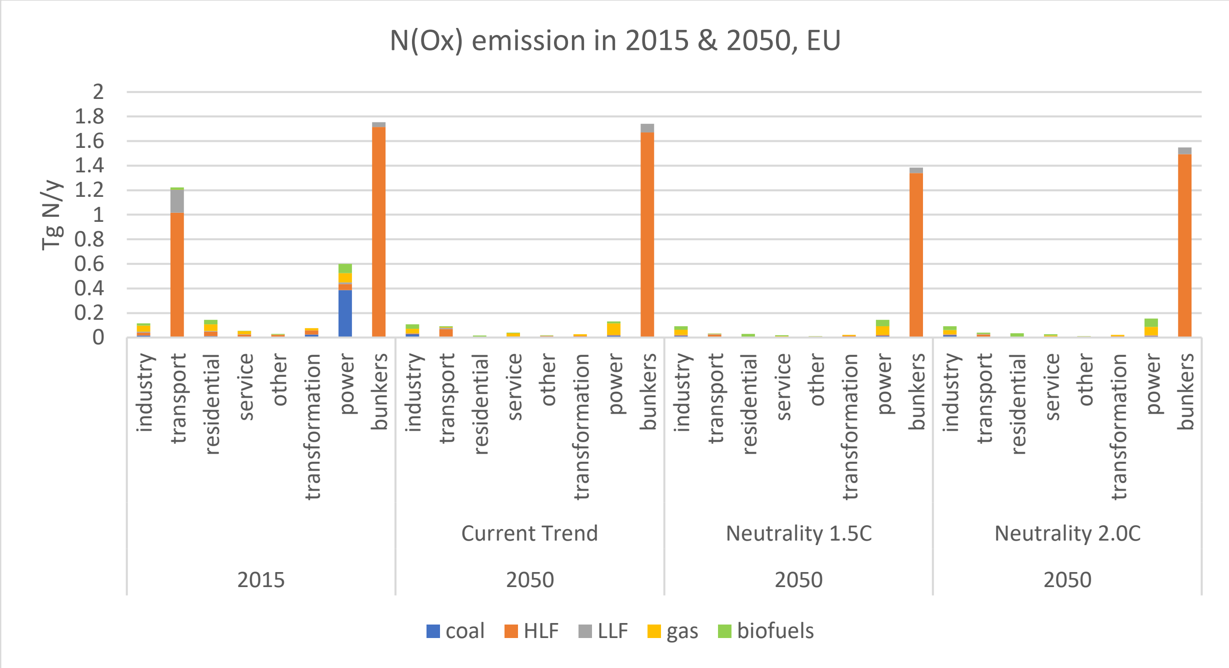


Figure 51. The sectoral Nitrogen Oxides (NO_x) emission in 2015 and 2050 in Europe (including Western Europe and Central Europe).

OC and BC emissions both decrease in the 2050 scenarios compared to the 2015 level as well (**Figure 52** and **Figure 53**). Interestingly, the OC and BC have higher emissions in the "**Neutrality**" scenarios in 2050 than in the "**Current Trends**" scenario (**Figure 53**), which is again caused by more traditional and modern biofuel use in the "**Neutrality**" scenarios in the residential sector.

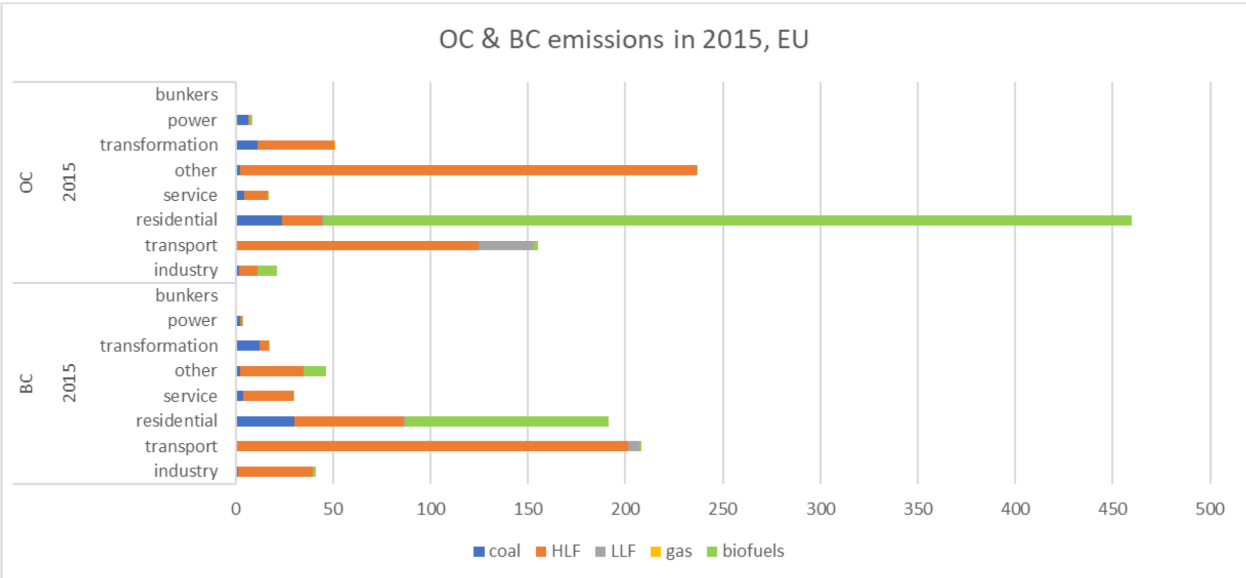


Figure 52. The sectoral Organic Carbon (OC) and Black Carbon (BC) emissions in 2015 in Europe (including Western Europe and Central Europe).

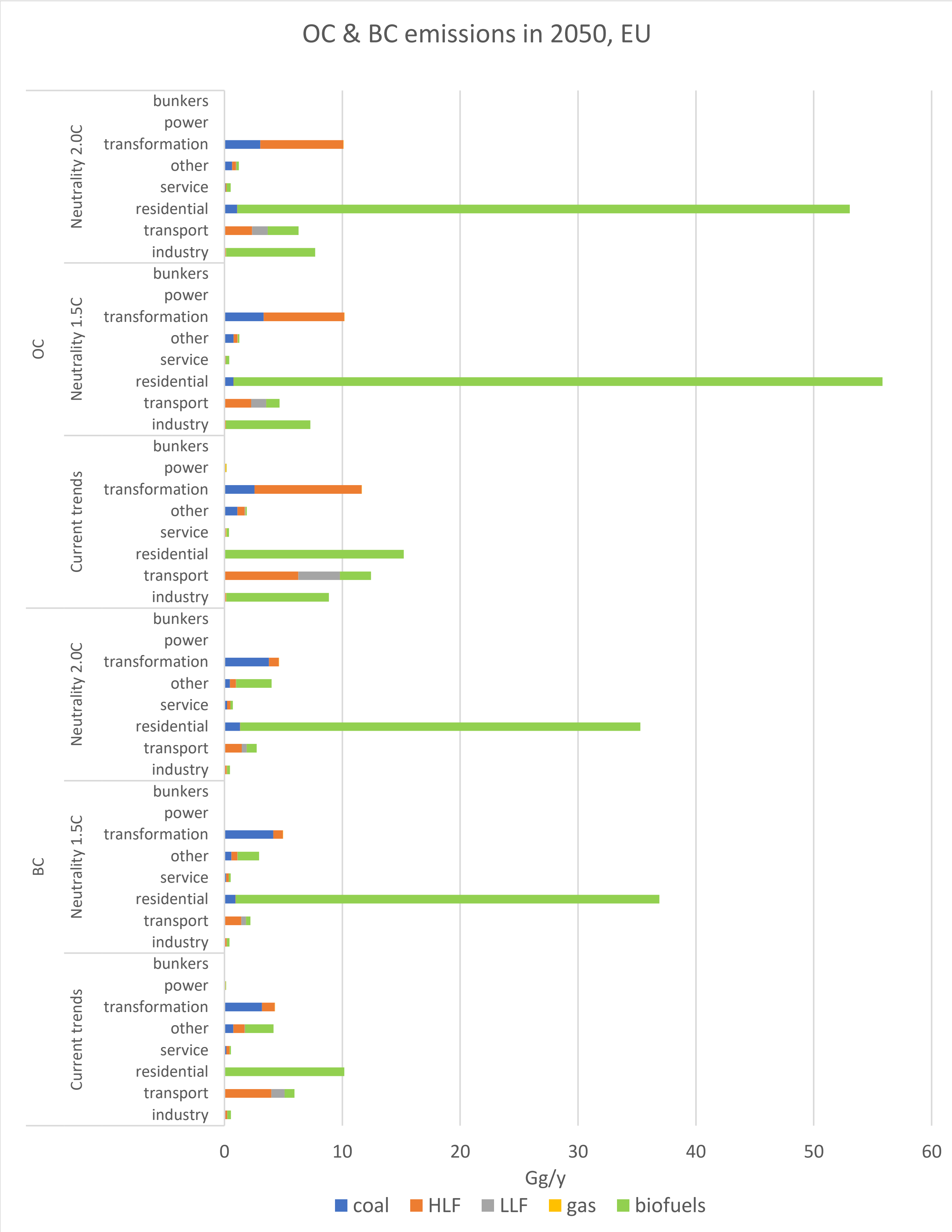


Figure 53. The sectoral Organic Carbon (OC) and Black Carbon (BC) emissions projection in 2050 in Europe (including Western Europe and Central Europe).

3.1.7.2. ***EU-C15***: *Roadblocks on the pathway to a renewable future. Potential raw material supply constraints for a European energy transition*

Contributing models: ENBIOS

Research Questions' Overview

While the transition to RES is widely perceived as the preferred pathway to achieving emissions reductions targets, a number of key constraints to the implementation of this transition have begun to gather attention within the EU and elsewhere, particularly regarding the supply of CRM required to produce additional infrastructure(Bleicher and Pehlken, 2020; Dominish et al., 2019; Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020; Giurco et al., 2019; Hund et al., 2020; Wellmer et al., 2018). A number of concerns have been raised, mostly regarding the supply of required materials (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b; Valero et al., 2018), but also issues regarding the geopolitical aspects relating to supply chains (D.-G. for I. M. I. E. and Sme. European Commission, 2021; Lee et al., 2020) and issues of social justice and localised environmental damages from extraction (Lèbre et al., 2020; Sovacool et al., 2019). All three of these aspects could very genuinely affect the potential implementation of different scenarios and renewable technologies going forward.

ENBIOS can determine the requirements of individual CRMs within each energy production process in a system using the material requirement information from LCI sources. More importantly, the module also includes methods for quantifying three specific raw material supply indicators–supply risk, local impacts of extraction and circularity–using this requirement data alongside known factors for each CRM. These per-unit-of-energy values can then be upscaled in accordance with system configuration (i.e., “energy mix”) information provided by Calliope outputs. Aggregating indicators across hierarchical levels also allows users to understand material-related factors at different levels throughout the overall system. Considering these capabilities, we endeavour here to answer the following RQs, adapted from those identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ73:** Which scenarios and technologies are more vulnerable to supply restriction relating to CRMs and intermediate products?
- **RQ74:** What amounts of rare-earth elements and other CRMs would be required to produce the projected levels of renewable energy by 2050?

Results and Discussion

In order to answer **RQ73**, energy system configuration (i.e., “energy mix”) data was imported into ENBIOS from the Calliope model for three specific “storylines”; information was provided as projections for the years 2030 and 2050. The annual energy production data (in TWh/yr) for each electricity, heat and fuel technology, and for each storyline, is summarised in **Table 24**. The derived level of supply risk for a given TWh of energy production–calculated independently of these values–is also listed. These values suggest that the highest supply risk per unit of energy is found in biodiesel production, which requires large amounts of phosphorus during its processing stages. Otherwise, electricity production processes tend to be the highest, particularly solar PV (which requires gallium and "high risk" rare earths like gadolinium, lanthanum, neodymium, praseodymium and samarium, alongside others like yttrium, terbium and dysprosium) and wind (which also requires dysprosium, neodymium and praseodymium and other rare earths). Fossil fuel sources of electricity can also be high, particularly natural gas which requires high amounts of several rare earths for its extraction and refinement. Aside from biodiesel, supplies of heat and fuels tend to significantly lower than electricity.

Such observations suggest that the planned "electrification" of energy systems that forms a key part of most energy transition scenarios–including the three storylines presented here, all of which rely heavily of large increases in electricity from wind and solar PV infrastructure–are likely to be subject to significant issues with respect to supplies of CRMs, and rare earths in particular. Indeed, **Table 25** presents the aggregated supply risk scores for the three storylines for 2030 and 2050. These are formed by summing the individual contributions of each energy production technology using the data listed in **Table 24**. The highest predicted risk by 2050 is observed for the **PPO** storyline (981), compared to the **GDI** (917) and **MDR** (873) storylines. The **PPO** storyline also presents a higher intermediate score in 2030 (474 compared to 332 and 313 for the other two storylines, respectively). These high scores are largely the result of higher use of wind and solar PV technologies going forward, confirming that these two technology groups present the greatest risk in terms of CRM supply restrictions.

Table 24. Provided energy mix values for each scenario and per-unit supply risk values for individual technologies.

Carrier	**Technology**	**"Energy mix" data for each storyline** *[TWh/yr]*						**Supply risk** *[yr/TWh]*
		GDI		**MDR**		**PPO**		
		2030	2050	2030	2050	2030	2050	
Electricity	Wind-Onshore	2033.2	6610.8	1864.9	8911.2	2730.3	9698.0	0.04174
	Wind-Offshore	488.2	2388.2	291.8	814.1	326.9	783.4	0.03587
	Hydro-Reservoir	324.8	408.9	414.1	414.0	407.0	412.5	0.00635
	Hydro-River	93.6	120.3	133.0	111.5	98.2	97.7	0.00799
	Solar PV-Field	78.1	96.5	86.6	77.4	105.8	102.5	0.09164
	Solar PV-Roof	12.0	59.0	0.0	0.1	1941.7	3337.1	0.07984
	Biomass	272.5	50.1	112.8	0.1	221.7	171.4	0.03071
	Waste	51.9	54.2	51.9	54.2	51.9	54.2	0.03071
	Coal	4.1	0.0	17.8	0.0	0.0	0.0	0.03388
	Natural gas	137.8	101.2	26.0	1.1	183.8	214.8	0.05114
	Nuclear	599.4	159.1	614.9	0.1	574.2	0.0	0.00631
Heat	Biomass	609.1	50.3	940.1	0.4	277.0	221.5	0.00521
	Waste	51.9	54.2	51.9	54.2	51.9	54.2	0.00521
	Natural gas	558.9	0.0	1341.8	0.1	7.1	0.5	0.00942
Fuel	Biodiesel	416.2	1418.3	284.3	1498.0	686.1	1185.8	0.14027
	Biomass	357.8	0.0	357.8	0.0	357.8	0.0	0.00727
	Coal	216.4	0.0	216.4	0.0	216.4	0.0	0.01251
	Natural gas	1182.2	743.6	1182.2	743.6	1182.1	743.7	0.01125

Diesel	3310.7	0.0	2732.3	0.0	2642.4	0.0	0.01261
Kerosene	934.7	0.0	934.7	0.0	927.8	0.0	0.01227
Methanol	0.0	0.0	0.0	0.0	0.0	0.0	0.01292

Table 25. Final aggregated supply risk values for each scenario.

Final supply risk data by scenario					
GDI		**MDR**		**PPO**	
2030	2050	2030	2050	2030	2050
332	917	313	873	474	981

Similarly, in order to answer **RQ74**, an analysis was also performed to quantity the specific amounts of each CRM that would be required under the three storylines, as presented in **Table 26**. Again, data is available for 55 of the EC's CRM candidate materials. However, the contributions of these materials to the individual supply risk scores for different technologies varies greatly. **Table 26** presents values for the 22 materials with average contributions above 0.1%, in order of average contribution, meaning that the materials not listed provide minimal contributions; in fact, only the first six materials provide average contributions of over 5%. Percentage increases between 2030 and 2050 are also shown.

Table 26. Actual material requirements for 22 key critical raw materials for each scenario. Values in kg are shown for 2030, while percentage increases (relative to 2030 values) are given for 2050.

Material	**Material requirements by scenario** *[kg]*					
	GDI		**MDR**		**PPO**	
	2030	2050	2030	2050	2030	2050
Samarium	227,786	*+68%*	224,107	*+66%*	259,487	+57%
Neodymium	2,930,511	*+65%*	2,884,924	*+63%*	3,323,722	+55%
Praseodymium	956,484	*+65%*	941,639	*+63%*	1,084,535	+55%
Gadolinium	119,161	*+66%*	117,296	*+64%*	135,243	+55%
Lanthanum	6,091,587	*+68%*	5,993,552	*+66%*	6,936,498	+57%
Gallium	343,302	*+280%*	405,812	*+150%*	617,484	+106%
Magnesium	44,666,280	*+245%*	46,597,620	*+164%*	82,243,754	+102%
Dysprosium	24,474	*+71%*	24,060	*+69%*	28,033	+59%
Phosphorus	568,409,936	*+207%*	417,654,982	*+337%*	892,092,206	+67%
Magnesite	187,713,016	*+158%*	174,313,494	*+173%*	229,500,676	+131%
Tellurium	93,188	*+240%*	94,066	*+193%*	256,724	+102%
Cerium	9,147,710	*+66%*	9,003,766	*+64%*	10,388,948	+55%
Europium	44,302	*+67%*	43,596	*+65%*	50,388	+56%
Tantalum	140,767	*+54%*	133,876	*+45%*	1,027,559	+67%
Baryte	1,679,836,997	*-85%*	1,469,769,593	*-85%*	1,463,015,030	-80%
Terbium	14,684	*+71%*	14,436	*+69%*	16,820	+59%
Tungsten	2,032,574	*+24%*	1,991,612	*+27%*	2,162,598	+14%
Beryllium	90,199	*+12%*	89,450	*+13%*	92,153	+8%
Natural graphite	29,437,071	*+384%*	37,812,177	*+180%*	79,552,793	+109%
Selenium	505,146	*+241%*	510,182	*+193%*	1,396,269	+102%
Fluorspar	131,191,899	*+148%*	137,181,353	*+85%*	227,958,344	+66%
Yttrium	89,737	*+71%*	88,221	*+69%*	102,787	+59%

These values suggest that increases are required for all materials (except baryte) and that most increases are over 50%. The five highest contributors to supply risk–samarium, neodymium, praseodymium, gadolinium and lanthanum–are expected to rise significantly in all storylines, although the expected rises for gallium and magnesium are significantly higher. In all storylines, the results demonstrate that the demand for a range of critical materials is likely to rise dramatically as the energy transition progresses and, again, this could well present a significant barrier to implementing the projected capacities of new infrastructure if reliable sources of raw materials, intermediate products and completed components cannot be guaranteed. Lastly, it is recognised that LCI data is only available for 25 of the materials identified by the EC as potentially critical and that the supply risk calculations derived from ENBIOS would be improved if a more complete dataset were available. In the meantime, it is believed that the presented results provide an overview of the potential material supply constraints that will need to be addressed as the energy transition progresses within the EU.

*3.1.7.3. **EU-C16**: The hidden impacts of the energy transition in Europe. Deeper assessments of renewable energy technologies via the life cycle approach*

Contributing models: ENBIOS

Research Questions' Overview

The majority of current modelling approaches used to inform long-term energy policy decisions, particularly those that surround the transition towards more sustainable technologies, are based on simplified considerations of GHG emissions and other environmental indicators that fail to consider the range of other 'background' impacts that may occur (Hertwich et al., 2015; Von Stechow et al., 2016). As such, these assessments offer incomplete and potentially misleading information about the real environmental aspects of future energy pathways. Adopting an LCA-based approach to the assessment of impacts can address these shortcomings by considering the full life cycles of energy processes within future energy systems (Pehl et al., 2017; Sacchi et al., 2022). This enables the full range of sub-processes, including material extraction activities, the creation, transportation and installation of infrastructure and fuel supplies, ongoing operation and maintenance processes and, ultimately, end-of-life disposal and/or recycling, to be included. Outputs of such assessments then provide more complete estimates of the GHG emissions, environmental impacts, land and water use, raw material requirements and various other aspects arising from all of these stages, providing more robust indicators to policymakers.

ENBIOS allows users to calculate a variety of indicators by using the LCI listings for individual technologies within an energy system in conjunction with a chosen set of LCIA "methods". These per-unit-of-energy values can then be upscaled in accordance with system configuration (i.e., "energy mix") information provided by Calliope outputs. Aggregating indicators across hierarchical levels also allows users to understand emissions and impacts at different levels throughout the overall system. Considering these capabilities, we endeavour here to answer the following RQs, adapted from those identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ78:** What annual life-cycle emissions and other environmental impacts are associated with increasing levels of RES technologies in future energy systems? How do the metrics for RES technologies compare with non-RES technologies in this regard?
- **RQ77:** What are the land use requirements that result from the deployment of additional RES infrastructure?

Results and Discussion

In order to answer **RQ78**, values for a selection of environmental indicators were derived for each energy production technology using Ecoinvent LCIA data, as listed in **Table 27**. Values were derived for GHG emissions ("global warming potential"), "human toxicity", "particulate matter formation", "terrestrial acidification", "photochemical oxidant formation", "water depletion" and "freshwater eutrophication" using the "ReCiPe Midpoint (H) V1.13" midpoint method and "human health (total)" using the "ReCiPe Endpoint (H,A)" endpoint method. Values were all transformed such that they represent the production of one TWh via the specified technological process. The results confirm that fossil fuels and waste generate the highest emissions, however the direct use of biodiesel and biomass as fuels also generates high levels. A variety of results can be observed for the other indicators, although electricity and heat from fossil fuels and biodiesel production tend to be higher in most categories. Not surprisingly, hydropower from reservoirs is the most water intensive.

Table 27. Greenhouse Gas (GHG) emissions and other environmental impact indicators, per TWh values for each technology.

Carrier	Technology	GHG emissions *[kg CO_2-eq]*	Human toxicity *[kg 1,4-DC]*	Human health *[points]*	Particulate matter formation *[kg PM10-eq]*	Terrestrial acidification *[kg SO_2-eq]*	Photochem oxidant formation *[kg NMVOC]*	Water depletion *[m^3]*	Freshwater eutrophication *[kg P-eq]*
Electricity	Wind-Onshore	1.43E+07	1.06E+07	7.97E+05	4.71E+04	6.87E+04	6.42E+04	1.43E+05	6.36E+03
	Wind-Offshore	1.60E+07	1.27E+07	8.91E+05	4.99E+04	7.88E+04	6.32E+04	1.93E+05	6.66E+03
	Hydro-Reservoir	4.97E+07	1.74E+06	1.51E+06	2.03E+04	2.08E+04	2.59E+04	2.92E+07	1.37E+03
	Hydro-River	4.35E+06	1.20E+06	2.58E+05	2.32E+04	1.65E+04	2.09E+04	2.12E+04	1.02E+03
	Solar PV-Field	7.60E+07	6.16E+07	4.05E+06	2.01E+05	3.94E+05	3.15E+05	2.44E+06	3.92E+04
	Solar PV-Roof	7.36E+07	8.74E+07	4.40E+06	2.13E+05	4.53E+05	3.21E+05	2.46E+06	4.76E+04
	Biomass	5.95E+07	1.11E+08	1.16E+07	5.55E+05	1.62E+06	1.75E+06	1.09E+06	4.10E+04
	Waste	1.60E+09	3.72E+08	6.27E+07	2.19E+06	4.85E+06	3.21E+06	1.98E+07	3.42E+05
	Coal	1.01E+09	5.35E+08	4.85E+07	2.55E+06	8.10E+06	3.89E+06	1.80E+06	5.15E+05
	Natural gas	6.38E+08	4.14E+07	1.97E+07	2.73E+05	7.28E+05	9.43E+05	1.20E+06	1.16E+04
	Nuclear	6.33E+06	2.52E+07	1.00E+06	4.48E+04	4.14E+04	4.11E+04	3.05E+06	4.12E+03
Heat	Biomass	1.01E+07	1.88E+07	1.96E+06	9.42E+04	2.75E+05	2.96E+05	1.84E+05	6.96E+03
	Waste	2.50E+08	7.38E+07	1.02E+07	3.84E+05	8.98E+05	5.75E+05	3.14E+06	6.13E+04
	Natural gas	1.18E+08	7.63E+06	3.63E+06	5.04E+04	1.34E+05	1.74E+05	2.21E+05	2.13E+03
Fuel	Biodiesel	6.72E+08	3.83E+07	1.63E+07	7.35E+05	2.50E+06	8.80E+05	6.53E+06	7.08E+04
	Biomass	4.64E+08	1.07E+07	1.56E+06	9.11E+04	1.52E+05	1.54E+05	1.92E+05	1.12E+04
	Coal	3.88E+08	1.26E+08	3.62E+06	1.22E+05	3.15E+05	3.52E+05	1.42E+05	1.83E+05
	Natural gas	2.57E+08	1.20E+07	1.01E+06	3.28E+04	1.12E+05	1.35E+05	2.52E+04	1.26E+03
	Diesel	3.08E+08	7.13E+06	1.82E+06	1.15E+05	3.80E+05	2.79E+05	1.30E+05	3.35E+03
	Kerosene	3.02E+08	6.95E+06	1.79E+06	1.14E+05	3.78E+05	2.79E+05	1.27E+05	3.26E+03
	Methanol	3.45E+08	1.67E+07	3.61E+06	1.16E+05	3.28E+05	3.41E+05	6.94E+05	1.11E+04

Energy system configuration (i.e., "energy mix") data was imported into ENBIOS from the Calliope model for three specific "storylines"; information was provided as projections for the years 2030 and 2050 and are listed within the response for cluster **EU-C15** (**Section 3.1.7.2**). Using these values, final aggregated values were then calculated for all six of these configurations for each of the indicators, as listed in **Table 28**. It is noted that combustion GHG emissions were added to the fuel production totals for all fuels using the combustion factors listed in **Table B.3** of the appendix. Furthermore, it is assumed that the "background" sub-processes that provide energy to each of these processes is assumed to have transitioned to RES (and, hence, produce zero or very low emissions) by 2050. Accordingly, all processes that do not involve combustion (i.e., all renewable and nuclear electricity and fuel production) were assumed to have zero emissions in 2050. This is not entirely accurate as some electricity is still predicted to be from fossil fuels in 2050. Conversely, the assumed background systems for electricity and heat derived from biomass, waste, coal and natural gas are assumed to remain "as-is", whereas these are likely to include low emissions sources by 2050. In any case, the total GHG emissions are seen to drop in all scenarios, as expected; the lowest GHG emissions for 2030 and 2050 were observed for the **MDR** storyline, while the **PPO** storyline results in the highest emissions. Tellingly, the values of all other indicators for all three storylines rise between 2030 and 2050, suggesting that the reductions in GHG emissions offered by transition scenarios of this kind tend to be offset by poorer performance in other areas.

Table 28. Final aggregated values of Greenhouse Gas (GHG) emissions and other environmental impact indicators for each scenario.

Storyline	Year	GHG emissions	Human toxicity	Human health	Particulate matter formation	Terrestrial acidificat	Photochem oxidant formation	Water depletion	Freshwater eutrophicat
		[kg CO_2-eq]	*[kg 1,4-DC]*	*[points]*	*[kg PM10-eq]*	*[kg SO_2-eq]*	*[kg NMVOC]*	*[m^3]*	*[kg P-eq]*
GDI	2030	2.55E+12	2.58E+11	3.62E+10	1.61E+09	4.53E+09	3.36E+09	1.88E+10	1.78E+08
	2050	1.48E+12	4.30E+11	5.36E+10	2.45E+09	6.21E+09	3.50E+09	3.35E+10	3.30E+08
MDR	2030	2.31E+12	2.55E+11	3.39E+10	1.47E+09	4.01E+09	3.04E+09	2.09E+10	1.76E+08
	2050	1.37E+12	3.63E+11	4.86E+10	2.28E+09	5.89E+09	3.11E+09	3.12E+10	2.98E+08
PPO	2030	2.74E+12	3.80E+11	4.33E+10	1.96E+09	5.35E+09	3.61E+09	2.59E+10	2.58E+08
	2050	1.61E+12	5.72E+11	5.82E+10	2.61E+09	6.46E+09	3.96E+09	3.35E+10	3.80E+08

In order to answer **RQ79**, an identical approach was adopted, this time involving the use of LCIA methods for calculating agricultural and urban "land occupation". The values for each technology are listed in **Table 29** and suggest that bioenergy processes present the highest overall land requirements. The final, aggregated values for the three storylines are listed in **Table 30**. They show that land requirements rise by around 11% and 19% for the **PPO** and **MDR** storylines, respectively, while they drop by 1% in the **GDI**. These changes are overwhelmingly influenced by differences in bioenergy levels employed in each case; the slight reduction in the latter case is caused by a sharper drop in electricity from biomass. Nevertheless, the **PPO** storyline presents the highest overall land requirement for 2050, while the **MDR** is the lowest. Lastly, it is recognised that the clearest shortcoming of the ENBIOS module in answering these two RQs is the uncertainties that arise regarding future electricity background systems and the fact that current LCI data assumes that the energy inputs required to undertake all processes is assumed to remain at current levels (i.e., containing significant levels of fossil fuels). Although we have attempted to remove future GHG emissions from some processes, these assumptions are somewhat inelegant and based on coarse assumptions. Future research is being undertaken to advance the integration of LCI data with prospective models to account for changing background systems, but such research remains in its infancy for now.

Table 29. Agricultural, urban and total land use requirements, per TWh values for each technology.

Carrier	Technology	Agricultural land use *[m²]*	Urban land use *[m²]*	Total land use *[m²]*
Electricity	Wind-Onshore	6.11E+05	1.21E+06	1.82E+06
	Wind-Offshore	7.21E+05	2.00E+05	9.22E+05
	Hydro-Reservoir	3.47E+07	7.73E+04	3.48E+07
	Hydro-River	4.76E+06	5.06E+04	4.81E+06
	Solar PV-Field	5.36E+06	3.26E+07	3.80E+07
	Solar PV-Roof	5.76E+06	8.28E+05	6.59E+06
	Biomass	2.25E+09	1.12E+07	2.26E+09
	Waste	2.72E+08	1.49E+07	2.87E+08
	Coal	1.69E+07	6.44E+06	2.34E+07
	Natural gas	2.43E+06	1.22E+06	3.64E+06
	Nuclear	5.15E+05	1.26E+05	6.41E+05
Heat	Biomass	3.81E+08	1.91E+06	3.83E+08
	Waste	4.07E+07	3.04E+06	4.38E+07
	Natural gas	4.47E+05	2.24E+05	6.71E+05
Fuel	Biodiesel	7.10E+08	7.00E+06	7.17E+08
	Biomass	3.65E+08	4.88E+06	3.70E+08
	Coal	4.64E+06	1.77E+06	6.41E+06
	Natural gas	1.22E+05	4.30E+04	1.65E+05
	Diesel	4.85E+05	4.62E+05	9.46E+05
	Kerosene	4.50E+05	3.94E+05	8.43E+05
	Methanol	7.91E+05	5.16E+05	1.31E+06

Table 30. Final aggregated values of agricultural, urban, and total land use requirements for each scenario.

Storyline	Year	Agricultural land use *[m²]*	Urban land use *[m²]*	Total land use *[m²]*
GDI	2030	1.31E+12	3.88E+10	1.35E+12
	2050	1.20E+12	1.38E+11	1.33E+12
MDR	2030	9.86E+11	4.39E+10	1.03E+12
	2050	1.12E+12	1.11E+11	1.23E+12
PPO	2030	1.27E+12	2.04E+10	1.29E+12
	2050	1.37E+12	5.65E+10	1.43E+12

*3.1.7.4. **EU-C17**: Biomass use and its effects*

Contributing models: IMAGE

Research Questions' Overview

Stakeholders interviewed during the preparation of Deliverable 7.1 (Stavrakas et al., 2021) highlighted that biomass can be used in many manufacturing processed, such as fine chemicals, food, fibre, fertilisers, and fuels. In fact, some sectors compete over biomass utilization, and there is strong dependency for some industries. Considering this, the following RQ is addressed:

- **RQ81:** What will be the total demand for biomass for energy production by 2030 and 2050? What are the environmental effects of biomass' use among different sectors? Which industries will be less dependent on biomass?

Results and Discussion

The IMAGE model is an integrated assessment model that covers both the energy system model (TIMER) and the land use system (agriculture, forestry and other land use). These sub-models are interlinked, where the IMAGE land use gives the potential of biomass production (from energy crops, and agricultural and forestry residues), TIMER determines the bio-energy use based on this potential, and IMAGE evaluates the change in land use and cover.

According to the modelling results presented in **Figure 54**, biomass use increases only slightly by 2030 compared to 2015. In the "**Current trends**" scenario this is caused by an increase in the transport sector due to the biofuel Directive (Directive (EU) 2018/2001) that applies to 2020 and is used as a lower limit until 2030. The increase in the "**Neutrality**" scenarios is mainly the result of increasing biofuels use in the buildings sector. For the energy demand sectors, biofuel usage rises by 2050 in the "**Current Trends**" scenario due to increasing biomass use (without CCS) in industry, while in the "**Neutrality**" scenarios, it increases less and biomass demand shifts to the building sector. However, in the energy supply sector, biomass use for electricity generation grows substantially in the "**Neutrality**" scenarios by 2050, from 1.4 EJ in 2015 to 5.2 EJ and 7.6 EJ respectively in "**Neutrality 1.5ºC**" and "**Neutrality 2.0ºC**" scenarios in 2050. In the end, biofuel use increases twofold by 2050 relative to 2015 for the "**Neutrality**" scenarios. In contrast, biomass demand in industry and transportation are less in 2050 in the "**Neutrality**" scenarios.

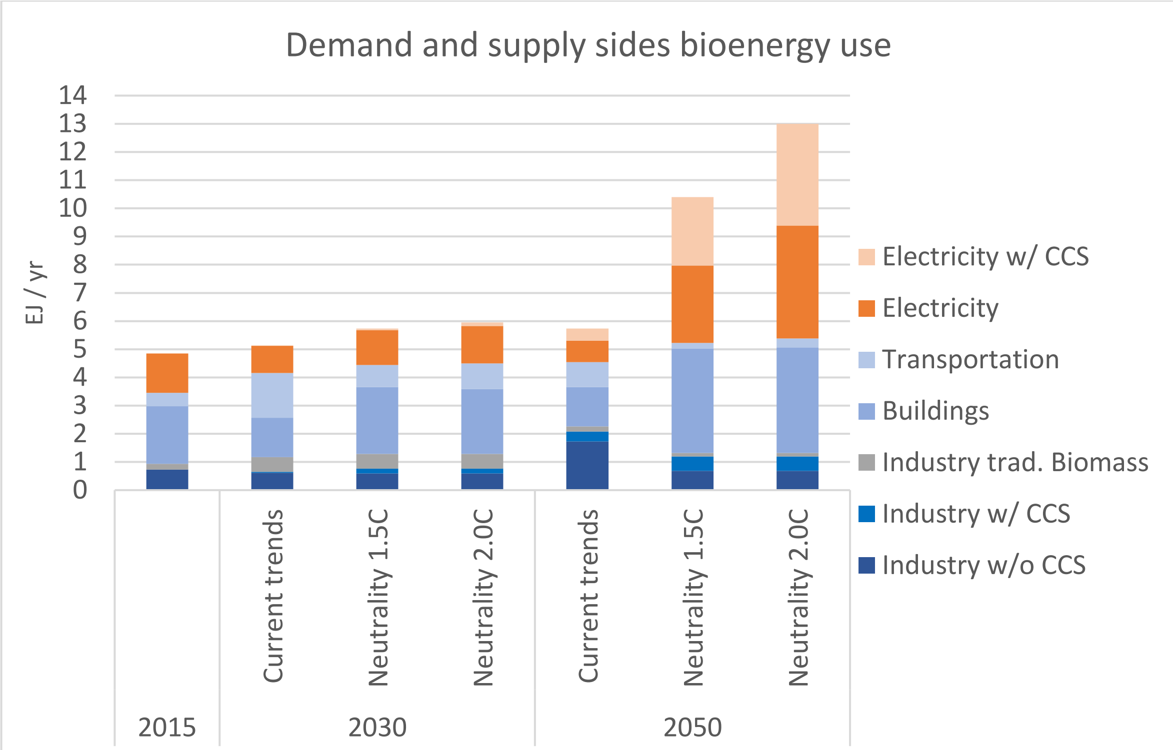


Figure 54. The EU biofuel usage from industry, buildings, transport, and power generation.

We consider change in land use an important environmental effect if food production replaces forests or other ecosystems. Bio crops may compete with food crops in reality, but in IMAGE for sustainability reasons bio-energy crops are only planted on abandoned agricultural lands and lands with low above ground carbon stocks (e.g., savannahs), and do not compete with food crops. Thus, the IMAGE model explicitly follows a 'food first' principle, where the biomass potential and production is determined after food requirements are met. Furthermore, the inclusion of agricultural and forestry residues also provides a significant biomass potential which does not have any additional land requirement. **Figure 55** shows the land-use change for energy crops in 2015, 2030, and 2050 for the three scenarios. In 2030, the land-use cover for energy crops is projected to increase from 18,000 km^2 in 2015 to 26,000-28,000 km^2 by 2030. In 2050, the land cover for energy crops increases even more in the neutrality scenarios, to 52,000 km^2 in the "**Neutrality 1.5ºC**" scenario and 27,000 km2 in the "**Neutrality 2.0ºC**" scenario. In contrast, the energy crop land-use reduces drastically in the "**Current Trends**" scenario by 2050. This is due to the increased biofuel import from other regions in 2050 (mainly from Brazil and South Africa). This is especially the case in the "**Current Trends**" scenario (6.3 EJ/yr) and "**Neutrality 2ºC**" scenario (9.8 EJ/yr) (**Figure 56)**. It is important to note that the energy crops are used for liquid biofuel production used in the transport and residential demand sectors. The solid biofuels are produced from residues and do not require land. The decarbonisation in the residential and transport sectors for the "**Neutrality**" scenarios leads to higher liquid biofuel use compared to the "**Current Trends**" scenario.

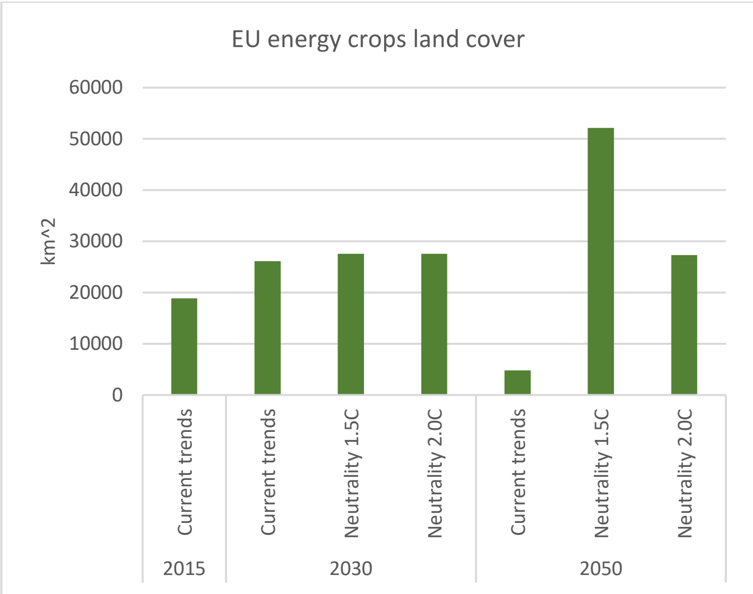


Figure 55. Europe energy crops land convers in 2015, 2030, and 2050 among the three scenarios under study.

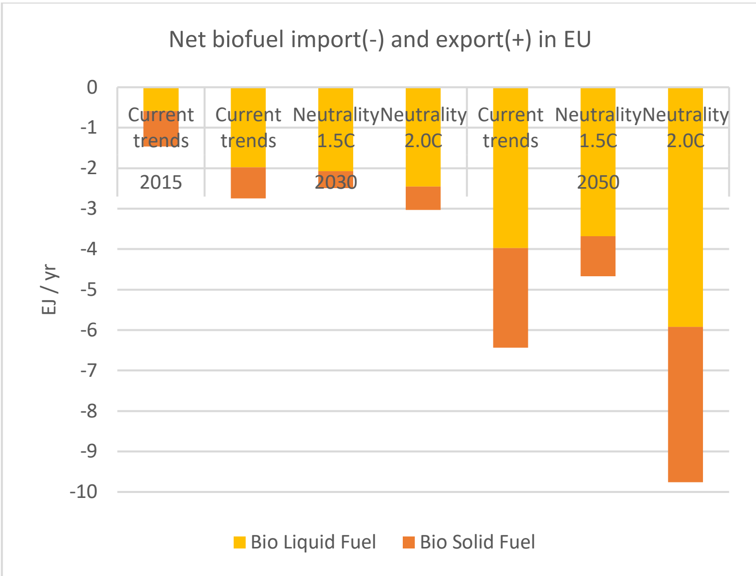


Figure 56. Biofuel net trade in Europe.

The production of liquid fuels (transport, buildings, non-energy) has the largest land footprint; this partially explains why energy crop land-use is much lower in the "**Current Trends**" scenario by 2050 compared to other scenarios. Power and industry depend more on solid biofuels made from residues (from agricultural and forestry processes); still, at high demand levels they may also lead to energy crops demanding land use.

Another environmental impact assessed in IMAGE is the CO_2 emissions from biofuel use. In IMAGE, the carbon content (Kg C / GJ) is 25.5 for coal, 19.3 for oil and 15.3 for natural gas. For bioenergy, the carbon content varies by source (**Figure 57**), from 0 to 27 Kg C / GJ. This emissions factor also includes emissions from land-use change (Daioglou et al., 2017), which drives the main variance over time, region, and feedstocks.

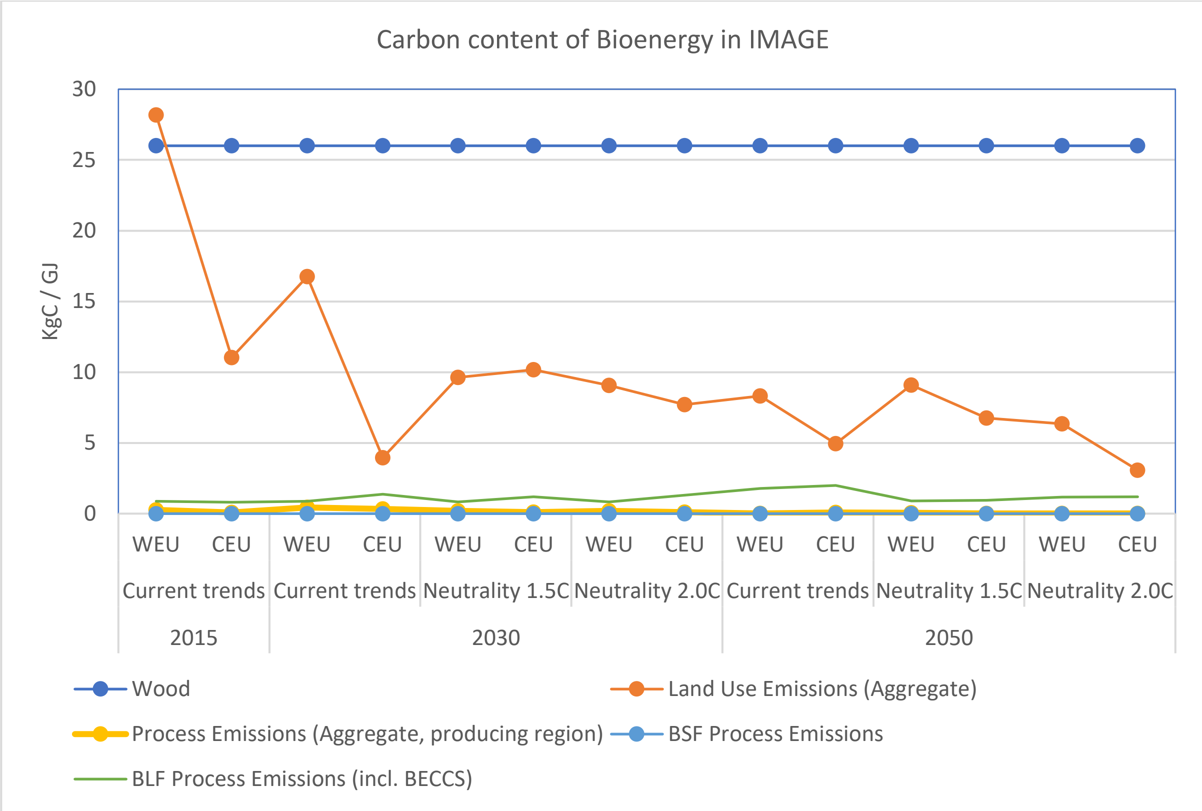


Figure 57. Carbon content assumptions of bioenergy in IMAGE.

Figure 58 shows the CO_2 emissions from biofuel use in IMAGE. In all three scenarios, the biofuel CO_2 emission decrease by 2050 compared to 2015, mostly because bioenergy carbon capture and storage power plants lead to negative CO_2 emissions from biofuel use in the "**Neutrality**" scenarios in 2050, which balances out the increased biofuel use in the residential sector.

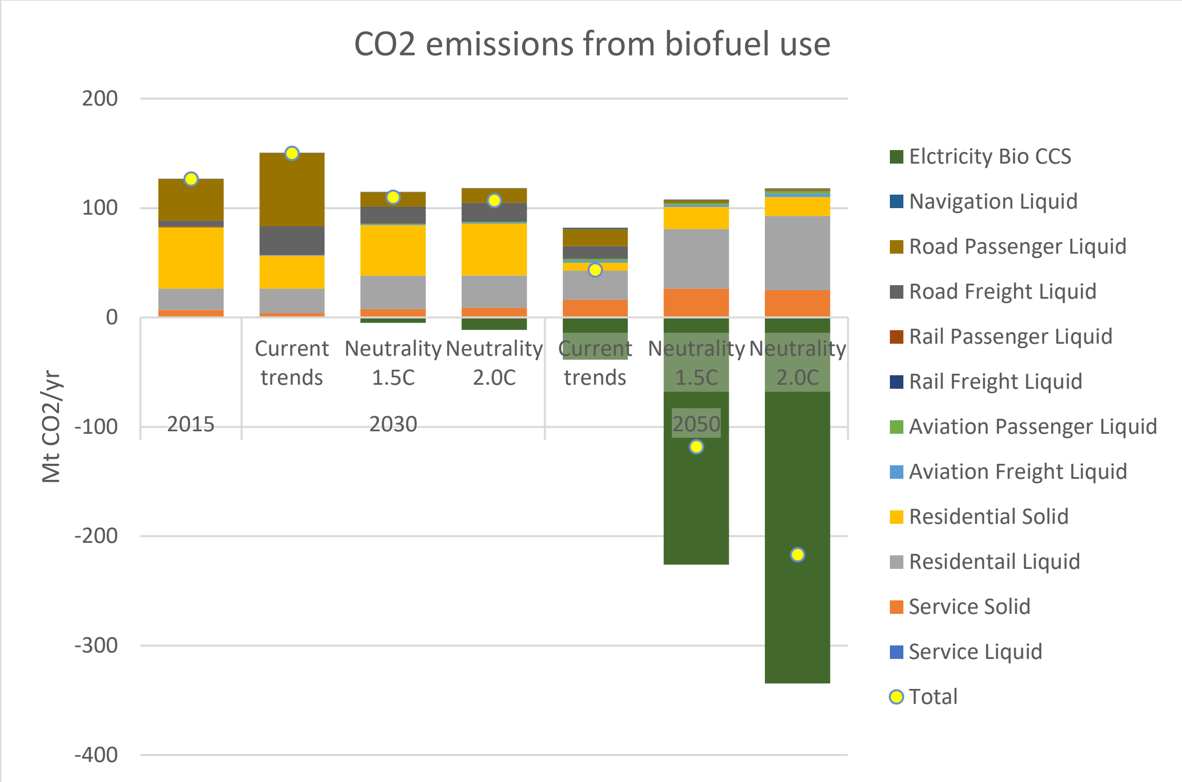


Figure 58. Carbon Dioxide **(**CO_2) emissions from biofuels among demand sectors and electricity production in Europe.

*3.1.7.5. **EU-C18**: Greenhouse gas emissions in the non-emissions trading system sectors including land use*

Contributing models: IMAGE

Research Questions' Overview

Following the notion that *"100% sustainable forestry would play an important role concerning land use"* which was raised during the workshops held as part of Deliverable 7.1 (Stavrakas et al., 2021), the following RQ is addressed:

- **RQ83:** What would be the annual emissions from non-ETS sectors and land use, land-use change, and forestry (LULUCF)?

From the IMAGE modelling results, we show the GHG emissions from agriculture, land use, transport, residential, service, and waste in the EU, comparing "**Neutrality**" scenarios with "**Current Trends**" in 2015 and 2030, 2050 projections. From the "**Clean Planet 1.5 TECH**" scenario (climate neutral scenario, achieving a 100% net GHG emission reduction in 2050 including sinks) (European Commission, 2018b), we show the GHG emissions from non-CO_2 agriculture, non-CO_2 other, transport, residential, service, and carbon removal technology in Europe.

Results and Discussion

Figure 59 shows that the total GHG emissions in 2015 are similar in both IMAGE and Clean Planet models, ranging from 2.4-2.5 Gt $CO_{2,eq}$ (excluding LULUCF). In 2030 modelling results, all three scenarios in IMAGE and the “**Clean Planet 1.5 TECH”** scenario (European Commission, 2018b) have similar GHG emissions, reducing to 1.7-1.8 Gt $CO_{2,eq}$. IMAGE in general has higher Agriculture, Forestry and Other Land Use emissions in 2030, while the “**Clean Planet 1.5 TECH**” scenario has higher transportation emissions but with carbon sink from LULUCF.

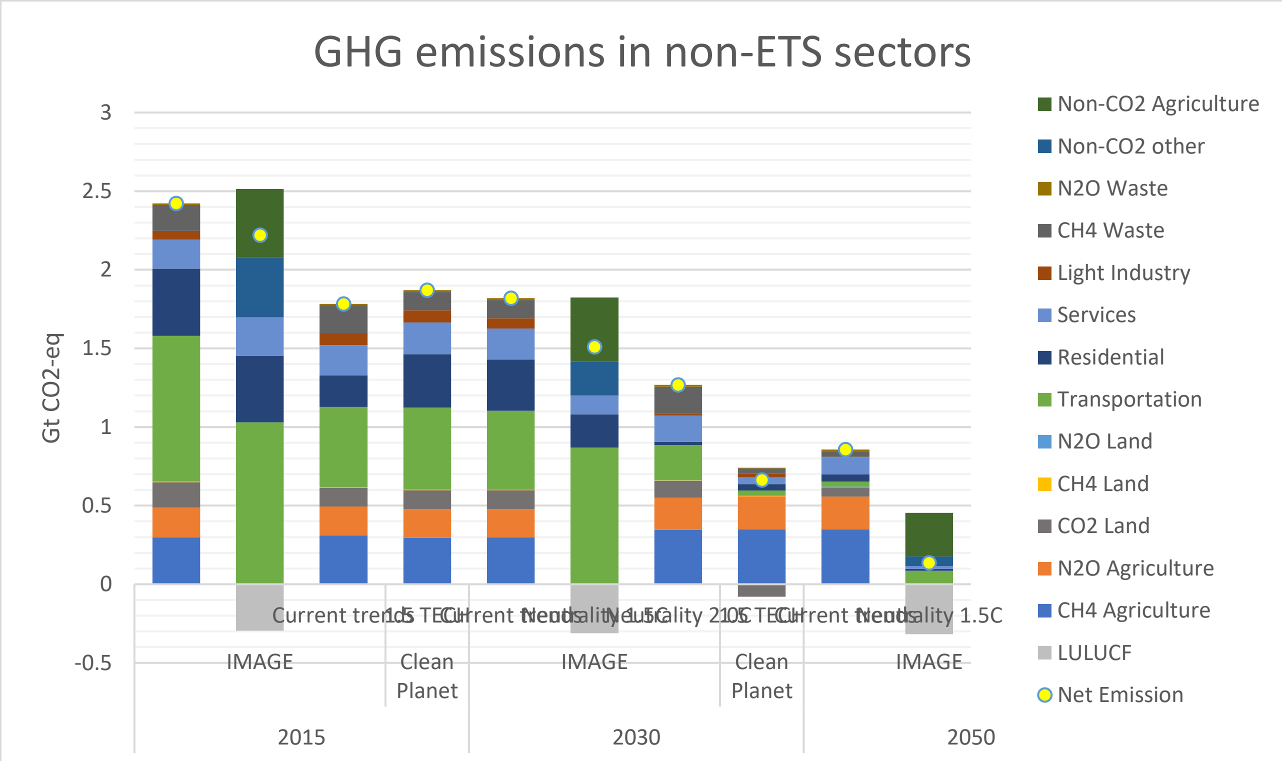


Figure 59. Greenhouse gas (GHG) emissions in non-ETS sectors in the EU.

In 2050, GHG emission reductions result in 1.3 Gt $CO_{2,eq}$ in the “**Current Trends**” scenario, and between 0.9 and 0.6 Gt $CO_{2,eq}$ in the “**Neutrality 2.0°C**” and “**Neutrality 1.5°C**” scenarios, while it decreases to 0.1 Gt $CO_{2,eq}$ in the “**Clean Planet 1.5 TECH**” **scenario**. In the “**Neutrality**” scenarios, the main reduction occurs in the transportation and residential sectors; in the “**Clean Planet 1.5 TECH**” scenario, non-CO_2 agricultural emissions together with the larger carbon sink from LULUCF contribute to the further GHG emissions reductions.

The GHG emissions from other land use (non-agriculture) and forestry in 2015 are 189 Mt $CO_{2,eq}$ in the IMAGE model, but -294 Mt $CO_{2,eq}$ in the Clean Planet for All report (**Figure 60**). Emissions for both sources decline by 2030, to 146-148 Mt $CO_{2,eq}$ in IMAGE and to -312 Mt $CO_{2,eq}$ in the “**Clean Planet 1.5 TECH**” scenario. By 2050, the “**Current Trends**” scenario slightly declines to 137 Gt $CO_{2,eq}$, and decreases further in the “**Neutrality**” scenarios, especially with the negative CO_2 emissions in the “**Neutrality 1.5°C**” scenario (-53 Mt $CO_{2,eq}$). For the “**Clean Planet 1.5 TECH**” scenario, the carbon sink from LULUCF increases by 2050, leading to more negative emissions (-317 Mt $CO_{2,eq}$).

The main difference between the IMAGE "**Neutrality**" scenarios and the "**Clean Planet 1.5 TECH**" scenario is the land GHG emissions. IMAGE "**Neutrality**" scenarios have higher GHG emissions from land since the "**Neutrality**" scenarios are without additional restrictions on GHG land emissions, while the "**Clean Planet 1.5 TECH**" scenario aims for the net GHG emissions in 2050 (including sink).

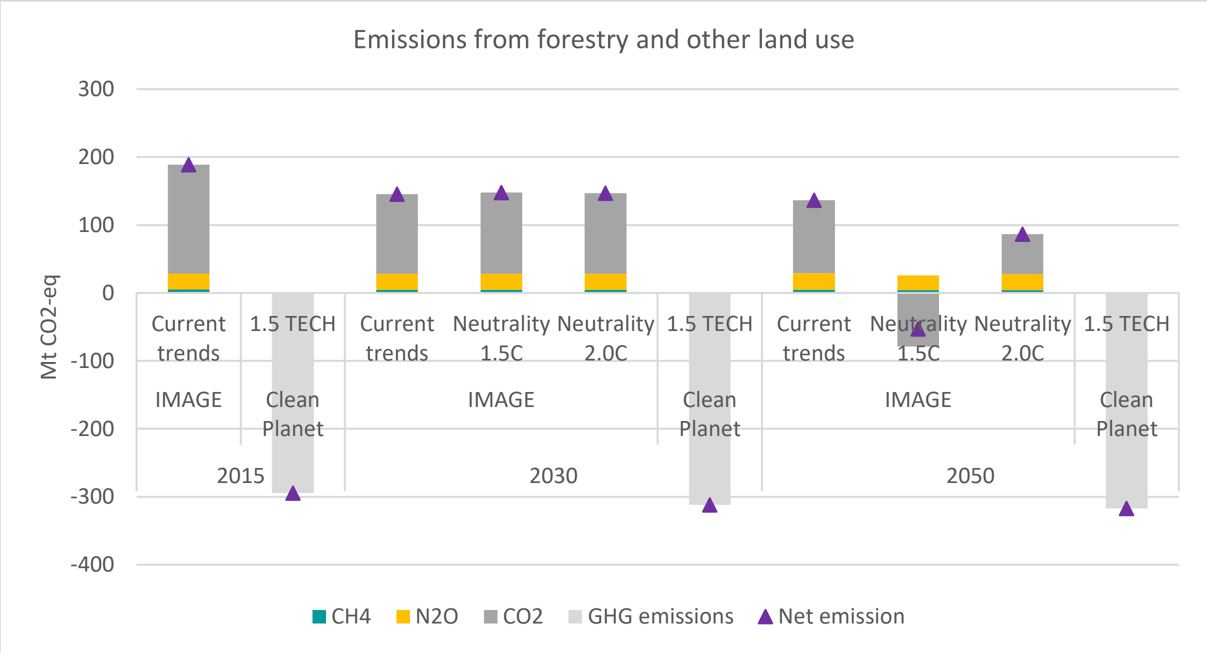


Figure 60. Greenhouse gas (GHG) emissions from forestry and other land use in Europe region.

3.1.8. Socioeconomic aspects &implications, including recovery packages

*3.1.8.1. **EU-C19**: Employment effects of the energy transition*

Contributing models: WEGDYN

Research Questions' Overview

Stemming from the Green Deal projections, stakeholder interviewed during the preparation of Deliverable 7.1 (Stavrakas et al., 2021) remained optimistic about new job creations, mentioning indicative positions in demand-side management, net-metering, services related to the H_2 technologies, and development of RES technologies and grids. In this respect, this cluster addresses the following RQs:

- **RQ84.** How many jobs in the RES sector should be created in various European regions and what share of those should be within energy communities?
- **RQ87:** How many workers from the coal, gas, and nuclear sectors should be reskilled annually to fulfil the employment needs in the RES sector?

Results and Discussion

While WEGDYN cannot inform on how many jobs should be created, it can deliver the employment effects if certain development paths are pursued, as shown in **Figure 61**. Constraining energy system configurations as specified in the three social storylines (see (Süsser et al., 2021c) for a description of storylines), the **GDI** leads to larger unemployment for all EU27+ regions but for Austria and France (with small reductions). The **PPO** reduces EU27+ wide unemployment but in a regionally diverse way. While countries such as Italy, Austria and the Northern European region experience job gains, others are affected by higher unemployment, for instance, Greece, the United Kingdom or the Iberian Peninsula. This is driven by the less transmission line connected configuration of the European energy system.

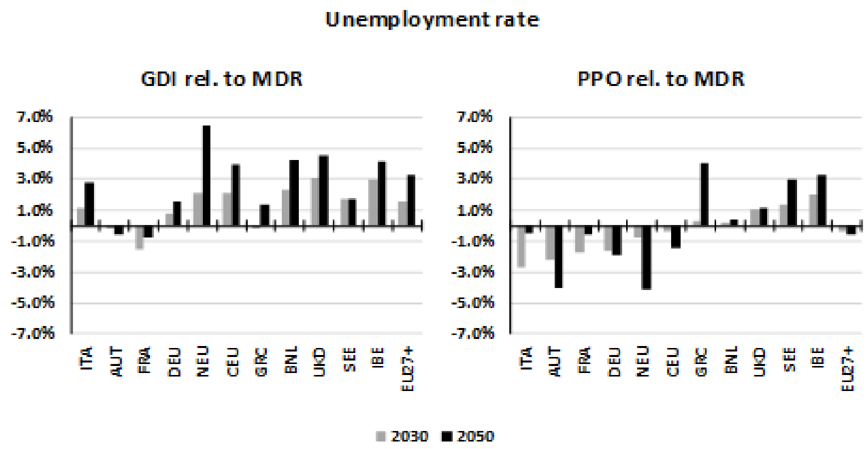


Figure 61. EU27+ and regional percentage-point change in unemployment rate for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline; AUT: Austria; BNL: Benelux and Switzerland; CEU: Central Eastern Europe; DEU: Germany; FRA: France; GRC: Greece; IBE: Iberian Peninsula; ITA: Italy; NEU: North-Eastern Europe; SEE: South-Eastern Europe; UKD: United Kingdom. Further details in **Table B.6**.

WEGDYN cannot inform how many workers should be reskilled but how many unskilled and skilled workers would be needed for certain energy system configurations. Compared to **MDR**, the **GDI** storyline implies less (un)skilled labour in the ELY sector and more in the GDT sector (**Figure 62**). The **GDI** storyline is connected to overall reduced employment. The **PPO** storyline requires more employment (both unskilled and skilled) in sectors of energy storage and conversion with respect to synthetic fuels and green H_2 such as the OIL, GAS, and P_C sectors. Overall, the **PPO** storyline induces more employment across the board of economic sectors.

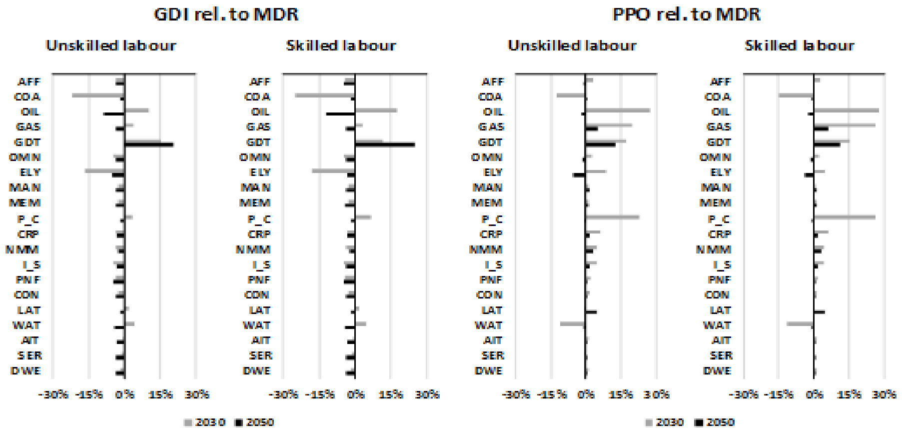


Figure 62. EU27+ unskilled and skilled employment effects per sector of the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline; AFF: Agriculture, Forestry and Fishery; COA: Coal; OIL: Crude Oil ; GAS: Natural Gas; GDT: Gas distribution and hot water supply; OMN: Other mining; ELY: Electricity; MAN: Manufacturing; MEM: Machinery, equipment, other; P_C: Refined oil products ; CRP: Chemical, rubber, plastic products; NMM: Manufacture of other non-metallic mineral products; I_S: Manufacture of basic iron and steel and casting; PNF: Manufacture of precious and non-ferrous metals, and fabricated metal products; CON: Construction; LAT: Transport – Land; WAT: Transport –Water; AIT: Transport –Air; SER: Other services; DWE: Dwellings and real estate. Further details in **Table B.7**.

*3.1.8.2. **EU-C20**: Energy transition and private-public income-expenditure effects*

Contributing models: QTDIAN, Calliope, WEGDYN

Research Questions' Overview

Using the QCW model ensemble (**Section 3.1.2.9**) allows generating and assessing the economic impacts of alternative climate-neutral futures of the European energy system. These are influenced by different governance logics and socio-political preferences and connected to a deep phase-out of coal, oil and natural gas use to prevent further atmospheric release of GHG. In this context, and due to a multitude of sectoral economic interdependencies, the income of private households and the public will be affected differently as well as their expenses for private and public goods and services. We here consider the following two RQs as specified in Stavrakas et al. (2021):

- **RQ90:** How would the coal phase-out affect regional economies and the countries' budgets?
- **RQ100:** What would be the socioeconomic impacts (e.g., change in households' savings and spending, etc.), if energy demand is reduced? How would this influence the member states' budgets?

Results and Discussion

On the aggregate EU27+ level, the **GDI** storyline implies larger public budgets by 2030 driven by larger revenues from CO_2 pricing and lower budgets by 2050 due to reduced income from taxing labour and commodities (**Figure 63**). Contrary, the **PPO** storyline implies smaller public budgets by 2030 due to lower carbon pricing and higher budgets by 2050 due to positive employment effects inducing larger labour tax income. Consequentially, and resolving at a regional level (**Figure 64**), higher (lower) public budgets translate into higher (lower) public consumption effects and imply different medium (2030) and long-term (2050) incentives for the government to provide fiscal impulses to different energy system configurations.

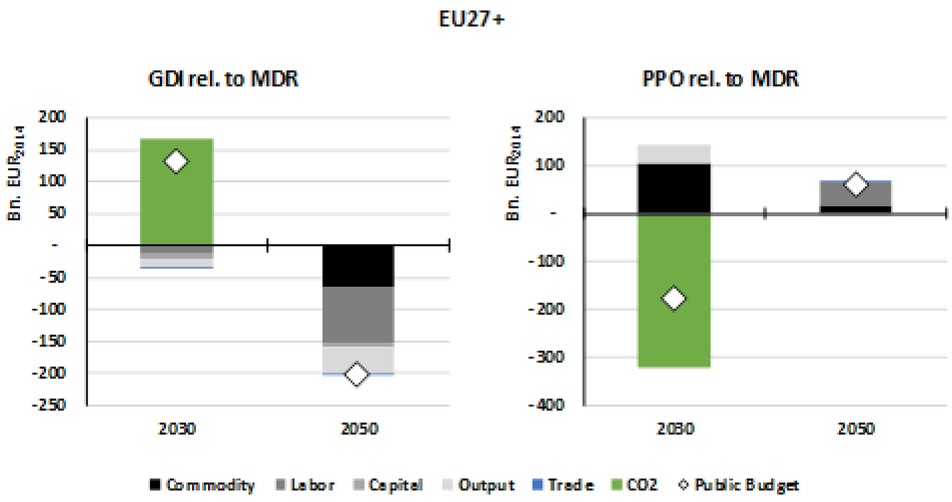


Figure 63. Public budget decomposition of the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

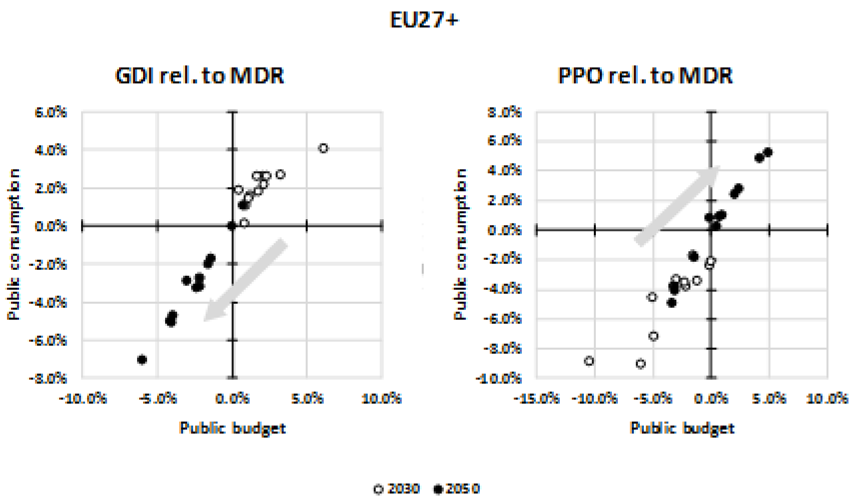


Figure 64. Regional public budget and public consumption effects for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

A market mechanism can allocate resources efficiently, which is reflected by lowest energy demand in the **MDR** storyline. Relative to **MDR**, negative private income effects emerge in the **GDI** storyline due to less efficient resource allocation, particularly for capital (**Figure 65**). By contrast, the **PPO** energy system leads to positive private income effects due to energy system cost savings by 2030 and positive employment effects by 2050. Deducing household savings and the capital account from total private income (including market and transfer income) gives disposable income, which is positively correlated with private consumption as shown for WEGDYN regions in **Figure 66**.

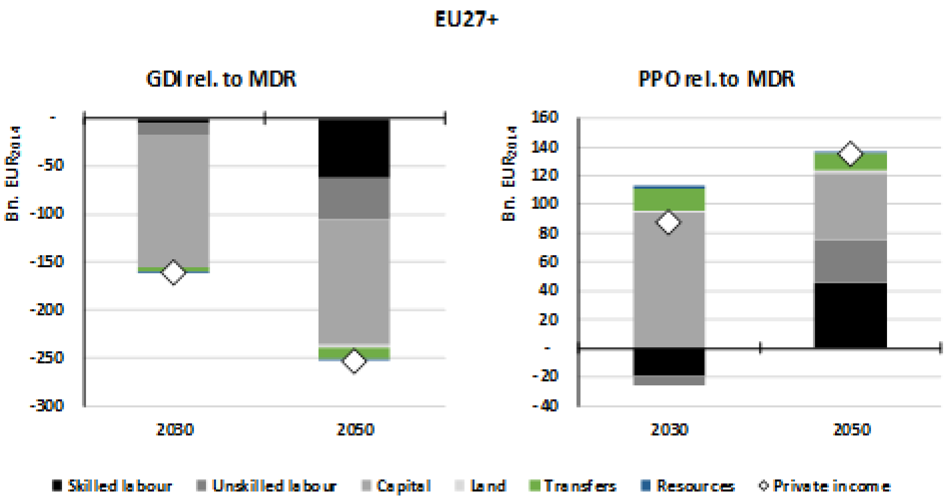


Figure 65. Private income decomposition of the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

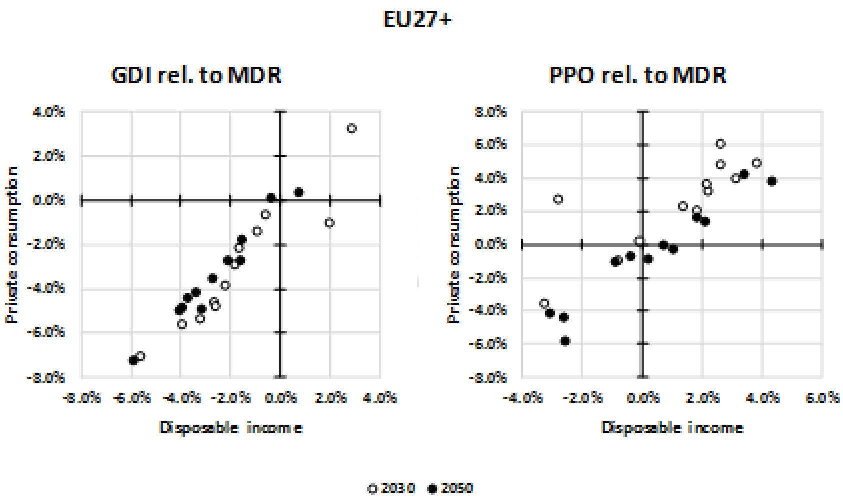


Figure 66. Regional disposable income and private consumption effects for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

Taking the consumption effects for the public and the private household together, we compute the effects on economy-wide consumption possibilities, also denoted welfare. This measure gives an intuition about the societies' willingness to accept changed relative prices. Regions with average cost reductions in the energy system experience welfare gains (and vice versa) indicated by the downward-sloping trend line. This relationship holds for both periods. While the **GDI** storyline implies smaller welfare at the aggregate EU27+ level compared to **MDR** (grey diamonds), the **PPO** storyline allows positive aggregate welfare effects (orange diamonds, **Figure 67**). The positive employment effect in **PPO** is the most important driver of this result, which raises income and lifts this (still negative) relationship upwards. This also means that there is a potential for compensatory transfer measures to mitigate adverse regional effects.

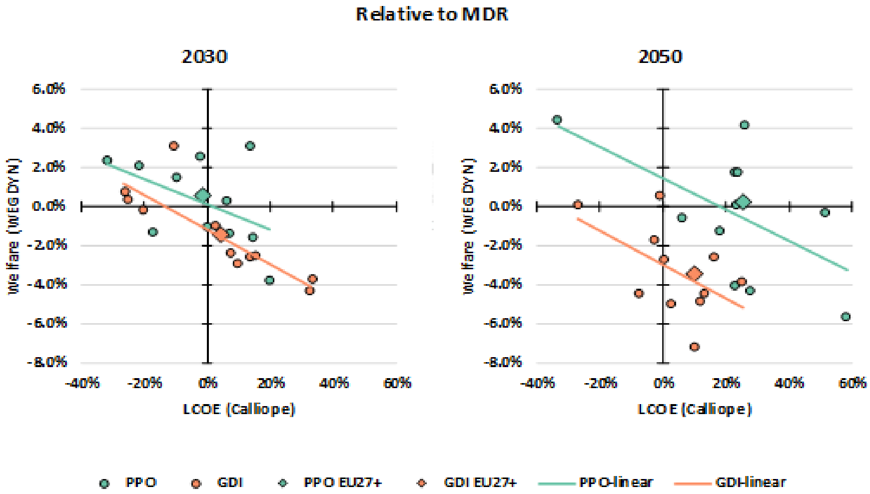


Figure 67. WEGDYN regional welfare (ordinate) and Calliope regional Levelized Costs of Energy (LCOE, abscissa) relative to Market-driven (MDR) storyline.

3.1.8.3. ***EU-C21****: Does the public accept renewable energy technologies?*

Contributing models: QTDIAN

Research Questions' Overview

Society can play a significant role in accelerating or impeding the energy transition (Cohen et al., 2016; Sovacool et al., 2022). Social acceptance is frequently highlighted in the context of renewable energy infrastructure development. Overall, the transition to renewable energy achieves high public approval levels within the EU (European Commission, 2021a): almost nine in ten Europeans think it is important that the EU sets ambitious targets to increase renewable energy use. Nevertheless, the energy transition has not remained unquestioned in the population and is contested in a variety of cases (Cohen et al., 2016; Sovacool et al., 2022). This is because different renewable energy technologies have different impacts such as visual and aesthetic impacts (Borch, 2018), biodiversity loss (Kati et al., 2021; Voigt et al., 2019), noise, and general human health issues (Knopper et al., 2014). As installed renewable energy capacities need to increase to 55% by 2030 to meet the EU climate and energy targets (European Commission, 2022, 2021b), social acceptance seems to be more important than ever. Considering the above, stakeholders raised the following RQs:

- **RQ97:** How can models contribute to the debate on social acceptance of renewable energy technologies among the European society?

Results and Discussion

Energy models, used to inform the energy transition, often ignore non technoeconomic factors, such as social acceptance. Modelers often omit social aspects, or only consider them as an exogenous narrative and tend to integrate them "on top" of existing models (Krumm et al., 2022). Nevertheless, there is a growing recognition that social factors must be included in models (Nikas et al., 2020; Trutnevyte et al., 2019), also because users of the modelling results request it (Süsser et al., 2022).

The question of which renewable technologies would be the most and least accepted by European societies is a social-scientific question, which cannot and should not be answered by a model but based on opinion surveys among citizens in the EU. An interesting question raised in the context of the development of the modelling toolbox QTDIAN is: "*What would future renewable energy landscapes look like if they are based on people's preferences? How does the deployment of (regionally, nationally) preferred renewable energy technologies affect potential and total costs?*" (Süsser et al., 2021a). For example, as shown in **Figure 68**, in Germany, different renewable energy technologies have a large support among the German population, and from 2017-2019, the agreement for renewable energy was increasing, except a decline for onshore wind in 2019, and a strong decline for ground-mounted solar energy after 2017. As shown in **Figure 69,** the support for renewable energy is also high in and near densely populated areas (Morris, 2019). If citizens have already experience with installed technologies in their neighbourhood, the support is even higher.

Such opinion surveys can provide interesting information sources of people's preferences for the expansion of different renewable energy technologies. Generally, there is a lack of data considering social acceptance of the energy transition and differences in people's preferred energy landscapes across Europe. Studies often consider only a specific study region, or specific RES. Thus, not only new modelling approaches are needed that consider such preferences in energy modelling, but also regular and cross-European opinion surveys that address people's opinions.

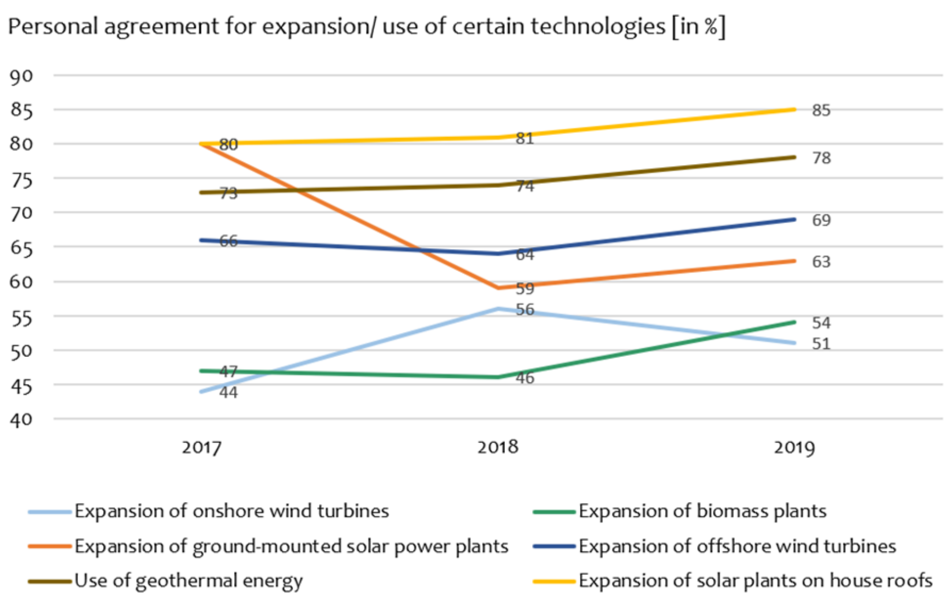


Figure 68. Personal agreement for the expansion/ use of certain technologies, respondents who answered 4 or 5 (strong agreement), surveys 2017-2019, Germany. Data source: (Wolf, 2020).

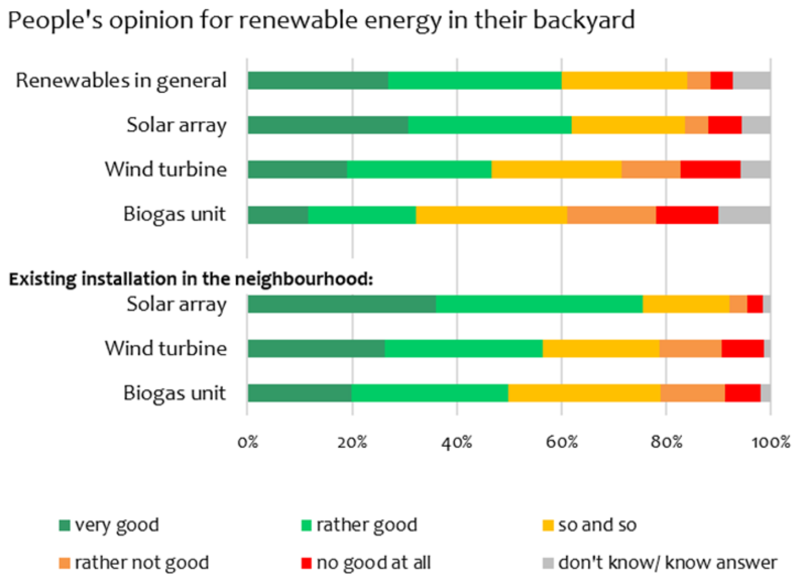


Figure 69. People's opinions about renewable energy in their backyard, survey 2020, n = 1051, Germany. Data source (Renewable Energy Agency, 2019).

3.2. Regional (Nordic) case study

The Nordic countries' institutional cooperation on energy and climate policy has accelerated significantly since 2015, when the Nordic Council of Ministers decided to strengthen cooperation and decide about strategic directions of the regional, Nordic development (Ollila, 2017). The "Nordic Energy Technology Perspectives" (NETP) report was published in 2016, delving into long-term technology pathways that could lead to a carbon-neutral energy system in accordance with the Paris Agreement (Norden & IEA, 2016). The "Carbon Neutral Scenario" (CNS) was included in NETP. The Nordic prime ministers signed the "Declaration on Nordic Carbon Neutrality" in 2019, signalling a new vision for a carbon-neutral region (Nordic Co-operation, 2019). Afterwards, the Nordic Energy Research Council (NERC) released reports that follow the Nordic commitment to a carbon-free society by 2050, emphasising the critical need for state-of-the-art technological options (Nordic Energy Research, 2020, 2019). In 2021, the Nordic Clean Energy Scenarios (NCES) report was published, highlighting various technological and societal pathways as well as illustrating how political choices may shape the future of the Nordic energy system (Nordic Energy Research, 2021).

3.2.1. Scenario Updates

The NCES comprises of three individual scenarios: **(i)** the "Carbon Neutral Nordic" (CNN) scenario, **(ii)** the "Climate Neutral Behaviour" (CNB) scenario, and **(iii)** the "Nordic Powerhouse" (NPH) scenario. The CNN scenario seeks the least-cost pathway, while also taking current national plans into account. In this scenario, the Nordics increase electricity exports to Central Europe slightly above current projections, as electrification of the heating, transportation, and industrial sectors requires considerable supply of electricity. The CNB scenario assumes a high level of political and citizen engagement, as additional energy and material efficiency measures across sectors are implemented, resulting in lower energy consumption. Energy demand is expected to fall as a result of more efficient transportation modes and fewer, but more efficient, heavy transport. Finally, the NPH scenario considers the possibility of the Nordics playing a larger role in the European energy transition by supplying low-cost clean energy and hosting low-carbon services. All of these activities increase the demand for electricity and other forms of energy. The NPH scenario additionally foresees a greater capacity for power transmission between the Nordic countries and from the Nordics to Central Europe, as well as an increased P2X fuel production.

The key targets of the energy transition scenarios for the Regional CS are summarised in **Table 31**, while direct energy-related CO_2 emissions by sector and country are presented in **Table 32**.

Table 31. Summary of the energy targets for the Regional case study.

Scenario	CNS (2030)	CNS (2050)	CNN (2030)	CNN (2050)	CNB (2030)	CNB (2050)	NPH (2030)	NPH (2050)
Total GHG emission	-42.5	-85	-52%	-95.9	-52.9	-95.8	-51.7	-95.9

reduction (%) compared to 1990 levels								
Total GHG emissions (Mt CO_{2eq})	119.8	30.6	98	8.3	96	8.6	98.6	8.3
FEC (TWh)	1058.2	949.8	1058.2	978.5	1041.6	910.9	1080.5	1022
RES share (%) in total electricity generation	75	89.1	80.3	93.3	80.3	94.3	79	90

Table 32. Nordic direct energy-related Carbon Dioxide (CO_2) emissions by sector and by country.

Mt CO_2	Denmark		Finland		Iceland		Norway		Sweden		Nordic Region	
CNS												
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Power generation	3.8	0	11.6	0	0	0	1.7	0	2.2	0	19.3	0
Other transform.	0.2	0	2.7	0	0	0	3.8	0	0	0	6.7	0
Industry	2.7	1.6	7.7	3.2	1.3	0.4	9	4.7	7.6	3.5	28.3	13.4
Transport	11.2	2.6	10.7	2.7	1.4	0.2	12.1	2.3	22.6	5	58	12.8
Buildings	0.6	0	0.9	0	0	0	0.3	0	0.1	0	1.9	0
Other	1,5	0.9	1.2	0.9	0.7	0.7	1.9	1.7	0.3	0.2	5.6	4.4
Total	**20**	**5.1**	**34.8**	**6.8**	**3.4**	**1.3**	**28.8**	**8.7**	**32.8**	**8.7**	**119.8**	**30.6**
CNN												
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Power generation	1.1	1.1	4.4	1.5	0.1	0.1	0.6	0.6	4.0	2.7	10.2	6.0
Industry	3.4	0.0	8.0	4.6	1.1	1.3	5.3	2.6	7.1	4.9	24.8	13.4
Transport	11.7	0.2	4.5	0.4	1.8	0.1	8.5	0.3	14.6	0.5	41.2	1.5
Buildings	0.2	0.0	1.2	0.2	0.0	0.0	0.2	0.0	0.2	0.0	1.7	0.2
Captured	-3.2	-6.5	-1.4	-4.3	-3.2	-6.6	0.0	-1.6	0.0	-9.8	-7.8	-28.7
Other	0.3	0.1	11.5	9.4	0.0	0.0	15.0	2.6	1.2	3.7	28.0	15.8
Total	**13.5**	**-5.0**	**28.1**	**11.9**	**-0.2**	**-5.1**	**29.6**	**4.6**	**27.0**	**2.0**	**98.0**	**8.3**
CNB												
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Power generation	1.1	1.1	4.3	1.6	0.1	0.1	0.6	0.6	4.0	2.7	10.1	6.1
Industry	3.4	0.0	8.0	4.7	1.1	1.3	5.2	2.1	7.1	3.3	24.8	11.5
Transport	11.7	0.2	4.5	0.4	1.8	0.1	8.0	0.2	13.2	0.5	39.2	1.3
Buildings	0.2	0.0	1.2	0.2	0.0	0.0	0.2	0.0	0.2	0.0	1.7	0.2
Captured	-3.2	-6.5	-1.2	-3.7	-3.1	-6.6	0.0	-0.9	0.0	-6.7	-7.6	-24.4
Other	0.3	0.1	11.6	9.0	0.0	0.0	14.8	2.5	1.1	2.2	27.9	13.8
Total	**13.4**	**-5.0**	**28.4**	**12.3**	**-0.2**	**-5.1**	**28.8**	**4.6**	**25.6**	**1.9**	**96.0**	**8.6**
NPH												
	2030	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**	**2030**	**2050**
Power generation	1.1	1.1	3.8	1.6	0.1	0.1	0.6	0.6	3.9	2.7	9.5	6.1
Industry	3.4	0.0	7.9	4.9	1.1	1.3	4.8	3.7	4.8	1.6	22.0	11.6
Transport	12.0	0.2	4.7	0.4	1.8	0.1	8.5	0.2	14.6	0.5	41.6	1.4
Buildings	0.2	0.0	1.2	0.2	0.0	0.0	0.2	0.0	0.2	0.0	1.7	0.2
Captured	-3.6	-6.5	-1.3	-5.4	-3.2	-6.6	-0.2	-3.0	-0.5	-10.1	-8.8	-31.6
Other	0.4	0.1	11.9	10.1	0.0	0.0	15.8	3.0	4.6	7.2	32.7	20.4
Total	**13.5**	**-5.0**	**28.1**	**11.9**	**-0.2**	**-5.1**	**29.7**	**4.6**	**27.5**	**1.9**	**98.6**	**8.3**

The main specifications of the energy transition scenarios for the Regional CS are presented in detail in **Table 33**.

Table 33. Summary of the main specifications for the Regional case study.

Scenario	CNS (2030)	CNS (2050)	CNN (2030)	CNN (2050)	CNB (2030)	CNB (2050)	NPH (2030)	NPH (2050)
Hydro plants capacity (GW)	52	55	54.8	54.4	54.8	54.3	55.7	57.6
Onshore wind plants capacity (GW)	28.7	47.8	27.3	49.1	27.3	42.6	26.6	56.5
Offshore wind plants capacity (GW)	3.4	3.4	8.3	33.5	8.3	30.1	8.3	59.6
PV plants capacity (GW)	4	4	1.6	31.3	1.6	30.3	1.6	40.2
Biomass plants capacity (GW)	8	5	2.1	0.8	2.1	0.8	2.1	0.9
Waste plants capacity (GW)	-	-	1.1	0.8	1.1	0.8	1.1	0.8
Coal plants capacity (GW)	-	-	1.2	0	1.2	0	1.2	0
Solid fuels plants capacity (GW)	-	-	3	4.1	3	3.9	3	4.2
Geothermal plants capacity (GW)	-	-	0.8	0.8	0.8	0.8	0.8	0.8
Nuclear plants (GW)	12	3	11.2	5	11.3	3.8	12.5	11.2
Natural gas plants (GW)	9	13	3.7	0	3.7	0	3.7	0
Natural gas with CCS plants (GW)	-	2	-	-	-	-	-	-
Electricity demand/supply (TWh)	440	427	505	596	503	552	526	787
Transmission capacity increase (GW)	+5	-	-	-	-	-	-	-
Renovation rate (%)	2 - 3	2 - 3	-	-	-	-	-	-
Share (%) of electricity in FEC (residential)	-	49.4	48.5	47.8	48.7	48	48.3	47.6
Share (%) of bioenergy in FEC (residential)	-	5.4	0	0	0	0	0	0
Share (%) of natural gas in FEC (residential)	-	0	0.1	0	0.1	0	0.1	0
Share (%) of diesel in FEC (residential)	-	0	2.1	0.3	2.1	0.3	2.1	0.2
Share (%) of RES (geothermal+solar) in FEC (residential)	-	9	2.5	6.4	2.5	6.5	2.5	6.6
Share (%) of biofuels in FEC (residential)	-	-	3.2	1.7	3.2	1.7	3.2	1.7
Share (%) of biodiesel in FEC (residential)	-	-	0.3	0	0.3	0	0.3	0
Share (%) of wood pellet in FEC (residential)	-	-	3.1	4.3	3.1	4.3	3.1	4.3
Share (%) of firewood in FEC (residential)	-	-	5.3	4.8	5.4	4.8	5.3	4.8
Share (%) of DH in FEC (residential)	-	36.1	33.2	33.5	32.9	33.4	33	33.6
Share (%) of biomethane in FEC (residential)	-	-	1.7	1.1	1.7	1.1	2.1	1
Passenger EVs+PHEVs (millions)	-	-	7.12	15.95	6.15	9.25	7.12	15.95
Passenger FCEVs (thousands)	-	-	21	3.1	6.2	0	21.1	3.1
Electric+Hybrid trucks (thousands)	-	-	87.5	253.8	85.6	208.6	87	221.2
H2 trucks (thousands)	-	-	0	8.2	0	8.2	0	2.7
Share (%) of biofuels in FEC (transport)	-	63	-	-	-	-	-	-
Share (%) of fossil fuels in FEC (transport)	-	25	-	-	-	-	-	-
Share (%) of electricity in FEC (transport)	-	10	9.8	46.3	9.8	43.2	9.8	45
Share (%) of biodiesel in FEC (transport)	-	-	11.1	3.5	10.5	3.6	10.6	3.2
Share (%) of bioethanol in FEC (transport)	-	-	4.2	0.9	3.5	1.5	4.2	1.4
Share (%) of biokerosene in FEC (transport)	-	-	0.6	17	0.2	12.1	0.6	17.3
Share (%) of biomethane in FEC (transport)	-	-	0.4	15.8	0.4	20.3	0.4	16.1
Share (%) of diesel in FEC (transport)	-	-	22.8	3	24.4	3.6	23.2	3.1
Share (%) of gasoline in FEC (transport)	-	-	15.9	0.9	15.7	1	15.9	0.9
Share (%) of heavy fuel oil in FEC (transport)	-	-	9.4	0.5	10	0.6	9.4	0.5
Share (%) of H2 in FEC (transport)	-	-	0	0.7	0	0.7	0	0.3
Share (%) of kerosene in FEC (transport)	-	-	21.7	6.4	21.1	7.2	21.7	6.4
Share (%) of LPG in FEC (transport)	-	-	0	0	0	0	0	0
Share (%) of natural gas in FEC (transport)	-	-	2.6	3.1	2.8	3.8	2.6	4.1
Share (%) of bunker fuel in FEC (transport)	-	-	1.5	1.8	1.6	2.3	1.5	1.8
Share (%) of methanol in FEC (transport)	-	-	0	0	0	0	0	0
Flexible charging of EVs (GW)	0.5	1.5	-	-	-	-	-	-
EV home chargers (millions)	-	-	5-7	12-18	5-7	12-18	5-7	12-18
EV public chargers (thousands)	-	-	30-60	100-150	30-60	100-150	30-60	100-150
Share (%) of electricity in FEC (industry)	-	46	-	-	-	-	-	-
Share (%) of natural gas in FEC (industry)	-	7.4	-	-	-	-	-	-
Share (%) of petroleum products in FEC (industry)	-	12.8	-	-	-	-	-	-

Share (%) of biomass & waste in FEC (industry)	-	26.1	-	-	-	-	-	-
Share (%) of solid fuels in FEC (industry)	-	4.2	-	-	-	-	-	-
Share (%) of DH in FEC (industry)	-	3.5	-	-	-	-	-	-
CO_2 capture ($MtCO_2$)	-	-	8.9	31.5	8.5	27	9.4	34.9

3.2.2. Key assumptions

3.2.2.1. DESSTINEE-specific assumptions

In order to answer RQs for the Nordic CS, modelling was conducted using DESSTINEE's demand module (Oreggioni and Staffell, 2022) by accounting for emission reductions, for the 'Nordic EU-Member countries'[9], compatible with the EU27 targets for 2030 and 2050 (European Commission, 2020c; Runge-Metzger, 2018). In the case of Norway (NOR) and Iceland (ISL), a hybrid approach was considered combining service demand trends from the NCES (Nordic Energy Research, 2021) and assumptions on technology deployment applied to the other countries of the Nordic group. Country-level changes for fuel baskets and the implementation of efficiency measures, across end-uses, for Denmark (DNK), Finland (FIN), and Sweden (SWE) were simulated in view of contributing to reaching the emission caps presented in Deliverable 8.1 (Roelfsema et al., 2021) for the "**2030 Climate Neutrality**" and the "**2050 Climate Neutrality**" scenarios at the EU level.

Results for EU Member States in the Nordic group correspond to the modelling outputs of the exercise conducted for the European CS and the SENTINEL intercomparison exercise (Roelfsema et al., 2021). Socioeconomic and demographic indicators and trends for transport service demand were based on the country-level projections reported by the EU Reference Scenario 2020 (European Commission et al., 2021) (in the case of DNK, FIN, and SWE). For NOR and ISL, population projections from the United Nations (UN) statistic division (UNPD, 2019) and GDP forecasts from the OECD database (OECD, 2014) were used in addition to passenger and freight travel service demand (for different vehicle types) from the NCES (Nordic Energy Research, 2021). Given that NOR and ISL are part of the European Free Trade Association (EFTA) bloc, it is reasonable to assume that standards in terms of fuel blending and fuel economy indicators for certain technologies, implemented in the EU, can be extrapolated to these two countries.

3.2.2.2. EnergyPLAN-specific assumptions

The "**Smart Energy Nordics**" scenario is based on the modelling for Smart Energy System for Europe described in **Section 3.1.2.6**. This means that based on demands modelled in HEB and DESSTINEE, the total electricity, heating, and cooling demands for Norway, Denmark, Sweden, and Finland are included. Iceland is excluded from the model.

To define the system capacities, numbers from the "**Smart Energy Europe**" scenario are split into national models, including information for hydro power in Norway. Industry and transport are based on models from

[9] Nordic countries: Denmark (DNK), Finland (FIN), Iceland (ISL), Norway (NOR), and Sweden (SWE).

the European scenarios and modelling work done from "TransportPLAN" and "IndustryPLAN" in collaboration with the sEEnergies[10] research project.

In summary, the following demands are included.

Table 34. Electricity demand assumptions for the Nordic case study in TWh.

	Neutrality scenario
Electricity - residential & services	135
Electricity - industry	178
Flexible electricity (demand response)	22
Heat from biomass	11
Indv. heat pumps	68
Indv. electric boilers	9
DH	109
Cooling	8
Biomass in industry	19
H_2	71
E-fuels (aviation – jet fuel)	65
Electrofuels	7
EVs - Dump charge	62
EVs - Smart charge (demand response)	31

3.2.2.3. HEB-specific assumptions

The assumptions of the HEB model for the Nordic CS are the same as the ones presented in **Section 3.1.2.5** for the European CS.

3.2.3. Transforming the power sector

*3.2.3.1. **NO-C1:** Technology mix for a decarbonised Nordic energy system*

Contributing models: EnergyPLAN

Research Questions' Overview

The electricity system in the Nordic countries must be decarbonised, and it might be done so earlier than in the rest of Europe. Thus, an important question is about the future electricity mix, especially considering the volatility of different RES. Essential questions are:

- **RQ1:** How much VRES capacity is needed in 2030 and 2050 in the Nordic region to meet demand requirements (e.g., electrification, etc.) of other sectors?
- **RQ2:** What should be the hydropower capacity in the context of balancing renewables?
- **RQ6:** Will nuclear energy be considered as a contributor to a future energy system in the Nordic Region? Will there be new nuclear power plants commissioned? What will be the contribution of power generation coming from the nuclear in the electricity mix by 2050?

Results and Discussion

[10] https://www.seenergies.eu

Based on the "**Smart Energy Nordics**" scenario, the total VRES capacity installed in **2050** are (**RQ1**):

Table 35. Variable renewable energy sources capacity (GW) planned for 2050 according to the "**Smart Energy Nordics**" scenario.

Technology	Capacity (GW)
Onshore wind	45
Offshore wind	49
PV	50

Furthermore, EnergyPLAN can provide answers to the role of hydropower capacity for the balancing, but the model does not do so for specific weather conditions (**RQ2**). Dammed hydro power from predominantly Sweden and Norway have a total production capacity of 46 GW with an estimated 100 TWh of storage capacity. A small pump back capacity of 1.4 GW is included to help with balancing, but the predominant balancing comes from operating the dammed hydro power flexibly in accordance with the VRES energy.

In addition, about the role of nuclear energy in the future energy system in the Nordic Region (**RQ6**), the "**Smart Energy Nordics**" scenario does not include nuclear power, but our analysis shows that if Sweden and Finland were to keep the existing nuclear power, the total Nordic systems would have 3 billion € higher annual costs compared to a system based only on renewables. Thus, in the least cost scenario, nuclear power will not contribute with power generation in the electricity mix by 2050.

*3.2.3.2. **NO-C2:** The fuel basket of a decarbonised industrial sector*

Contributing models: DESSTINEE

Research Questions' Overview

Stakeholders interviewed as part of the preparation of Deliverable 7.1 (Stavrakas et al., 2021), highlighted that already certain industries find challenges in operating due to lack of power. High industrialisation levels in parallel with the electrification of the entire system can pose a challenge to stable electricity supply along the transformation process of the power sector. In this respect, the following RQs are addressed:

- **RQ23:** How much will power consumption increase as a consequence of electrification?
- **RQ24:** What is the H_2 potential for decarbonising industry? Which sources could be considered?

Results and Discussion

As explained in the cluster on industrial transition for the European CS, a hybrid methodological approach was used for projecting fuel usage rates across secondary activities. This approach accounted for country-level trends in value-added for different industrial categories, mostly for steel and metallic, chemicals, and cement and minerals, from the EU Reference Scenario 2016 (Capros et al., 2016) and continental fuel share increases (from EC-conducted scenarios (European Commission, 2020c; Runge-Metzger, 2018)) applied to national sectoral fuel baskets (for DNK, FIN, and SWE). In the case of NOR and ISL, the increase in industrial value-added for the different categories was estimated as the average of the other Nordic countries.

In terms of power usage for H_2 production, an average electricity consumption ranging between 50-83 kWh/kg of H_2 was assumed based on previous studies (IRENA, 2020). This range covers both the energy penalty associated with H_2 synthesis using polymer electrolyte membrane and alkaline electrolysers.

Figure 70 displays the FEC for industries, according to fuel type, across the different scenarios. A replacement of fossil vectors by low carbon options, such as electricity, H_2, and biomass, is projected to take place in view of meeting emission reduction targets. This can partially be achieved thanks to the electrification of low enthalpy heat generation, the substitution of coal as feedstock for the production of steel and cement, and a decrease in the use of liquid fossil fuels for thermal energy generation purposes. It must be noted though that in our estimations, fuel used as feedstock/reactants in chemical plants has been excluded from the accounting of the FEC for secondary activities.

It is expected that coal-based production steel processes, relying on blast furnace technologies for the production of pig iron, will be partially replaced by electric arc methods using recycled steel and electricity. Furthermore, it is also projected that sensible heating of liquid fuels will be conducted as well using heat pumps or electric boilers replacing fossil-fuelled devices. Different alternative cement production processes will be widespread in view of reducing the carbon intensity of this sector, particularly substituting coal with biomass and equipping plants with carbon capture units. This will allow 'negative emission' cement manufacturing, being useful as a way to compensate for residual emissions from other sectors.

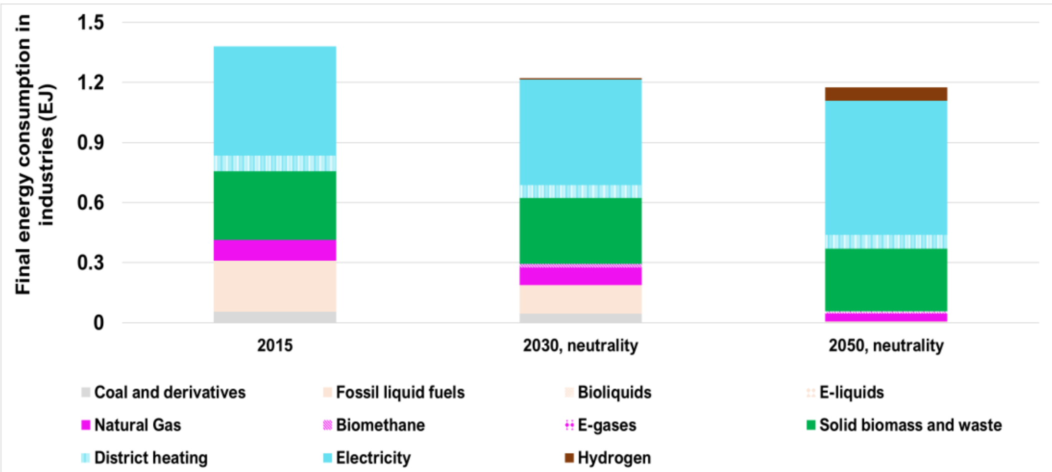


Figure 70. Final energy consumption in industries, according to fuel type, across the scenarios.

Table 36 reports the corresponding power consumption for H_2 synthesis accounting for the aforementioned upper and lower limits.

Table 36. Power consumption for the synthesis of industrially consumed hydrogen across the scenarios.

	Lower limit energy consumption		Upper limit energy consumption	
Year	**2030**	**2050**	**2030**	**2050**
Industrial H_2 consumption (TJ/year)	5595	68581	5595	68581
Power generation for H_2 synthesis (GWh/year)	2.6	32.1	4.3	53.2

3.2.4. Sector coupling: implementing smart energy systems & power-to-X solutions

*3.2.4.1. **NO-C3:** The contribution of power-to-X and hydrogen towards decarbonisation*

Contributing models: DESSTINEE

Research Questions' Overview

P2X fuels and biofuels are considered to be an important decarbonisation strategy for end-uses supplementing electrification, especially for technologies for which it would be challenging. In this modelling exercise, we have focused on understanding the decarbonisation potential of P2X, biofuels, and H_2 in the context of industrial facilities, aviation, navigation, and freight road transport. Possible incorporation for these fuels has been projected on the basis of sectorial increase across end-uses from EU wide scenarios (European Commission, 2020c; Runge-Metzger, 2018), tailoring the results (if necessary), so that overall emission caps are met. Specifically, the following RQ is addressed:

- **RQ32:** What is the decarbonisation potential for P2X fuels?

Results and Discussion

FEC by fuel type for the Nordic countries, across the scenarios, is displayed in **Figure 71**. An upward trend in the use of biofuels, P2X, and H_2 is projected in the coming years. In 2015, biofuels (mostly due to solid biomass) represented 16% of the FEC, with their usage expected to reach 19% in 2030 and 24% by 2050. This rise is driven by bioliquids and biomethane, despite solid biomass being the majoritarian vector within the biofuel group.

P2X (including e-liquids and e-gases) and H_2 are modelled to contribute by 2% in 2030 and by 8% in 2050. For the 2050 time horizon, H_2 is projected to account for 5.3% whilst P2X for the remainder. With the exception of solid biomass, transportation is the sector in which most of these fuels will be consumed. In the case of solid biomass, the largest usages are projected for industries substituting coal feedstocks in cement industries and with energy-related purposes within other industrial subcategories.

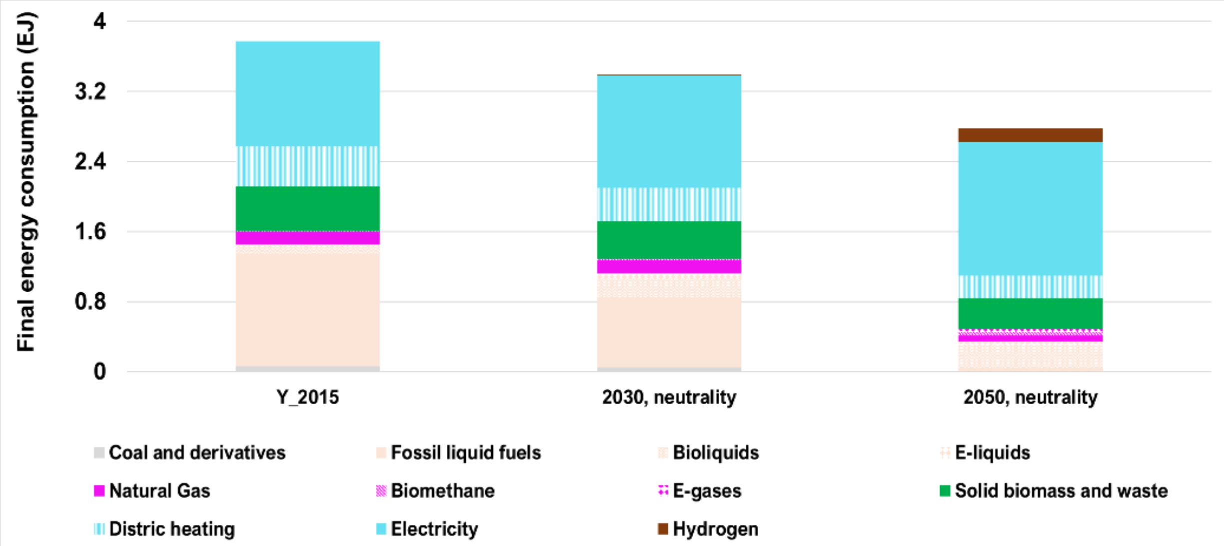


Figure 71. Final energy consumption, by fuel type, across the scenarios.

*3.2.4.2. **NO-C4:** Fuel basket and demand profiles for the transport sector*

Contributing models: DESSTINEE

Research Questions' Overview

Transportation, particularly road transport, is currently a key driver for fossil fuel consumption. Decarbonising this end use will require a significant transformation, involving the replacement of ICEs by battery and fuel cell units in the case of passenger cars, and the use of natural gas and H_2 for freight. These changes will also influence the overall energy system and hourly profile demands, as explored in the questions below:

- **RQ36:** What are the additional electricity consumption patterns resulting from the electrification of the transport sector? What would be the change in energy consumption after a certain incorporation of EVs?

Results and Discussion

For the different vehicle categories within the road transport sector, we projected fuel baskets and efficiency improvements for DNK, FIN, and SWE aligned with emission reduction targets at the EU level (European Commission, 2020c; Runge-Metzger, 2018). As further described in the analogous cluster for the European CS (**Section 3.1.6.3**), an income-based correlation was proposed to project the shares of EVs in the car fleet, downscaling continent-wide values to country-level figures using the ratio of GDP per capita. This correlation was also used for defining the shares for Norway and Iceland. Changes for other fuel types were aimed to fulfil the emission caps for this sector.

Future fuel economy indicators were modelled by accounting for EU regulated post-2020 standards for new vehicles (European Commission, 2019b), calculating an age-weighted fuel consumption per unit of travelled distance for every vehicle category in 2030. For 2050, different trends for fuel economy indicators were essayed (at the continental level) in the context of the European CS to meet the emission targets for road transport in EU wide scenarios (European Commission, 2020c; Runge-Metzger, 2018). It was assumed that these standards would also be followed by Norway and Iceland, given that these two countries are part of the EFTA.

As aforementioned, service demands from different vehicle categories and transport modes were based on the EU Reference Scenario 2020 (European Commission et al., 2021) (for DNK, FIN, and SWE) and the NCES (Nordic Energy Research, 2021) (for ISL and NOR). EU-wide projections for efficiency improvement for rail, navigation, and aviation (European Commission, 2020c; Runge-Metzger, 2018) were applied to the Nordic countries.

Figure 72 presents the FEC by fuel type, accounting for road transport, rail, domestic navigation, and total fuel usage for aviation. Regarding electricity, it must be noted that three categories were defined: electricity for non-road transport (mostly including power usage from rail) and electricity consumed in hybrid and battery road transport vehicles.

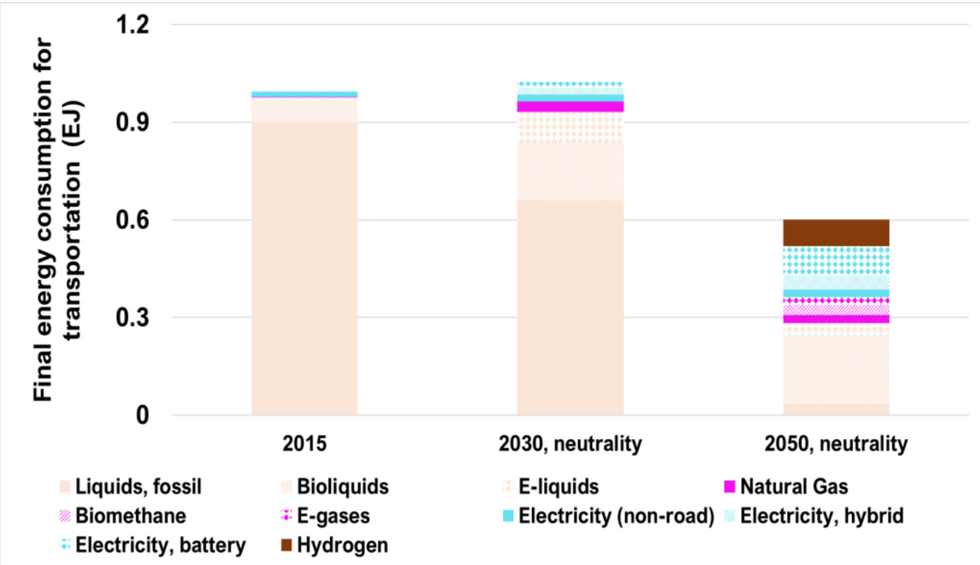


Figure 72. Final energy consumption for transportation. 'Electricity' accounts for power used mostly by non-road transport modes whilst 'Electricity, hybrid' presents power usage for hybrid road transport vehicles and 'Electricity, battery' for battery-equipped road transport units.

Low-carbon vectors (electricity, H_2, P2X, and biofuels) are projected to significantly contribute to the energy input for the transportation sectors by 2050, representing 90% of the FEC for transportation. Electricity and H_2 are mostly consumed in road transport (**Figure 73**), becoming the majoritarian fuels for road transport (especially for passenger transport). Biofuels and e-fuels are modelled to significantly contribute to the decarbonisation of freight road transport and non-road transport modes such as aviation and navigation.

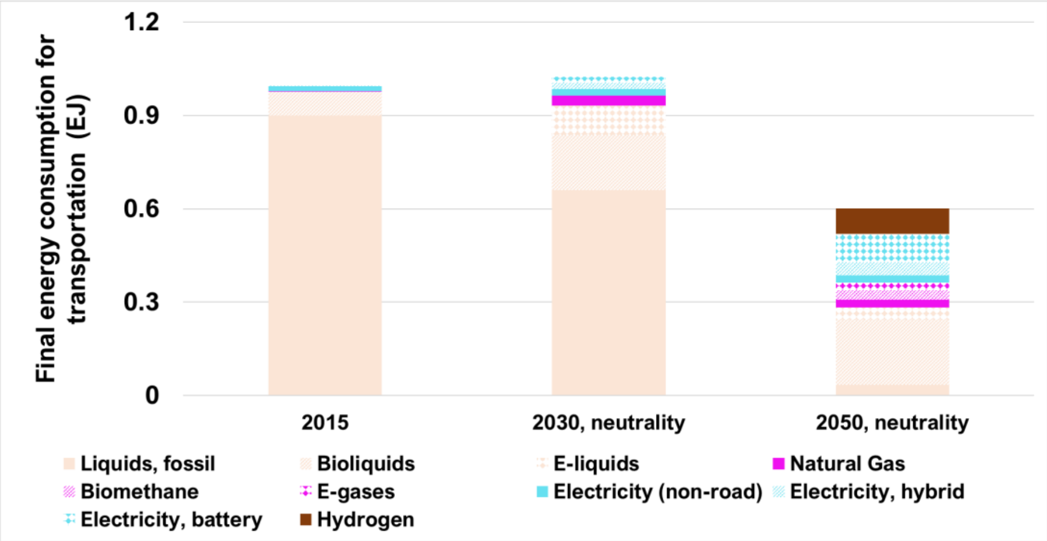


Figure 73. Final energy consumption for road transport. Electricity' accounts for power used mostly by non-road transport modes whilst 'Electricity, hybrid' presents power usage for hybrid road transport vehicles and 'Electricity, battery' for battery-equipped road transport units.

It can be appreciated that the share of road transport in total energy consumption for transportation decreases over time. This is a consequence of the fact that EVs and H_2 units replace ICE vehicles, which exhibit a 2 to 3 times higher fuel usage per travelled distance in addition to a significant increase in the travel demand for aviation, despite assumed efficiency increase.

Table 37 presents country-level figures for power usage in the transportation sector, distinguishing between road transport and other modes whilst **Figure 74** shows the effects of electrification within the transport sector on hourly power profiles.

Table 37. Country-level final power consumption for road and non-road transport modes across the different scenarios.

Final power consumption (TJ)	2015		2030		2050	
	Road	Non-road	Road	Non-road	Road	Non-road
DNK	0	1429	9571	1777	31321	2055
FIN	11	2520	4680	3502	21306	4191
ISL	0	0	323	0	1934	0
NOR	677	2416	7538	3485	27220	4652
SWE	0	9346	16913	11300	53187	11443

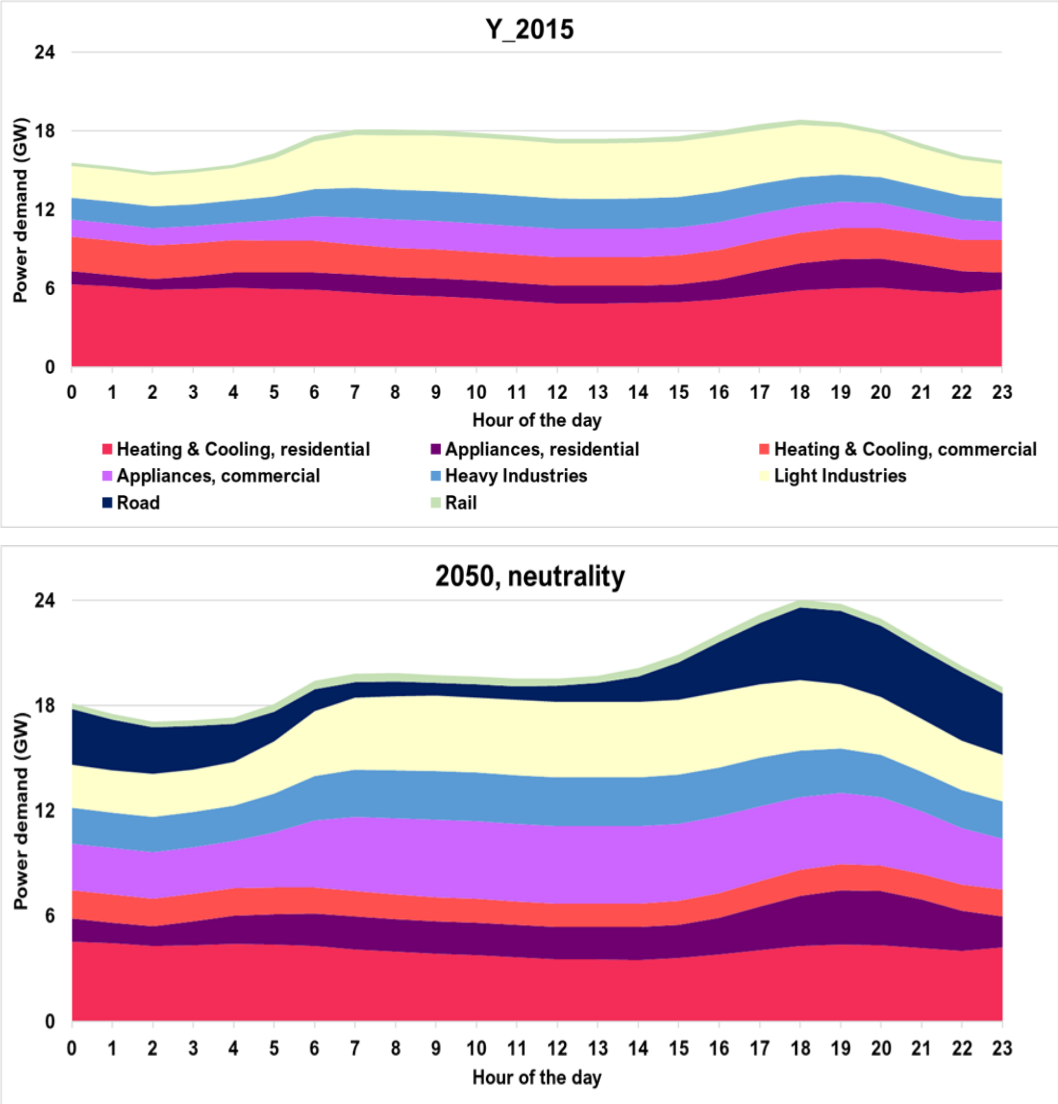


Figure 74. Hourly power demand profiles for a winter weekday in Sweden during 2015 and under the assumptions of the 2050 Neutrality scenario.

As evidenced by the presented data, the share of electricity (as well its absolute figures) consumed in road transport (in comparison with other transport modes) increases across the scenarios. As a consequence, especially for the 2050 time horizon, this translates into changes in the amplitude of the hourly peak demand due to EV charging. Assumptions for EV charging blending profiles, particularly on the shares of 'home', 'work', and 'smart' charging have further been discussed in the analogous RQ for the European CS (**Section 3.1.6.3**).

3.2.5. Energy efficiency & smart buildings

*3.2.5.1. **NO-C5:** Evolution of building sector energy demand*

Contributing models: HEB

[*Research Questions' Overview*]

The building sector is one of the main contributors to GHG emissions and consumers of energy in the Nordic countries, making it one of the most relevant sectors for climate change mitigation policies (Maniak-Huesser et al., 2021). Due to the cold climates in the Nordic countries, some of the end-use such as space heating, hot water, energy demand contributes to the majority of the demand (Fazeli et al., 2016). However, the building sector has an immense potential to contribute to the mitigation options by reducing substantial energy demand in the Nordic region. Thus, in this study, we identify some key RQs relevant for Nordic building sector and provide insights on how the energy demand of the Nordic building sectors evolves under different policy scenarios.

- **RQ57:** What would be the energy demand of the building sector in Nordic countries by 2050, if no further actions/ policies are taken?

Results and Discussion

In order to answer **RQ57**, HEB uses data of the "**Moderate efficiency**" scenario (see **Section 3.1.2.5**) which is corresponding to the national building standards of each of the Nordic countries modelled in HEB. For instance, HEB calculates building energy demand for three Nordic countries namely: Denmark, Sweden and Finland. The "**Moderate efficiency**" scenario includes the present population growth, GDP growth, rate of urbanisation, share of advance buildings, and retrofit rates for each of these countries. Since, the Nordic countries have already implemented some stringent building codes for new constructions and renovations (see (Allard et al., 2021)), modelling results show that by 2050, the building energy demand in each of the Nordic countries will decrease compared to 2022. Overall, the reduction will be significant (58%) compared to 2022, since the energy demand of the Nordic building sector is supposed to decrease from 754,165 TJ in 2022 to 319,649 TJ. For these countries, especially the fall of space heating is modelled to be significant with the existing building codes and renovation rates. Precisely, a reduction from 596,200 TJ to 220,025TJ (63%) is expected for this end-use by 2050. Most of the reduction is achieved from the residential building sector with a 60% share in the total demand reduction by 2050. At country level, reduction in total demand for the building sector is expected to be highest for Finland (60%) and lowest for Denmark (55%), whereas, in Sweden the reduction in demand is in between these two, corresponding to a 57% decrease by 2050. **Table 38** below presents the total demand data in different years:

Table 38. Total energy demand of the building sector of the Nordic countries.

Countries	Unit	2022	2030	2040	2050
Denmark	TJ/y	185,322	178,845	131,456	82,667
Finland	TJ/y	244,137	229,940	165,469	98,453
Sweden	TJ/y	324,705	304,645	221,476	138,529

*3.2.5.2. **NO-C6:** Building stock area and thermal energy demand evolution*

Contributing models: DESSTINEE and HEB

Research Questions' Overview

As mentioned in Deliverable 7.1 (Stavrakas et al., 2021), energy efficiency interventions can work together with RES in buildings. In this respect, stakeholders stated that substantial energy savings can be achieved by energy-efficient water heating systems and replacement of existing heating systems with heat pumps. In this respect, the following RQs are addressed:

- **RQ63:** What adoption rates of heat pumps are expected in the residential sector?
- **RQ64:** How can renovation rate/insulation improvement influence thermal energy service demand? How many new, passive, or nearly-zero emission buildings shall be built due to the growing urban population in the Nordic countries? What should be the renovation rate and pace of the old building stock?

Results and Discussion

HEB results

In order to answer **RQ64**, the floor area projections of the HEB model's "**Deep Efficiency**" scenario (**Section 3.1.2.5**) are considered for the Nordic countries. In this scenario, it is assumed that after 2027, all new buildings will be constructed at per low carbon energy standard, and hence, all advanced including the newly constructed and retrofitted, buildings have a very low energy intensity level. As per the model assumptions, the share of advanced buildings become increasingly dominant within the total buildings stock after 2027 in each of the Nordic countries. HEB also assumes that the total renovation rate in Nordic countries will be 3% annually after 2027, while from 2022 until 2027, the retrofit rate is assumed to be 1.4% per year. As a result of the growth in the population (both Denmark and Sweden population is projected to increase by 2050, however for Finland, the population is projected to decrease by 2050) and GDP in Nordic countries, the total floor area of advanced buildings is expected to grow to 1559.1 million m^2 in 2050 from 2.6 million m^2 in 2022. This substantial share of advance buildings results in significant decrease in final energy demand for each of the Nordic countries (**Table 38**). **Table 39** presents the total area of advance floor space for each of the Nordic countries.

Table 39. Total area of advance floor space in Nordic countries in million m^2.

Countries	Unit	2023	2030	2040	2050
Denmark	million m^2	0.6	45.5	255.6	476.4
Finland	million m^2	0.4	30.8	177.8	326.4
Sweden	million m^2	1.6	78.1	410.4	756.3

These values result in different shares of advanced buildings within the entire stock [(Denmark; residential: 81%, tertiary: 93%), (Finland; residential: 79%, tertiary: 91%), (Sweden; residential: 85%, tertiary: 96%)]. Based on these modelling results, two major conclusions can be derived: Firstly, the pace of renovating the old building stock should be accelerated substantially as soon as possible and, the standard of renovation should remain advanced, which implies a 30% reduction in building energy demand after renovation.

Secondly, all new constructions should be aiming at low-carbon, or passive house standards to achieve a net zero transition by 2050.

DESSTINEE results

FEC is projected accounting for: changes in the building area, fuel swapping and assumptions for heat pump deployment, and trends for the building envelope efficiency improvement. The increase in residential building area is modelled by using correlations between the number of people and area per household and the GDP per capita, obtained using past data from the "JRC IDEES" database (Mantzos et al., 2017). The projections for heat pump deployment were based on extrapolating trends, from the aforementioned database, on the share of electrically supplied heat provided by heat pumps. The fraction of thermal energy, delivered by electricity in residential households was defined on the basis of the rises proposed in EU wide scenarios (European Commission, 2020c; Runge-Metzger, 2018), being applied to the current fuel basket for heating in the different Nordic countries. The evolution for the thermal energy service demand per surface unit (normalised by HDD) was modelled by correlating the ratio of the country-level and the EU figures (Mantzos et al., 2017) with the ratio of GDP per capita and extrapolating that correlation to the time horizons of the scenarios.

Figure 75 and **Figure 76** respectively display the thermal service demand and FEC for residential buildings. It can be appreciated that heat pumps are projected to deliver 87% of the thermal energy service for residential buildings by 2050 in the Nordic countries. The observed downward trend for the absolute amount of delivered heat is a consequence of the building envelope efficiency improvement, contributing to lower FEC for heating purposes. It must be noted that heat pumps are 2-3 times more efficient than direct heating electricity devices thus the deployment of heat pumps supplements the reduction effects of better insulation in terms of FEC.

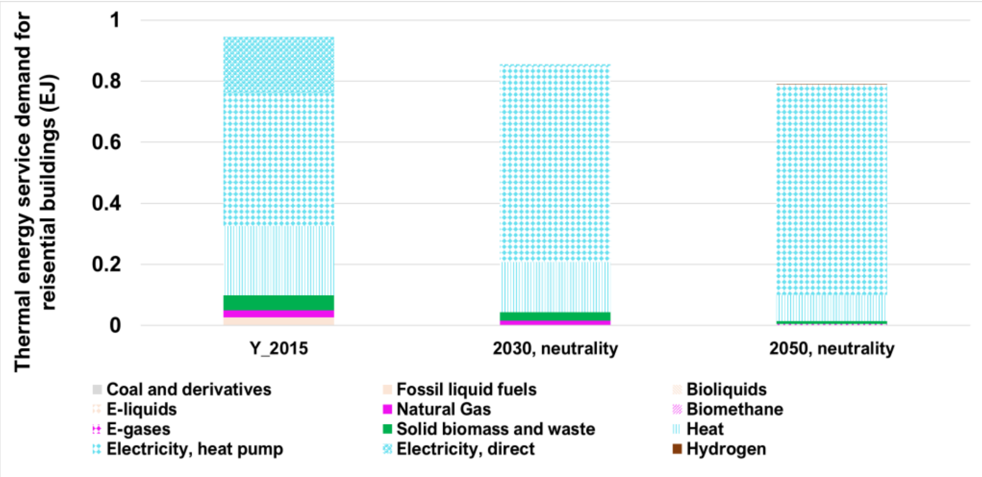


Figure 75. Thermal energy service demand for residential buildings across the scenarios.

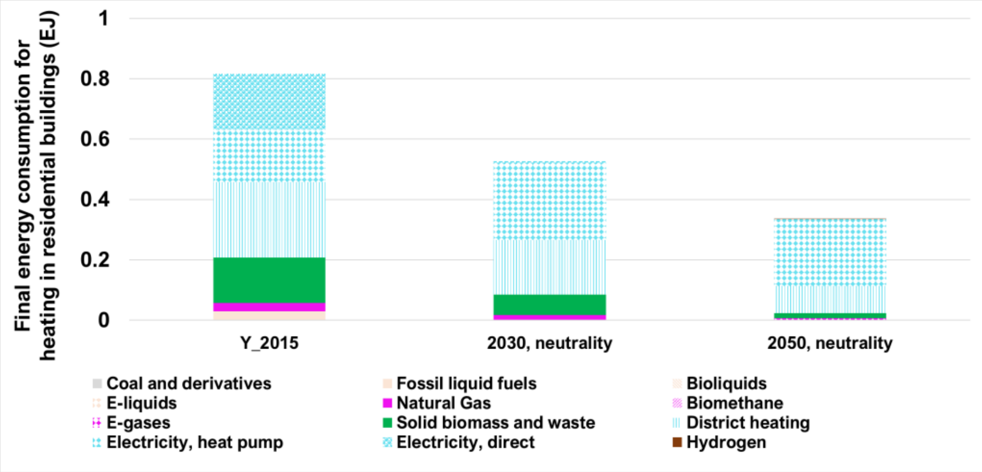


Figure 76. Final energy consumption for residential buildings across the scenarios.

3.3. National (Greek) case study

In 2019, the Greek government made the decision to completely phase out lignite by 2028, which was required for both climatic and economic reasons (The Green Tank, 2019). This led to the revision of the NECP, which outlines the national energy and climate scenario and targets until 2030 (Greek Ministry of Environment and Energy, 2019). The commitment of the Greek government to climate neutrality goals and the need for relevant modelling analysis led to the creation of the Long-Term Strategy for 2050 (LTS50), which presents various energy transition scenarios according to the long-term European vision for climate neutrality (Greek Ministry of Environment and Energy, 2020). A new announcement to phase out lignite by 2025 was made in 2021 (euro2day.gr, 2021), while during the same year, the Greek Independent Transmission System Operator (IPTO) launched a public consultation for their new "National Resource Adequacy Assessment" report, including key supply data and assumptions (IPTO, 2021). At the time of preparing this deliverable, both the NECP and the LTS50 documents have been under revision to consider the effects of the COVID-19 pandemic, however, they should be further adapted to account for the impacts of the new energy crisis due to the Russian invasion of Ukraine.

3.3.1. Scenario Updates

In Deliverable 7.1, energy scenarios towards 2030 and 2050 were specified based on the NECP and LTS50 documents, namely **(i)** the "**Reference (RF)**" scenario (2020-2050), **(ii)** the "**Renewable Electricity (RE)**" scenario (2030-2050), and **(iii)** the "**Power-to-X (P2X)**" scenario (2030-2050) (Stavrakas et al., 2021). All scenarios assume that the NECP targets will be met by 2030 and include goals, priorities, and policy measures for the post-2030 period.

The "**RF_2050**" scenario anticipates a reinforcement of NECP policies after 2030. The "**RE_2050**" scenario considers that developing new climate-neutral energy carriers to replace fossil fuels is economically and technologically risky and promotes the electrification of energy uses in all sectors as well as EEMs. The "**P2X_2050**" scenario, on the other hand, assumes that appropriate EU policies ensure the gradual maturation of technologies and means to produce H_2, biogas, and synthetic methane via electricity.

The new "National Resource Adequacy Assessment" report, recently published by IPTO foresees a more environmentally ambitious storyline for the RF scenario (IPTO, 2021). More specifically, IPTO formed a new reference case regarding VRES penetration, storage, and electricity demand until 2030, called as the "**IPTO-Baseline**". Furthermore, IPTO proposes alternative scenarios for 2030 by examining higher levels for VRE penetration and storage. We have clustered these scenarios under the "**IPTO-Green Deal**" case.

All the key targets of the energy transition scenarios for the National CS are presented in **Table 40**.

Table 40. Summary of the energy targets for the National case study.

Scenario	RF (2030)	RF (2050)	RE (2050)	P2X (2050)
Total GHG reduction targets	-43% relative to 1990 (-56% relative to 2005)	-74.7% relative to 1990	-94.7% relative to 1990	-95.3% relative to 1990
Total GHG emissions (Mt CO_{2eq})	60.6	27.2	5.7	5.0
RES & efficiency targets	**1.** >35% RES in gross FEC **2.** 42.5% RES in gross FEC for heating and cooling, 19% RES in gross FEC for transport, 61.6% RES in total electricity generation, 0% lignite in electricity generation **3.** >38% EE improvement (compared to the forecast on FEC by 2030 and to achieve lower FEC in 2030 compared to that in 2017), leading to energy savings of 7.3 Mtoe (2021– 2030) **4.** FEC: 16.1– 16.5 Mtoe, primary energy consumption: 20.5 Mtoe **5.** -32% energy intensity (2020 – 2030)	**1.** 67.6% RES in gross FEC **2.** ~52% RES in gross FEC for heating and cooling **3.** ~230%* RES in gross FEC for transport, **4.** ~84% RES in total electricity generation, primary energy consumption: 16.1 Mtoe **5.** -30% energy intensity (2030- 2050)	**1.** 95.9% RES in gross FEC **2.** ~81% RES in gross FEC for heating and cooling **3.** 494.7%* RES in gross FEC for transport **4.** ~97.3% RES in total electricity generation, primary energy consumption: 15.2 Mtoe **5.** -30% energy intensity (2030-2050)	**1.** 113.8% RES in gross final energy consumption **2.** ~92.9% RES in gross final energy consumption for heating and cooling **3.** ~330%* RES in gross final energy consumption for transport **4.** ~97.3% RES in total electricity generation, primary energy consumption: 24 Mtoe **5.** -8% energy intensity (2030- 2050)

* Targets as calculated using the EU calculation formula.

The main specifications of the energy transition scenarios for the National CS are presented in detail in **Table 41**.

Table 41. Summary of the main specifications for the National case study.

Scenario	RF (2030)	IPTO-Baseline (2030)	IPTO-Green Deal (2030)	RF (2050)	RE (2050)	P2X (2050)
RES capacity for power generation (GW)	19	-	-	26.5	33.9	63.8
Hydro plants capacity (GW)	3.9	-	-	4	4.7	5.1
Wind (offshore) plants capacity (GW)	7	6.6	7.1	11.6 (0.4)	13.4 (0.6)	19.7 (2.2)
PV plants capacity (GW)	7.7	7.3	9.8	9.8	14.6	37.3
Total auto-production & net-metering PV systems capacity (GW)	>1	-	-	-	-	-
New auto-production & net-metering PV systems capacity (GW)	0.6	-	-	-	-	-
Natural gas plants capacity (GW)	6.91	-	-	6.5	-	-
Synthetic gas plants capacity (GW)	-	-	-	-	4.9	7.9
Electricity demand/supply (TWh)	61.8	57.3	-	80.3	100.9	173.2
Energy utilisation of storage (TWh)	2.2	-	-	8.2	22.4	42.4
Pumped hydro storage (GW)	1.6	-	-	1.7	1.7	1.5
Battery storage (GW)	1.2	1.1	1.4	2.6	2.5	3
H_2 storage (GW)	-	-	-	0.4	4.3	23.5

Number of residential buildings to be renovated	600,000	-	-	856,000	1,136,000	956,000
Share of electricity in FEC (residential)	39.1 %	-	-	58.9 %	81 %	59.2 %
Share of bioenergy in FEC (residential)	19.3 %	-	-	9.9 %	7.9 %	11.9 %
Share of natural gas in FEC (residential)	15.1 %	-	-	21.7 %	3 %	-
Share of petroleum products in FEC (residential)	9.7 %	-	-	0.2 %	-	-
Share of RES (geothermal+solar) in FEC (residential)	15.9 %	-	-	8.6 %	10.2 %	7.9 %
Share of DH in FEC (residential)	0.9 %	-	-	0.7 %	-	-
Share of synthetic methane in FEC (residential)	-	-	-	-	-	15.7 %
Share of H_2 in FEC (residential)	-	-	-	-	-	4.5 %
Fuel cell two-wheelers and passenger cars	0	-	-	62,000	46,000	229,000
Battery electric two-wheelers and passenger cars	459,000	-	-	4,376,000	7,861,000	7,178,000
PHEV electric two-wheelers and passenger cars	133,000	-	-	1,653,000	150,000	429,000
Hybrid two-wheelers and passenger cars	312,000	-	-	306,000	70,000	142,000
Internal combustion two-wheelers and passenger cars	6,496,000	-	-	2,327,000	123,000	395,000
Fuel cell buses and trucks	0	-	-	17,000	16,000	47,000
Battery electric buses and trucks	1,000	-	-	12,000	47,000	12,000
PHEV electric buses and trucks	0	-	-	0	0	0
Hybrid buses and trucks	16,000	-	-	107,000	69,000	59,000
Internal combustion buses and trucks	252,000	-	-	220,000	183,000	216,000
Share (%) of liquid fossil fuels and bunker fuels in FEC (transport)	91.1	-	-	63.2	39.6	37.9
Share (%) of bioenergy in FEC (transport)	5.3	-	-	-	-	-
Share (%) of (natural+bio) gas in FEC (transport)	1.4	-	-	6.1	1.3	2
Share (%) of electricity in FEC (transport)	2.2	-	-	8.7	17	12
Share (%) of bioliquids in FEC (transport)	-	-	-	20.5	40.4	15
Share (%) of H_2 in FEC (transport)	-	-	-	1.5	1.7	6.6
Share (%) of synthetic liquid fuels and synthetic methane in FEC (transport)	-	-	-	-	-	26.5
Share (%) of electricity in FEC (industry)	39.6	-	-	53.5	63.2	55.4
Share (%) of natural gas in FEC (industry)	26.7	-	-	20.5	9.3	1.5
Share (%) of petroleum products in FEC (industry)	20.4	-	-	-	-	-
Share (%) of bioenergy in FEC (industry)	7.9	-	-	21.7	24.3	22.2
Share (%) of solid fuels in FEC (industry)	5.2	-	-	0.5	0.2	0.1
Share (%) of DH, solar and geothermal in FEC (industry)	-	-	-	3.8	3	3.3
Share (%) of synthetic methane in FEC (industry)	-	-	-	-	-	7.2
Share (%) of H_2 in FEC (industry)	-	-	-	-	-	10.3
Carbon dioxide (CO_2) reduction target compared to 2005 levels	64%					
Sulphur dioxide (SO_2) reduction target compared to 2005 levels	88%	-	-	-	-	-
Nitrogen oxides (NO_X) reduction target compared to 2005 levels	55%	-	-	-	-	-
Non-methane volatile organic compounds (NMVOCs) reduction target compared to 2005 levels	62%	-	-	-	-	-
Ammonia (NH_3) reduction target compared to 2005 levels	10%	-	-	-	-	-
Fine particulate matter (PM2.5) reduction target compared to 2005 levels	50%	-	-	-	-	-

3.3.2. Key assumptions

3.3.2.1. Harmonised data

Fuel and carbon price projections until 2050 were made using a trendline, fit to the price developments by the end of 2021 and the price projections mentioned in the resource adequacy assessment of the Greek IPTO until 2040 (IPTO, 2021). The resulting projections are shown in **Table 42.**

Table 42. Natural gas and emission allowance (CO_2) price projections.

Year	2030	2050
Natural gas price projection (€/MWh)	22.43	45.32
CO_2 Cost Projection (€/tonne)	64.67	114.79

3.3.2.2. BSAM-specific assumptions

BSAM is applied only to the "**RF_2030**" and "**RF_2050**" scenarios for Greece, as narrated in Deliverable 7.1 (Stavrakas et al., 2021). For these scenarios, two literature cases for the evolution of installed capacities of wind turbines (WT) and PV are considered, as shown in **Table 43**. The "**IPTO-Baseline**" and "**IPTO-Green Deal**" cases follow the capacity specifications until 2035, as presented in the new "National Resource Adequacy Assessment" report published by the Greek IPTO (IPTO, 2021), which sets more ambitious requirements than the VRES targets mentioned in the NECP (Greek Ministry of Environment and Energy, 2019), extended to the projections of the "**RF_2050**" scenario. The "**IPTO-Green Deal**" case is modelled only until 2030, since the report includes projections only until 2035.

Table 43. Literature cases for the evolution of variable renewable energy sources generating capacity in Greece for the Reference ("**RF**") scenarios specified under SENTINEL Deliverable 7.1 (Stavrakas et al., 2021).

Year	Scenario	Case	PV (MW)	WT (MW)
2021	Current Situation	-	3055	3755
2030	"**RF**"	"**IPTO-Baseline**"	7342	6619
		"**IPTO-Green Deal**"	9763	7149
2050	"**RF**"	"**IPTO-Baseline**"	11229	10171
		"**IPTO-Green Deal**"	-	-

For the installed capacities of thermal and hydro GUs, one literature case is considered, as shown in **Table 44**. The "**IPTO-Baseline**" case, which corresponds to the baseline scenario presented in the "National Resource Adequacy Assessment" report of the Greek IPTO (IPTO, 2021), extended to the projections of the Greek "**RF_2050**" scenario.

Table 44. Literature case for the evolution of thermal and hydro generating capacity in Greece for the Reference ("**RF**") scenarios specified under SENTINEL Deliverable 7.1 (Stavrakas et al., 2021).

Year	Scenario	Case	Nat. gas ST (MW)	Nat. gas CCGT (MW)	Lignite (MW)	Hydro (MW)
2021	Current Situation	-	0	5007	1000.5	3170.7
2030	"**RF**"	"**IPTO-Baseline**"	1000	6657	0	4268.3
2050	"**RF**"	"**IPTO-Baseline**"	1000	5082.4	0	4858.3

For the evolution of the annual electricity demand, one literature case is considered too, as shown in **Table 45**. The "**IPTO-Baseline**" **case** which corresponds to the baseline scenario presented in the "National Resource Adequacy Assessment" report, extended to the projections of the Greek LTS50 (Greek Ministry of Environment and Energy, 2020).

Table 45. Cases for the evolution of the annual electricity demand until 2050 in Greece.

Year	Scenario	Case	Annual electricity demand (TWh)
2030	**"RF"**	**"IPTO-Baseline"**	57.3
2050	**"RF"**	**"IPTO-Baseline"**	80.3

Storage capacity is also considered to follow the baseline scenario of the "National Resource Adequacy Assessment" report, extended to the projections of the Greek LTS50 (Greek Ministry of Environment and Energy, 2020), as shown in **Table 46**.

Table 46. Cases for the evolution of storage capacity until 2050 in Greece.

Year	Scenario	Case	Storage Capacity (MW)
2030	**"RF"**	**"IPTO-Baseline"**	1050
2050	**"RF"**	**"IPTO-Baseline"**	2600

Finally, regarding interconnections, the electricity system in Greece is interconnected with five neighbouring countries, namely: Albania, Bulgaria, Italy, North Macedonia, and Turkey. The related net transmission line capacities as well as their projected values, as obtained from the most recent TYNPD of ENTSO-e and ENTSOG (ENTSO-e and ENTSO-g, 2020) are shown in **Table 47**.

Table 47. Transmission line capacities for imports from interconnected countries until 2050 in Greece.

Interconnected country	Imports capacity in 2022 (MW)	Projected capacity in 2030 (MW)	Projected capacity in 2050 (MW)
Albania	250	250	250
Bulgaria	700	1350	1350
Italy	500	500	500
North Macedonia	850	850	850
Turkey	166	580	580

3.3.2.3. EMMA-specific assumptions

Allowed emissions, projected EU ETS prices, and fuel prices are implemented according to the National CS specifications and, thus, harmonised with BSAM. The evolution of the annual electricity demand (**Table 45**) is split into three components as shown in **Table 48**:

A. An hourly exogenous electricity demand.

B. A yearly exogenous hydrogen demand by the industry sector (that translates into an electricity demand when hydrogen is produced by electrolysers).

C. An endogenous hydrogen demand by the power sector (hydrogen is produced by electrolysers but also reconverted to electricity by hydrogen-fuelled plants).

This allows for representing the temporal flexibility of the added yearly demand (B.), as well as the usage of hydrogen as a mean to store electricity and its interaction with other electricity production technologies (C.). These individual components are reverse engineered from CS data points and assumed conversion efficiencies (exception made for the "**RF_2030**" and "**RF_2050**" scenarios). In the "**RE_2050**" and "**P2X_2050**" scenarios

(**Table 40**) the exogenous electricity demand is calculated as the difference between the total electricity consumption and the electricity demand of refineries and production of synthetic fuels (Greek Ministry of Environment and Energy, 2020). Hydrogen equivalents are calculated based on EMMA internal conversion efficiencies (i.e., electrolysers: 75%; H_2-fuelled CCGT: 63%). Further assumptions, including the projected build-out costs and installed capacities, are captured with the model's default parameterisation. For further details please see the EMMA model's documentation (Hirth and Ruhnau, 2021).

Table 48. EMMA-specific assumptions of each scenario.

Scenario / Assumptions	"RF_2030"	"RF_2050"	"RE_2050"	"P2X_2050"
Total power consumption ($TWh_{electric}$)	57.3	80.3	100.7	173.3
Refineries/production of synthetic fuels ($TWh_{electric}$)	-	-	8.7	74.4
A. Exogenous electricity demand ($TWh_{electric}$)	57.3	80.3	92.0	98.9
Gross electricity production from H_2 (TWh_e)	-	-	5.9	9.9
B. Exogenous H_2 demand ($TWh_{thermal}$)	-	-	-	42.9[11]

3.3.2.4. WEGDYN-specific assumptions

In the framework of applying the QTDIAN-Calliope-WEGDYN (QCW) model ensemble to the European CS (i.e., see **Section 3.1.2.9**), we introduce a EU27+ emission allowance market covering (in addition to ETS sectors) also sectors currently under effort sharing regulations (i.e., transport, buildings). We report here results for Greece in this broader context. Greece pledged emission reductions until 2030 to achieve a level of around 62 Mt $CO_{2,eq}$ (Stavrakas et al., 2021). We derive emission levels of 45, 47, and 50 MtCO_2 in the **MDR**, **GDI** and **PPO** storylines respectively for Greece by 2030 (see (Süsser et al., 2021c) for a description of storylines). These larger reductions are consistent with the European targets for 2030 (<2,000 Mt CO_2) and 2050 (<200 Mt CO_2), as indicated by the dashed black line in **Figure 77**. The corresponding allowance prices are discussed in **Section 3.3.3.2** where the linking of the model ensemble *QCW* and the application of different storylines are described in detail.

[11] We impute the difference between the additional electricity consumption for synthetic fuels and the additional electricity from hydrogen to a growing industrial hydrogen demand, 42.9 =(74.4 - 8.7) · 75% - (9.9- 5.9)/63%.

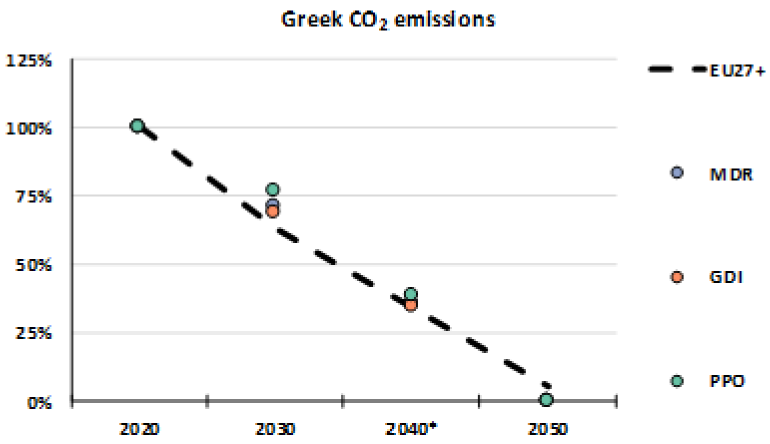


Figure 77. EU27+ and Greek Carbon Dioxide (CO_2) emission reductions across storylines; note that 2020 is calibrated to pre-pandemic levels amounting to around 65.7 MtCO_2 without Land Use, Land-Use Change and Forestry (LULUCF); *interpolated.

3.3.2.5. DESSTINEE-specific assumptions

DESSTINEE has been employed for the modelling of energy consumption across end uses including building renovation rates, proposed fuel baskets, and fleet compositions for households and road transport (from the scenarios) in the National CS narrative text (Stavrakas et al., 2021). For other end uses, for which highly detailed information was not straightforwardly available, it was decided to use the fuel baskets defined for Greece by DESSTINEE in the context of the Continental CS.

For the "**RF_2030**" scenario, assumptions for non-building and non-road transport end uses rely on the country-level inputs and considerations for Greece in the "**Current Trends**" scenario, modelled by DESSTINEE in the context of the Continental CS. The "**RF**" scenarios considered here are a blending of the proposed technology incorporation for building and road transport, in the National CS narrative, and the country-level results for Greece within the Continental CS. An analogous scenario blending occurred for the decarbonisation pathways, combining inputs from the "**RE_2030**" and "**P2X_2050**" scenarios with results for Greece from the "**2050 Climate Neutrality**" scenario in the Continental CS.

Soft linkages with other models, like the DREEM model, are further discussed within the detailed answers to the respective RQs.

3.3.2.6. DREEM-specific assumptions

In this section, we report on the DREEM-specific assumptions for **RQ54** in the **GR-C13** (**demand-response (DR) and digitalisation**) **cluster** (**Section 3.3.7**). The parameterisation of the individual components/modules of the DREEM model is presented below, along with the main data inputs and outputs, to explore the energy performance of a single-family residence in the city of Athens, for one-year period (i.e., 1/1–31/12 2020).

i. Weather-climate data

The International Weather for Energy Calculations (IWEC) weather data is used (ASHRAE, 2001). The data on weather conditions were accumulated by recording an 18-year period (1982–1999) in Athens region. The data consists of location information, such as latitude, longitude and the time zone relative to Greenwich Mean Time, along with detailed hourly data of temperature, relative humidity, wind speed and direction, solar direction and radiation, etc. Additionally, the DREEM model allows for seasonal simulations to account for the effects of weather and temperature on electricity demand. The three typical seasonal profiles considered to present simulation results are: **(I). Period 1 (mild weather)**: April, May, October, and November, **(II). Period 2 (hot weather):** June to September, and **(III). Period 3 (cold weather)**: December to March.

ii. Building envelope & properties

The building envelope studied is a detached house, modelled as a thermal zone with four elements for exterior walls, interior walls, floor plate, and roof, with two windows with double glazing. The floor area of the building is 81m^2 and its height is 3.2 m. The building envelope specifications and the properties of different elements are set according to the specifications of the Greek Energy Performance Buildings Directive, or "KENAK" regulation (Spyridaki et al., 2016), as defined in the guidelines of the Technical Chamber of Greece (Technical Chamber of Greece, 2017). The properties are summarised in **Table 49** and the U-values of each structure element is less than the maximum requirements set by the Technical Chamber of Greece.

Table 49. Properties and U-values of the different structure elements for the building envelope under study.

Structure Elements	Surface A (m^2)	U-values (W/m^2·K)	Maximum U-value allowed (W/m^2·K) - Zone B	Total solar heat transmittance (g)
External wall	28.8	0.27	0.5	-
Roof	81	0.095	0.45	-
Floor	81	0.095	0.45	-
Windows	3	2.8	3	0.46

iii. Domestic occupancy and energy demand modelling

A typical Greek nuclear (conjugal) family is assumed, consisting of two working parents and two children: one school-aged child (6–11 years old) and one adolescent (12–18 years old). For their occupancy profiles fixed typical schedules were adopted. These schedules were not distinguished between seasonal profiles, as typically parents' working hours or children's school hours are not differentiated between summer and winter. On the other hand, these schedules were differentiated between weekdays and weekends, while it was assumed that all the family members were out of their residence for family vacation for one week during Christmas and Easter, and for two weeks during summer. Finally, a weighted stochastic function was applied for some days and evening hours to account for some after-work/school activities (e.g., sports, arts, outdoor education, extracurricular activities, etc.). Higher weight values were chosen for the case of weekends, as typically people tend to do such activities when they do not work. Activity profiles showing occupants' tendencies were also created, to account for the types of end-use and for sleeping. These profiles were also distinguished between weekdays and weekends, as people tend to do more housekeeping activities during weekends.

The appliances in the model were configured using the "Development of detailed statistics on energy consumption in households 2012-2013" survey data (**Table 50**), describing their mean total daily energy demand and associated power use characteristics, including steady-state consumption, or typical use cycles as appropriate, along with ownership levels (Hellenic Statistical Authority, 2013). Additionally, activity profiles and end-uses for appliances were specified according to the statistics and the occupancy profiles and were distinguished between working days and weekends.

Table 50. Weekly energy consumption from appliances based on the "Development of detailed statistics on energy consumption in households 2012-2013" survey data in Greece.

Appliances	**Ownership Rate** (%)	**Nominal Power** (W)	**Time-of-Use** (days/week)	**Time-of-Use** (hours/day)	**Weekly consumption** (kWh/week)
Cooking					
Hobs	91.82	1600	1.56	1.92	4.77
Electric cooker with oven	86.89	2150	2.86	3.21	19.75
Microwave oven	33.33	1150	2.13	1.03	2.51
Toaster	61.80	1300	2.52	0.20	0.66
Coffee maker	36.91	1100	2.32	1.00	2.55
Water boiler	31.41	1250	1.79	1.00	2.23
Cooker hoods	89.64	108	1.56	1.89	0.32
Lighting					
Incandescent lamp (x6)	80.54	80	7.00	3	1.68
LED lamp (x2)	4.75	10	7.00	2	0.14
Night light (x1)	95.01	1	7.00	8	0.06
Other appliances					
Fridge-freezer	80.57	150	7.00	24.00	25.20
Dishwasher	29.02	1350	3.09	0.52	4.95
Washer (without tumble dryer)	94.30	500	2.46	0.50	1.76
Iron	94.98	1000	1.82	0.31	2.15
Vacuum cleaner	78.06	450	2.19	0.21	0.67
Colour-television set	99.03	100	7.00	5.19	3.63
DVD or VCR	37.05	40	2.51	0.39	0.11
Stereo	30.59	24	4.21	1.00	0.17
Computer (desktop, laptop, tablet, etc.)	41.84	300	3.06	0.53	1.10
Peripheral devices (printer, scanner, etc.)	13.91	50	0.56	0.13	0.05
Internet devices (printer, scanner, etc.)	38.21	10	7.00	24.00	1.68
Video Game Consoles	6,36	160	3.73	0.77	0.86
Charger: mobile phone charger	99.36	1	6.58	1.27	0.08

iv. Thermal comfort: Acceptable indoor temperature setpoints

DREEM determines, based on international standards, the appropriate indoor thermal conditions and temperature ranges that result in thermal satisfaction of the occupants based on the "DIN EN ISO 7730" (DIN EN ISO 7730, 2005), "ASHRAE 55" (Taleghani et al., 2013), and "EN 15251" (CEN, 2007) standards. It builds on the Fanger approach (Fanger, 1970), using the characteristic numbers Predicted Mean Vote (PMV) to compute the thermal comfort of occupants.

v. Photovoltaic and storage installations

Following Waffenschmidt, a sizing of 1-to-1 for storage capacity to PV peak power was assumed (Waffenschmidt, 2014), with a typical capacity for a small residential stationary storage selected (i.e., 5kW) as stated in (Pfeifer et al., 2018), with nominal voltage of 12 volts. In addition, direct-current storage is a suitable choice, as it is typically applied when the primary aim is to store solar energy directly from the PV panels and use it during peak loads.

vi. Demand-Response: Real-time price-based signals

Building on a "real-world" approach, it was assumed that the energy supplier has to choose the optimal DR action to maximise its profits, from the action space $A = [a_1, a_2, a_3, a_4, a_5]$, which corresponds to "No Signal" (a_1), "Signal 1: Shift total demand by ≥5%" (a_2), "Signal 2: Shift total demand by ≥10%" (a_3), "Signal 3: Shift total demand by ≥15%" (a_4) and "Signal 4: Shift total demand by ≥20%" (a_5). To do so, a Python implementation of the SARSA (**S**tate **A**ction **R**eward (next)**S**tate (next)**A**ction) reinforcement learning algorithm was developed, as adapted (Sutton and Barto, 2017) and further presented in **Table 51**.

Table 51. State Action Reward (next)State (next)Action (SARSA) algorithm: pseudocode as adapted from Sutton and Barto (2017).

```
Output: action value Q
Initialize Q arbitrarily, e.g. to 0 for all states, set action value for terminal states as 0
initialize state s ← historical data
until Q converges
    for each episode do
      for each step of episode, state s is not terminal do
        a ← action for s derived by Q, e.g. ϵ-greedy
        take action a, observe r, s′
         a′ ← action for s′ derived by Q, e.g. ϵ-greedy
                        Q(s,a) ← Q(s,a) + a · [r + γ · Q(s′,a′) − Q(s′,a′)]
        s ← s′, a ← a′
     End
   end
   state s ← simulation results
```

vii. Control supervision

Load shifting is one of the main DR manners, as DR schemes can be more beneficial, if suppliers can increase the value of the maximum shiftable load (Vahid-Pakdel et al., 2017). The control algorithm assumes that occupants comply with the DR signals if active at home, shifting energy demand related to appliances to the next hour they are active, and a DR event is not signalled. **Figure 78** below depicts the flowchart of the supervisory control strategy implemented. Note that T_{set} is the indoor temperature setpoint, $T_{set,normal}$ is the normal indoor temperature setpoint, and $T_{set,min}$ is the minimum acceptable indoor temperature setpoint.

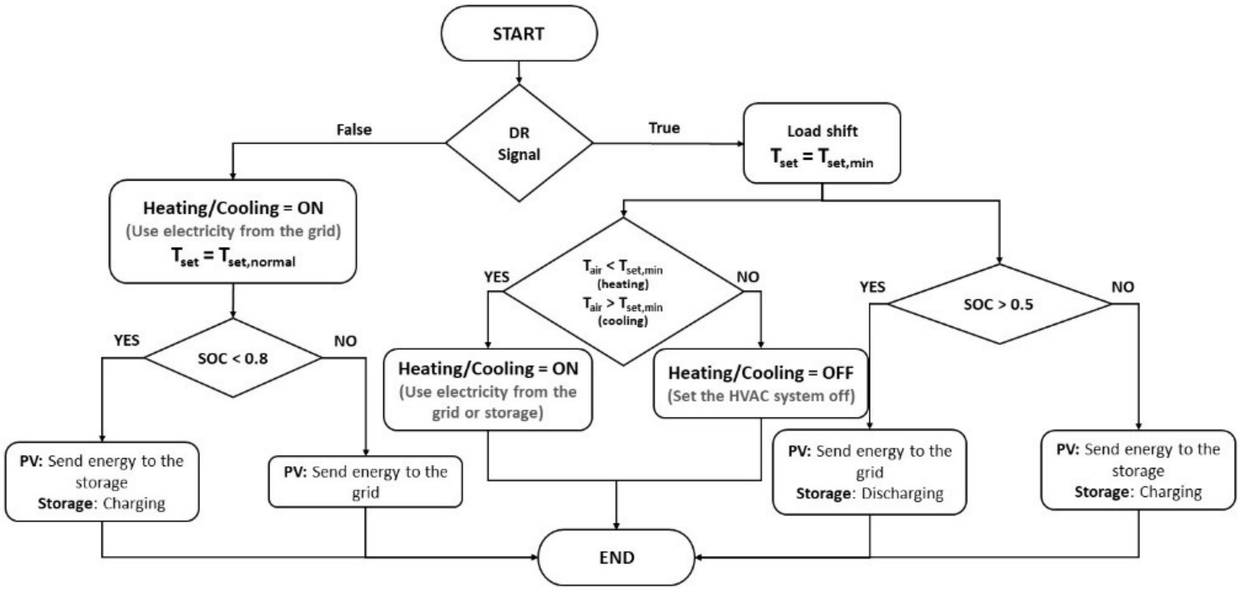


Figure 78. Flowchart of the Momentary Control Algorithm used in DREEM, as implemented by the "Control supervision" component.

3.3.2.7. ATOM-specific assumptions

The ATOM model is used in this CS to simulate the potential diffusion of small-scale PV adoption among Greek consumers, under two currently available policy schemes in Greece, Net-Metering (NEM) and Feed-in Tariff (FiT):

- **Net-Metering (NEM)**: In this scheme, the final electricity bill of consumers results from the difference between the consumed electricity and the PV-produced electricity, injected to the grid in a billing period. In case of excess electricity produced, it is credited to the next billing period for three years when the final settlement takes place.
- **Feed-in Tariff (FiT):** This scheme consists of a fixed rate, set at a national level by the government, at which any individual with an eligible PV installation can sell the electricity produced locally to the grid. In December 2021, a new household RES programme named "Solar Panels on Roofs" was introduced, offering to households a fixed tariff of 87 euros per MWh over 25-year contracts.

Agent-related parameters are modelled in ATOM to simulate the behaviour of potential technology adopters. Furthermore, other technical and market-related parameters are included in the model, as for example, small-scale PV investment costs, competitive electricity consumption tariffs and other regulated charges, the evolution of annual electricity demand, solar PV generation profiles, etc., which are collected from available sources (Eurostat, 2022; Hellenic Association for Energy Economics (HAEE), 2022; PPC, 2022). The definition of the different agent-related parameters and how they are modelled is described next, while **Table 52** presents the market-related parameters values used in the context of this study. For more information about the model, its structure, and the assumptions/parameters used, see (Stavrakas et al., 2019).

- **Belief** is each agent's private initial belief about the expected annual cash inflows from investing in a PV system of 300 Wp. The value ranges of the beliefs' parameter are highly dependent on the various market variables and each scheme's explicit features.
- **Social learning**: The following definition is provided for social learning: *"People adopt [the innovation] once they see enough empirical evidence to convince them that [the innovation] is worth adopting, where the evidence is generated by the outcomes among prior adopters. Individuals may adopt at different times, due to differences in their prior beliefs, amount of information gathered, and idiosyncratic costs"* (Young, 2009). The social circle of each agent remains constant during the simulation (i.e., the neighbouring agents are the same till the end of the simulation). The updated belief value during simulations comes as a result of a weighted summary of the previous value and the calculated annual revenue of the "neighbouring" agents that have already invested.
- **Resistance towards PV investments**: Agents are characterised by their resistance toward investing in solar PV installations. Resistance is defined as a weighted sum of two parameters:
  - The profitability of the investment expressed in terms of its payback period. Payback period ranges between 1-20 years and is a crucial factor that influences agents' decisions. According to historical data, when a new scheme is introduced, higher profitability leads to significant uptake of early adopters.
  - The difference between the total number of agents in the simulation and the number of those who have already invested in PV**.** The smaller the difference, the larger the installed base; and the larger the installed base, the smaller is the resistance. Resistance towards PV investments is influenced by the maturity of the scheme. In general, when a new scheme is introduced to the market, the installed base factor exercises more influence on agents' final decisions. Thus, the weight of the installed base is set lower to schemes that are more mature and operational, while the weight is higher for new schemes and schemes that even though they are operational, they have not attracted many adopters.
- **Probability of investing**: The parameter is defined as a threshold value for the resistance parameter of each agent. When the resistance is lower than a set threshold, agents are willing to adopt. The threshold mean value range is decided to be constant for each policy scheme, while the weights of the factors are adjusted according to the different features of each socio-political storyline derived by the QTDIAN model (**Section 3.3.2.9**).
- **Inertia to invest**: This is the simplest reason why innovations take time to diffuse, as people delay acting based on new information. In ATOM, even if the resistance towards PV investments is lower than the set threshold (probability of investment), not all the agents take the final decision to adopt. For example, even

if the investment environment seems favourable for adopting a new technology, many agents do not take the final decision, especially when it comes to a new policy scheme.

Table 52. Technical and market-related parameter values (model inputs) in ATOM.

Technical and market related parameters values (inputs)	
Annual average electricity demand	4162 kWh (mean value)
PV investment cost	1333 €/kWp
Electricity retail price	0.245 €/kWh
Feed-in Tariffs (FiTs)	87 €/MWh

3.3.2.8. EnergyPLAN-specific assumptions

For the EnergyPLAN analysis of the Greek energy system, the primary principle is that it is based on a Greek split of the European Smart Energy System. Electricity and heating demands are based on DESSTINEE and HEB modelling while transport and industry are based on own definitions from the work on Smart Energy Europe.

The EnergyPLAN scenario for Greece is based on the concept of Smart Energy Systems. This means that system integration and utilisation of different energy grids are key. Thus, DH and cooling is implemented in the Greek system to provide an overall system efficiency, by utilising waste heat, geothermal, and solar thermal energy. Furthermore, the EnergyPLAN "**Smart Energy Greece**" scenario is based on a principle of self-sufficiency, as such enough power plant capacity is installed in the country to cover the needed demands. In principle interconnectors to surrounding countries could be applied instead/as well.

For estimating transport demand, a combination of the electricity demand from DESSTINEE is used with the identification of the transport demand for Greece estimated in TransportPLAN as shown in **Table 53.** The overall principle applied is that private EVs will use smart charging technologies, with electrification of rail and heavy transport to be "dump" charge, with on demand charging.

Table 53. Overview of the transport scenario from TransportPLAN 2050 for the National case study.

Energy consumption/fuel	2050
All transport	PJ
Petrol	0
Diesel	0
Jet-fuel fossil	0
Biogas	11
Bioethanol	0
Biodiesel	0
Bio e-fuel	0
Bio e-jet fuel	17

CO_2 e-fuel	14
CO_2 e-jet fuel	18
Ammonia	5
H_2	0
Natural gas	0
Electricity train/bus/trucks/ships/aircrafts	58
Electricity BEV + Plug-in-hybrid	22

3.3.2.9. Model linkages

EMMA - BSAM

Apart from the literature cases presented in **Section 3.3.2.2,** for BSAM, a soft-linkage between the EMMA and BSAM models has also been established for the "**RF_2030**" and "**RF_2050**" scenarios of the national CS. EMMA, as a partial equilibrium model of the wholesale electricity market, is capable of simulating investments in power plants, as well as storage assets, in order to cover electricity demand (Bachner et al., 2022). In this respect, EMMA ran for the reference demand assumptions presented in **Table 48** and produced results for the required VRES, dispatchable and storage capacity shown in **Table 54** and **Table 55**.

Table 54. EMMA case for the evolution of variable renewable energy sources generating capacity in Greece for the Reference ("**RF**") scenarios.

Year	Scenario	Case	PV (MW)	WT (MW)
2030	"**RF**"	EMMA	6841.7	13835.7
2050	"**RF**"	EMMA	44497.8	14297.8

Table 55. EMMA case for the evolution of dispatchable generating capacity and storage in Greece for the Reference ("**RF**") scenario.

Year	Scenario	Case	Nat. gas OCGT (MW)	Nat. gas CCGT (MW)	Lignite (MW)	Hydro (MW)	Battery Storage (MW)	PHS Storage (MW)
2030	"**RF**"	EMMA	2378.7	8108.2	0	2744.3	356.2	1524
2050	"**RF**"	EMMA	1871.9	6680.5	0	3334.3	10572.9	1524

Calliope - EMMA

As part of SENTINEL, the geographical coverage of the EMMA model has been extended and calibrated to simulate the Greek electricity system as well. Nevertheless, cross-border flows with neighbouring regions contribute to the overall flexibility of the power market. This would be neglected if the Greek power system was modelled in isolation. To overcome this limitation, we interlinked EMMA with Calliope. Calliope covers a broader geographic scope, thus, calculates Greek Net Transfer Capacity (NTC) flows endogenously with an hourly granularity. We added the NTC flow calculated by Calliope in the "**Current Trends**" and "**Carbon Neutrality**" scenarios of the European CS as exogenous power flow in EMMA; the 2030 and 2050 "**Current**

Trends” scenario assumptions of the European CS are used for the “**RF_2030**” and “**RF_2050**” scenarios specifications of the National CS, while the “**2050 Carbon Neutrality**” scenario assumptions of the European CS are used for the “**RE_2050**” and “**P2X_2050**” scenarios of the National CS.

ATOM-QTDIAN

In order to assess how different socio-political storylines could impact the diffusion of small-scale PV systems in the residential sector in Greece, we soft-linked the QTDIAN toolbox with ATOM. The QTDIAN storylines cover three governance logics (Süsser et al., 2021c). The three storylines consist of different qualitative features/variables and quantitative parameters that influence the potential, design, and speed of the energy transition. Three of the six QTDIAN quantification themes are of specific interest to this study: “*citizen energy*”, concerning the status quo and potential for self-production; “*attitudes towards renewables*”, presenting people’s opinions and preferences for RES; and “*policy preferences & dynamics*”, addressing how different policy strategies of countries influence the transition. We apply them to ATOM to broaden the existing pathways and translate the storylines’ features/variables in different agent-related parameter value ranges **Table 56.**

Table 56. Agent-related parameters adjusted to the three socio-political storylines for the policy schemes under study.

		People-powered (PPO)		**Government directed (GDI)**		**Market driven (MDR)**	
		People want to participate and invest and motivate their close social circle.		Public acceptance is high for solar projects when supported by policy instruments. People tend to follow governmental directions; thus, they are not so much influenced by their social circle.		People envisage rooftop PV strictly as an investment opportunity and their decision is mainly driven by the expected profitability.	
	Schemes / Parameters	**NEM**	**FiT**	**NEM**	**FiT**	**NEM**	**FiT**
Agent-related parameters	**Beliefs**	Mean value range: 76 - 80 Variance range: 2 - 3	Mean value range: 43 - 47 Variance range: 2 - 3	Mean value range: 76 - 80 Variance range: 3 - 8	Mean value range: 43 - 47 Variance range: 3 - 8	Mean value range: 76 - 80 Variance range: 5 - 10	Mean value range: 43 - 47 Variance range: 5 - 10
	Social learning	Updated belief = 0.7 * beliefs + random(0.3, 0.5) *revenue		Updated belief = 0.5 * beliefs + random(0.2, 0.5) * neighbours' revenue		Updated belief = 0.3 * beliefs + random(0.3, 0.7) * neighbours' revenue	
	Resistance towards PV investments: The weight of profitability (payback period)	Mean value range: 3.3 - 3.5 Variance range: 0.15 - 0.25	Mean value range: 3.3 - 3.5 Variance range: 0.15 - 0.25	Mean value range: 3.8 - 4.2 Variance range: 0.15 - 0.32	Mean value range: 3.8 - 4.2 Variance range: 0.15 - 0.32	Mean value range: 4.1 - 4.4 Variance range: 0.3 - 0.5	Mean value range: 4.1 - 4.4 Variance range: 0.3 - 0.5

	Resistance towards PV investments – the weight of the installed base (1 - adopters/total agents).	Mean value range: 15 - 17 Variance range: 1 - 2	Mean value range: 9 - 13 Variance range: 1 - 2	Mean value range: 13.5 - 15.5 Variance range: 1.5 - 3	Mean value range: 8 - 13 Variance range: 1.5 - 3	Mean value range: 12 - 14 Variance range: 2 - 3.5	Mean value range: 6 - 11 Variance range: 2 - 3.5
	Probability of investing	Mean value range: 35 - 37 Variance range: 0 - 1.5	Mean value range: 48 - 52 Variance range: 0 - 1.5	Mean value range: 35 - 37 Variance range: 1.5 - 3	Mean value range: 48 - 52 Variance range: 1.5 - 3	Mean value range: 35 - 37 Variance range: 3 - 4.5	Mean value range: 48 - 52 Variance range: 3 - 4.5
	Inertia to invest	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3	0.1 - 0.3

QTDIAN-Calliope-WEGDYN (QCW)

Addressing RQs of the clusters **GR-C2 (Section 3.3.3.2)**, **GR-C4 (Section 3.3.3.4)**, **GR-C14 (Section 3.3.8.1)** and **GR-C16 (Section 3.3.9.1)**, we test the functionality of a soft-linkage between QTDIAN (Süsser et al., 2021c, 2021a), Euro-Calliope (Pickering et al., 2021) and the WEGDYN models (Bachner et al., 2022), denoted as QCW, as presented in **Section 3.1.2.9** in the European CS. The abovementioned research clusters are addressed using the soft-linked WEGDYN model, which is why we mainly report and explain WEGDYN input and output data. General information about input data from QTDIAN and Calliope to WEGDYN are described in the European CS section (**Section 3.1**) of this Deliverable. The soft-linkage concerns supply- and demand-side adjustments in the WEGDYN model by embedding the restructured energy system in an economy-wide framework. Note that the proposed model ensemble is applied at the EU27+[12] level. Here, we describe changes of the Greek energy system. The Greek electricity mix and corresponding productivity measured by LCOE (and differentiated by generation, storage, and transmission) are shown in **Figure 79** for the three storylines under study. These energy system configurations represent Calliope outputs processed for implementation in WEGDYN. We observe four developments at the national level of Greece.

[12] EU27 member states plus Norway, Iceland, United Kingdom, Switzerland, Serbia, Bosnia and Hercegovina, Albania, North Macedonia, Montenegro.

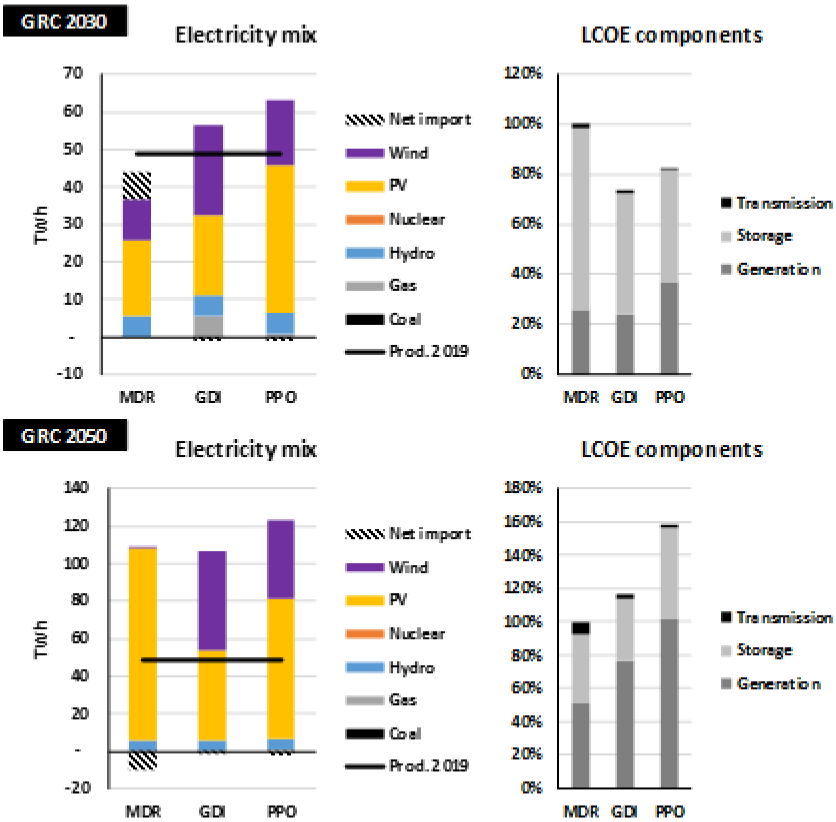


Figure 79. Greece electricity mix and Levelized Costs of Energy (LCOE) components across storylines for 2030 (top) and 2050 (bottom); note that gas-fired generation by 2050 is based on green hydrogen amounting to less than 1 TWh.

First, the electricity mix is largely composed of renewable-based generation driving out remaining coal-based capacities and almost all gas-fired capacities already by 2030, with less than 1 TWh in the **MDR** and **PPO** storylines and around 6 TWh in the **GDI** storyline. Second, and on an annual basis, Greece becomes a net electricity importing country in 2030 in the **MDR** storyline but net exports green electricity by 2050. Third, the push of cheap renewable generation into the system is much larger in the **GDI** and **PPO** storylines requiring less storage capacities, which cuts LCOE compared to the **MDR** storyline by -26% to -17%, respectively. By 2050, this comparison turns around, with larger transmission in the **MDR** system lowering additional generation capacity requirements to serve by then the fully decarbonised steel, cement and chemicals production. Compared to the **MDR** storyline, LCOE by 2050 is 16% to 58% higher in the **GDI** and **PPO** storylines, respectively. All three storylines imply cheaper energy supply in 2050 compared to their respective counterparts in 2030 due to further renewables' penetration. In 2030, system costs covering generation, conversion and storage as well as transmission amount to 21.3 €/MWh in the **MDR** storyline, 15.7 €/MWh and 17.6 €/MWh in the **GDI** and **PPO** storylines, respectively. In 2050, the corresponding numbers are 5.2, 6.0 and 8.2 €/MWh. The underlying merit order for electricity generation across storylines is depicted in **Figure 80**.

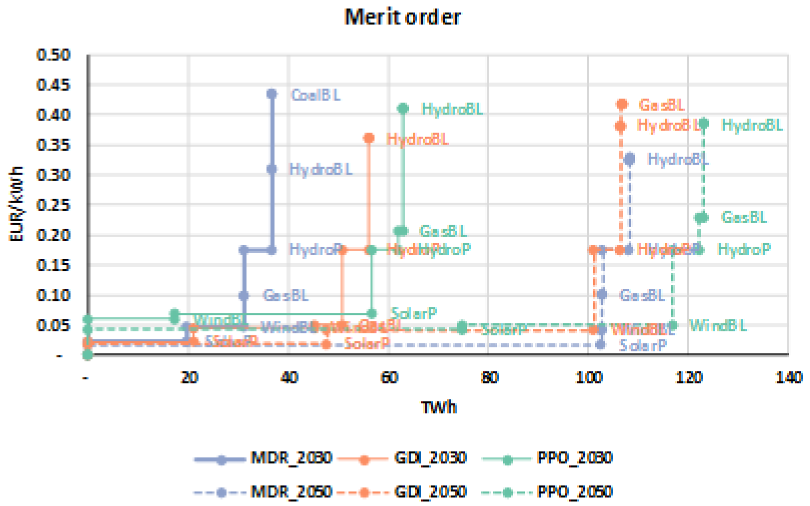


Figure 80. Merit order of the Greek electricity generation across the three storylines.

The Greek economy's structure of energy demand, assumed in Calliope and processed for inclusion in WEGDYN, is shown in **Figure 81**, which points to strong electrification of the economy. Note that by 2050, refinery products and gases are synthetically produced, and industrial processes (e.g., steel, chemicals, etc.) are based on H_2 and thus are climate neutral. To also reflect this change in WEGDYN, respective emission factors are adjusted accordingly. Within Calliope, energy-related emission cuts amount to 63% by 2030 and 20% for non-energy-related in the **MDR** and **GDI** storylines resulting in a 55% system-wide reduction consistent with the European CS. The **PPO** storyline achieves larger system-wide reductions with 65% by 2030 (74% for energy- and 34% for non-energy-related emission cuts) due to the underlying governance logic with stronger diffusion of particularly rooftop PV systems. This means that emission cuts in Greece are different from the case specification presented in Deliverable 7.1 (Stavrakas et al., 2021), but consistent with the EU-wide 55% reduction target by 2030 and the climate neutrality objective by 2050. Emission cuts in EU27+ and Greece are reported and discussed in **Figure 77** of **Section 3.3.2.4**, where WEGDYN-specific assumptions are described.

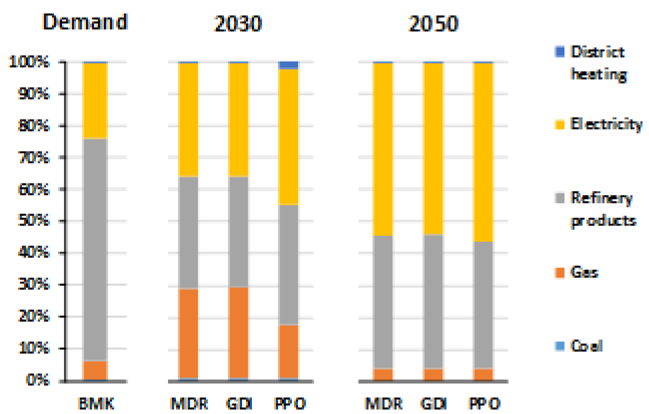


Figure 81. Structure of Greek system demand in the benchmark (bmk) year 2011 of WEGDYN and across storylines for 2030 and 2050; note that gas and refinery product demand by 2050 are almost climate neutral synthetic sources and green hydrogen.

3.3.2.10. Case combinations in BSAM simulations for the Reference scenario of SENTINEL

Table 57 shows how the different cases presented in **Sections 3.3.2.2** and **3.3.2.9** are combined in BSAM simulations.

Table 57. BSAM scenario runs for the Reference (“**RF**”) scenario of the National case study.

Year	BSAM Simulation Case	Demand Case	VRES Case	Thermal and Hydro Case	Storage Case
2030	“IPTO-Baseline”	“IPTO-Baseline”	“IPTO-Baseline”	“IPTO-Baseline”	“IPTO-Baseline”
	“IPTO-Green Deal”	“IPTO-Baseline”	“IPTO-Green Deal”	“IPTO-Baseline”	“IPTO-Baseline”
	“EMMA-BSAM”	“IPTO-Baseline”	“EMMA”	“EMMA”	“EMMA”
2050	“IPTO-Baseline”	“IPTO-Baseline”	“IPTO-Baseline”	“IPTO-Baseline”	“IPTO-Baseline”
	“EMMA-BSAM”	“IPTO-Baseline”	“EMMA”	“EMMA”	“EMMA”

Interconnections are assumed to follow the projections of **Table 47** in all the BSAM simulation cases.

3.3.3. Energy resource planning with a focus on security of supply

3.3.3.1. ***GR-C1****: Investigating evolutions of the Greek electricity generation mix*

Contributing models: EMMA and BSAM

Research Questions' Overview

Currently, electricity markets worldwide are transitioning to cleaner energy. This is especially the case in Greece, where not only the market structure has recently changed to the harmonised EU target model, but also the RES share in gross final electricity consumption is projected to reach 61-64% by 2030 and exceed 74%[13] by 2050 according to the Greek NECP (Greek Ministry of Environment and Energy, 2019) and LTS50 (Greek Ministry of Environment and Energy, 2020) documents. The plan for the transition of the Greek power system is described as a procedure of two parallel phases. According to the NECP, all currently operating lignite-fired power plants will be shut-down by 2023, while according to the most recent "National Resource Adequacy Assessment" report published by IPTO (2021), all currently operating lignite-fired units should be shut down by 2021, and the newly built "Ptolemaida V" lignite plant, which will start operating in 2023, will be shut down by 2024, to re-enter the market in 2026 as a natural gas unit.

Yet, according to consultation with experts from the Greek PPC, the operation of some lignite units may be extended (e.g., extension of the "Ptolemaida V" plant until 2028, etc.) due to the recent energy crisis and geopolitical developments. This will result in the capacity mix presented in **Table 44** (**Section 3.3.2.2**). In parallel, significant increases in VRES shares are foreseen, as shown in **Table 43** (**Section 3.3.2.2**). The intentions to phase out lignite plants and incrementally increase the installed RES capacity, eliminates the options for generation of electricity with domestic fossil-fuel resources and positions natural gas, which is imported in Greece, as an intermediate fuel for power generation. Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ3:** What is the expected contribution of fossil fuels ("**RF_2030**": 19.13 TWh, "**RF_2050**": 9 TWh, "**RE_2050**": 0 TWh, "**P2X_2050**": 0 TWh) and RES GUs in the electricity mix in view of the "delignitisation" (i.e., lignite phase-out) of the Greek power system?
- **RQ5:** How much thermal ("**RF_2030**": 6.91 GW, "**RF_2050**": 6.5 GW, "**RE_2050**": 4.9 GW, "**P2X_2050**": 7.9 GW) and RES ("**RF_2030**": 19 GW, "**RF_2050**": 26.5 GW, "**RE_2050**": 33.9 GW, "**P2X_2050**": 63.8 GW) capacity is needed in 2030 and 2050 to meet demand requirements with an aim to maximize RES penetration?
- **RQ10:** What is the contribution of interconnections ("**RF_2030**": 4.58 TWh, "**RF_2050**": 3.4 TWh, "**RE_2050**": 3.4TWh, "**P2X_2050**": 3.4 TWh) to the operation of the Greek power system under high RES penetration? What level of power independency can be achieved?

Results and Discussion

RF Scenario (BSAM results)

In terms of expected contribution of fossil fuel-fired and RES GUs to the electricity mix (**RQ3**), the results of BSAM indicate significant differentiations between the current situation (i.e., 2021) and the simulated years

[13] According to the Greek LTS50 (Greek Ministry of Environment and Energy, 2020) the remaining share is covered by biomass and gas units which are equipped with CCS, and by gas units without CCS only to a small degree (i.e., about 9% in 2050) .

(2030 and 2050). Furthermore, differences among the "**EMMA-BSAM**" and "**IPTO**" cases (namely "**IPTO-Baseline**" and "**IPTO-Green Deal**") are observed as well. **Table 58** presents the simulated generation outputs for all the different cases under study, accompanied by the real generation mix of 2021, as obtained from the ENTSO-e Transparency Platform[14]. For each generating technology, its share to the domestic generation mix is presented in **Figure 82**.

Table 58. Electricity mix[15] of 2021 and BSAM simulations for 2030 and 2050.

Case	Unit	Current Situation	IPTO-Baseline	IPTO-Green Deal	EMMA-BSAM	IPTO-Baseline	EMMA-BSAM
Year		2021	2030	2030	2030	2050	2050
Lignite	TWh	5.45	0	0	0	0	0
Nat.Gas	TWh	21.30	24.81	21.82	21.20	28.43	17.00
Hydro[16]	TWh	5.27	3.23	2.36	2.00	3.56	2.61
PV	TWh	4.39	10.66	13.79	9.63	16.21	57.98
Wind	TWh	9.01	15.09	16.17	31.18	23.16	30.70
Imports	TWh	7.49	3.54	3.25	2.89	8.95	5.79

As it can be observed in **Table 58**, there is no lignite-fired electricity generation in the years 2030 and 2050, as all the lignite-fired GUs are closed by 2030. In 2021, the lignite-fired generation held a small share of about 10% in the generation mix, which is fully replaced by fossil gas, RES and electricity imports in the following years. According to **Figure 82**, natural gas GUs hold the largest share in all IPTO cases and simulation years (compared to each generating technology, separately) with at least 35% contribution in the electricity mix. In fact, in the "**IPTO-Baseline**" case, the share of natural gas increases by about 3% in 2030 compared to the current situation, reaching an electricity mix contribution equal to 43.3%. This is not surprising, since the natural gas units along with the increased contribution of PV and WT units, which increase their contribution to the electricity mix by almost 20% until 2030, hedge the shutdown of the lignite-fired GUs.

[14] https://transparency.entsoe.eu

[15] Please note that the increased generation from wind and solar resources in the EMMA-BSAM case for 2030 is due to the inclusion of demand for electricity exports equal to 9.43TWh in 2030 and 32.16TWh in 2050, which is an output of simulations with the Calliope model.

[16] Please note that hydro generation in BSAM is random, based on BSAM-assumed precipitation levels.

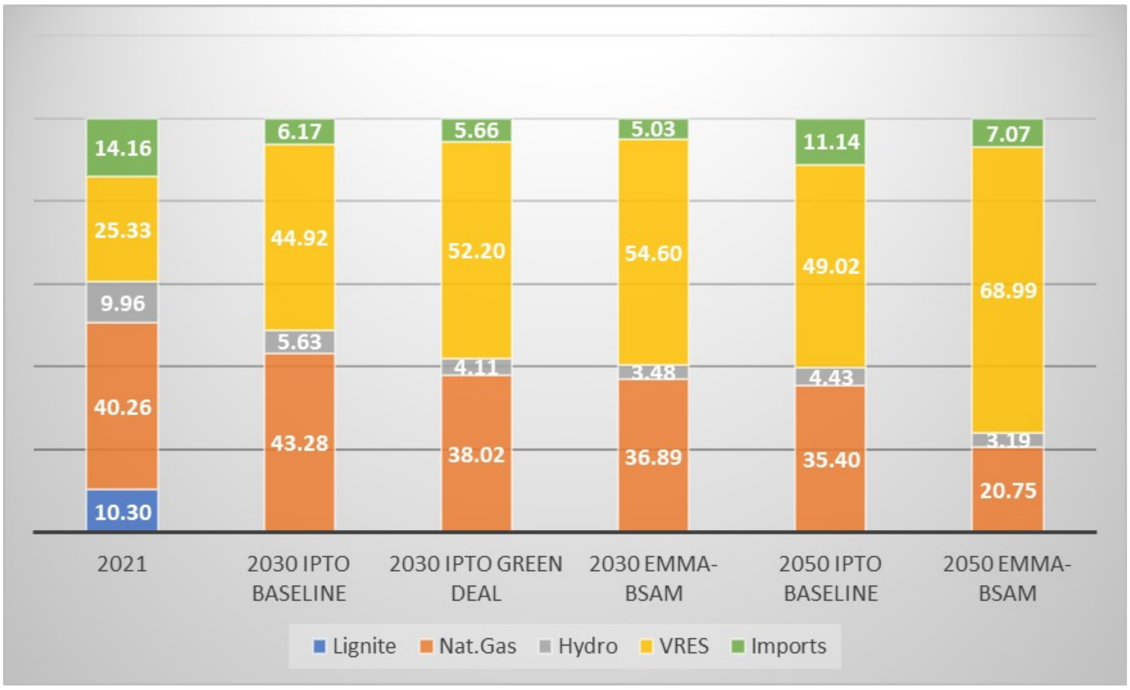


Figure 82. Electricity mix shares of 2021 and BSAM simulations for 2030 and 2050.

Further increase in RES-generation capacity until 2050 (**Table 43**) and the shutdown of some natural gas capacity (**Table 44**), leads to a reduction of natural gas contribution to 35.4% of the total electricity generation. However, in terms of energy output, the electricity generated from natural gas units increases between 2030 and 2050, due to the increasing electricity demand that is observed during the same period (**Table 45**). This also implies that despite the high penetration of VRES in 2050 (i.e., about 49% by 2050), natural gas still holds a large share in the generation mix and will still be a significant fuel to cover electrical needs.

This picture is significantly influenced with higher VRES capacity. Specifically, in the "**IPTO-Green Deal**" case for 2030, which features 8.2% more VRES capacity with reference to the "**IPTO-Baseline**" case, we can see that the energy output of natural gas units is reduced by 3 TWh, a 5.3% reduction in the contribution of natural gas in the electricity mix. More evidently, in the "**EMMA-BSAM**" case which features at least 54.6% VRES penetration, electricity generation from gas is reduced by 3.61 TWh in 2030 and is 40% less in 2050 compared to the "**IPTO-Baseline**" case, respectively. Such a finding suggests that part of the gas-fired GUs can be displaced by market-driven RES buildout. However, to achieve the ambition for a nearly net-zero emission power sector, significant mitigation of electricity generation from natural gas should be realised. This ambition is even more relevant today, in light of the Russian aggression against the Ukraine. In fact, the EU discusses to phase out fossil oil and gas from Russia, pushing in parallel for a "massive" expansion of RES (Euractiv, 2022).

With regards to the RES share (VRES plus hydro) in total electricity generation, we find that the "**IPTO-Baseline**" case results in 50.6% share of RES penetration to the electricity mix in 2030 and 53.5% in 2050, while the "**IPTO-Green Deal**" case leads to 56.3% in 2030, highlighting the importance of increased RES capacity in reaching ambitious RES penetration targets. It should be noted that these shares are lower than those foreseen in the reference scenarios in the NECP and LTS50 documents, i.e., 61.6% RES in total electricity generation in 2030 and ~84% RES in total electricity generation in 2050. Even in the "**EMMA-BSAM**" case which features more RES capacity, we find a 58.08% share of RES penetration to the electricity mix in 2030 and 72.2% in 2050. Taking these insights into consideration, either more stringent emission targets, or higher RES targets would be required in order to offset even more the need for electricity generated with natural gas, reducing both its contribution to the electricity mix, as well as its total energy output.

In terms of imports (**RQ10**), it can be noted that they are inversely proportional to the level of VRES penetration. Specifically, from 2021 until 2030, when the VRES capacity increases by 105% in the "**IPTO-Baseline**" case, the electricity imports' contribution to the electricity mix is reduced to less than half of the contribution they held in 2021. Accordingly, with higher VRES capacities, as in the "**IPTO-Green Deal**" and "**EMMA-BSAM**" cases, the contribution of imports is further reduced compared to 2021. However, from 2030 until 2050, a significant increase is observed in the "**IPTO-Baseline**" case. This could be attributed on the one side to the shutdown of some natural gas GUs after 2035 and the forecasted increase in electricity demand in 2050 compared to 2030 (**Table 44** and **Table 45**), and on the other side, to the projections for increased natural gas and emission allowance prices (**Table 42**) which make generation from natural gas units less competitive due to high operational costs. Also, from 2030 until 2050, the increase in RES share (i.e., about 4%) is not sufficient to cover the decrease in natural gas production (about 8%).

When accounting for natural gas generation and electricity imports together, it can be concluded that the electricity generation in Greece remains highly dependent on imported commodities (either gas or electricity directly) by more than 43% in all the IPTO cases. This is because Greece does not possess any other dispatchable domestic fuels apart from lignite, therefore, after the shutdown of lignite units, the only domestic fuels rely on weather and water availability. Specifically, according to BSAM simulations for the "**IPTO-Baseline**" case, the sum of electricity imports and natural gas-fired electricity tend to slowly decrease from about 55% in 2021, to about 49% in 2030 and about 47% in 2050. This means that despite significant efforts for increase in the VRES capacity (more than 200% from 2021 to 2050), the increased electricity demand allows for a reduction of electricity dependency by only 8%, making Greece being dependent on natural gas and electricity imports from other countries for almost half of its electricity demand even in 30 years ahead. This highlights once more the need for more disruptive VRES capacity targets towards higher self-sufficiency levels for electricity supply in Greece. This is supported by results from the "**EMMA-BSAM**" case, in which the share of electricity derived from imported commodities are around 41.9% and 27.8% of the total electricity produced in 2030 and 2050, respectively. The highly decreased dependency for imported electricity and gas that results from this case is one of the key benefits that come with investing in clean energy technologies. The **PPO** storyline of the QTDIAN modelling toolbox provides a potential pathway with high local renewable energy production, reducing import demand substantially (**Section 3.3.2.9**). However, this would require policy schemes in place that enable people to produce their own electricity such as via solar PV.

Renewable Energy (RE) and P2X scenario (EMMA results)

As a consequence of the lignite phase-out and the set emission target (**Table 41**), there is no "typical" baseload technology in any of the scenarios (**Figure 84**). The contribution of non-RES is limited to CCGTs, OCGTs, and coal units, all equipped with CCS. The supply from these technologies is negligible in the "**RE_2050**" and "**P2X_2050**" scenarios (**Figure 83**). In all scenarios, including the "**RF**" one, most of the needed energy supply is produced from intermittent RES, whose market-driven buildout is fostered by their projected investment cost reduction.

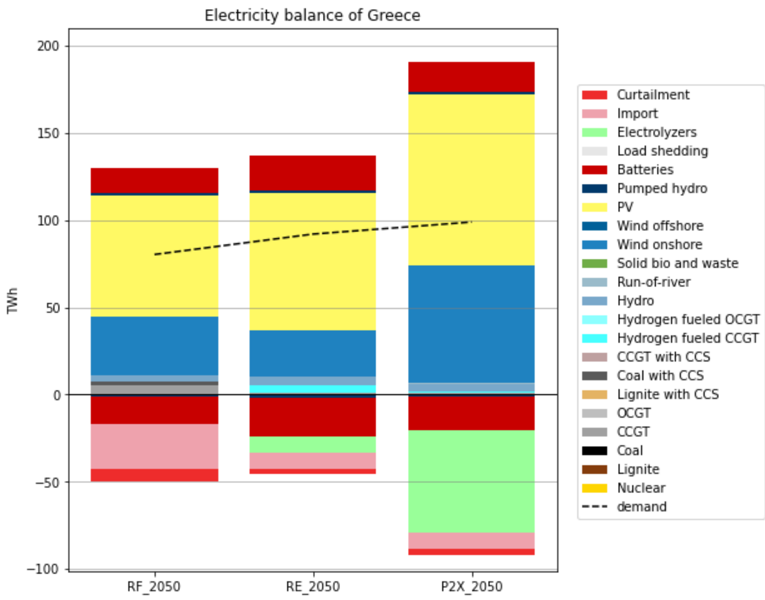


Figure 83. Electricity balance of the 2050 scenarios in Greece. "**RF_2050**": 2050 Reference scenario; "**RE_2050**": 2050 Renewable Electricity scenario; "**P2X_2050**": 2050 Power-to-X scenario.

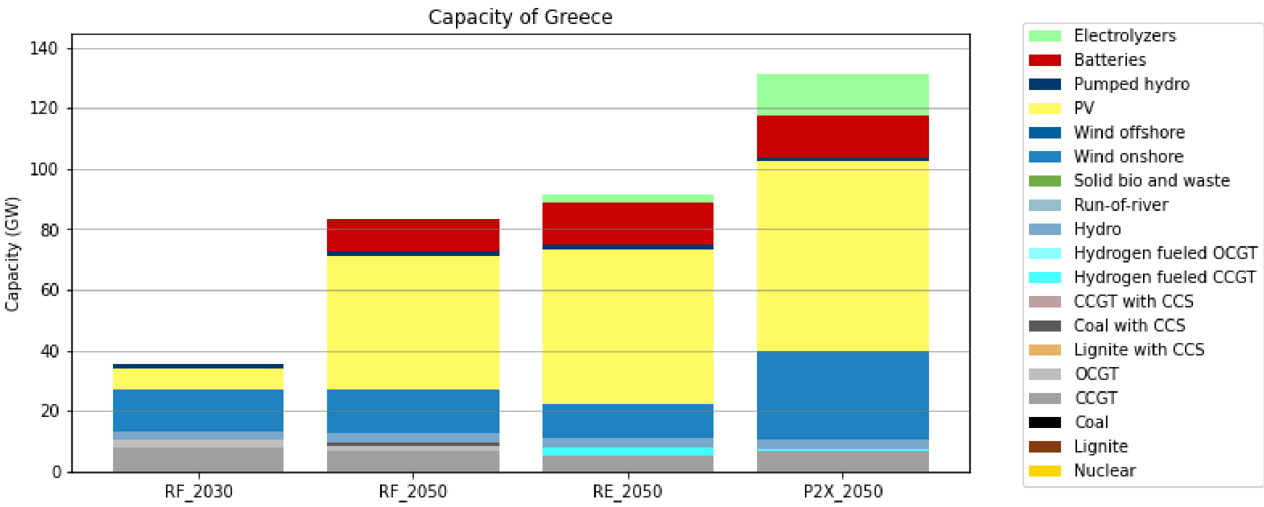


Figure 84. Capacity mix by scenario in the Greek electricity market. "**RF_2050**": 2050 Reference scenario; "**RE_2050**": 2050 Renewable Electricity scenario; "**P2X_2050**": 2050 Power-to-X scenario.

In terms of (intermittent) renewable integration, in the "**RE_2050**" scenario, a lower CO_2 cap is achieved with additional supply from renewable technologies (including H_2-fuelled GUs), although the share of intermittent renewables alone slightly decreases compared to the "**RF_2050**" scenario. In the "**RE_2050**" and "**P2X_2050**" scenarios, two factors facilitate the integration of high shares of intermittent renewables whilst reducing curtailment (see cluster **GR-C6 (Section 3.3.4.2)** for further details about curtailment):

- The surplus electricity is used by electrolysers to produce H_2, which then can be used by H_2-fuelled GUs to produce electricity at a later point in time.
- The possibility of storing excess electricity with batteries (**Table 55**). This technology is especially useful for photovoltaic generation due to the short (daily) seasonality of their profile.

Finally, in the "**P2X_2050**" scenario, exogenous H_2 demand is introduced whilst a nearly zero emission budget remains. The result is a higher production from intermittent renewables (solar and onshore wind power) to operate the electrolysers. The exogenous hydrogen demand also lets the price of H_2 increase perceptibly (see cluster **GR-C4 (Section 3.3.3.4)**), pushing H_2-fueled CCGT out of the market.

*3.3.3.2. **GR-C2**: About the interaction between the EU emissions trading system and gas plants in 2030*

Contributing models: EMMA, BSAM and WEGDYN

Research Questions' Overview

Following the governmental plan for lignite phase-out until 2025, it has been criticised that too many advantages have been given to natural gas plants (Stavrakas et al., 2021). However, the rising emission allowance and natural gas prices as well as the increasing RES shares are expected to result in natural gas units becoming less and less competitive in the wholesale market (Greek Ministry of Environment and Energy, 2019), thus possibly turning new natural gas investments into stranded assets. Greek stakeholders referred to carbon pricing as a key policy option for mitigating electricity generation from natural gas (Stavrakas et al., 2021) .

There are two recent developments that may have a considerable impact on the future of gas: First, the decision by the EC to label some natural gas capacity as sustainable investment under the EU taxonomy might cause new investments in gas infrastructure (Simon, 2022). This decision happened despite the fact that methane emissions from natural gas systems are an important contributor to GHG emissions (Rutherford et al., 2021). A second development that will impact the future of gas in Europe is the Russian war against Ukraine. The war brought up the urge for Europe to rapidly reduce its gas dependence (Rosenow and Holl, 2022).

Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ2:** Should natural gas plants which will start operating after 2025 be shut down after 2035? And what is the time horizon of gas as an intermediate fuel towards decarbonisation, in financial terms?
- **RQ4:** Will the EU ETS carbon price policies be sustainable in 2030? Should other strategies be considered so that natural gas can be the intermediate fuel that period?

Results and Discussion

Electricity system

EMMA results: Dispatch and investments

Gas in 2030 contributes to the Greek power supply with 10.5 GW installed capacity and a yearly generation of 20 TWh (**Figure 85**). One quarter of gas capacities results from new investments. Its role decreases in 2050, totalling around 8.5 GW in the “**RF_2050**” scenario, 6 GW in the “**RE_2050**” scenario, and 7 GW in the “**P2X_2050**” scenario. In the “**RF_2050**” scenario, 2 GW are new-build capacities, whereas in the “**RE_2050**” and “**P2X_2050**” scenarios 1 GW is endogenously decommissioned in addition to the exogenous end-of-lifetime decommissioning. These capacities are partially replaced by H_2-fuelled technologies. This shift in the capacity mix is driven by the increasingly stringent CO_2 budgets. This constraint on emissions affects the system and reflects on the endogenous CO_2 price that is discussed below. Therefore, with relevance to **RQ2**, although gas units remain in 2050 because they provide firm capacity, they are characterised by a low load factor, especially when the CO_2 budget is stringent.

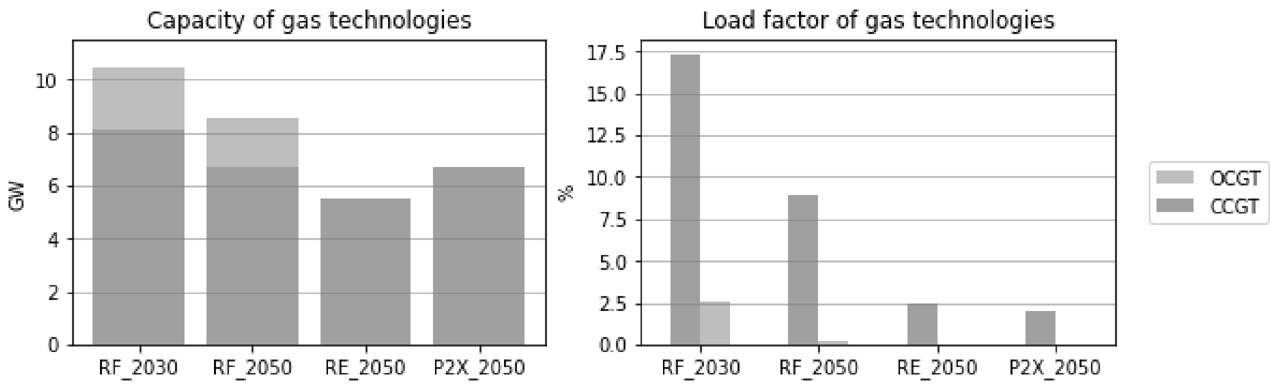


Figure 85. Capacity and load factor of gas-fired capacities, Open Cycle Gas Turbines (OCGT) + Combined Cycle Gas Turbines (CCGT). "**RF_2030**": 2030 Reference scenario; "**RF_2050**": 2050 Reference scenario; "**RE_2050**": 2050 Renewable Electricity scenario; "**P2X_2050**": 2050 Power-to-X scenario.

Regarding the sustainability of the EU ETS carbon price policies (**RQ4**), a fixed CO_2 budget (representing the national emission targets) as well as a CO_2 price floor (representing the EU ETS) are implemented. Consequently, the endogenous CO_2 shadow prices can be higher than the assumed EU ETS projections. The projected CO_2 price of 115 €/tonne in 2050 (**Table 42**) is sufficient to meet the emission targets in the "**RF_2050**" scenario. However, more ambitious targets appear to require a higher price (**Figure 86**). The endogenous prices in the "**RE_2050**" and "**P2X_2050**" scenarios increase to 210 and 343 €/tonne, respectively. These figures exceed the EU ETS price and indicate the need for complementary national policies in order to reach the national emission targets.

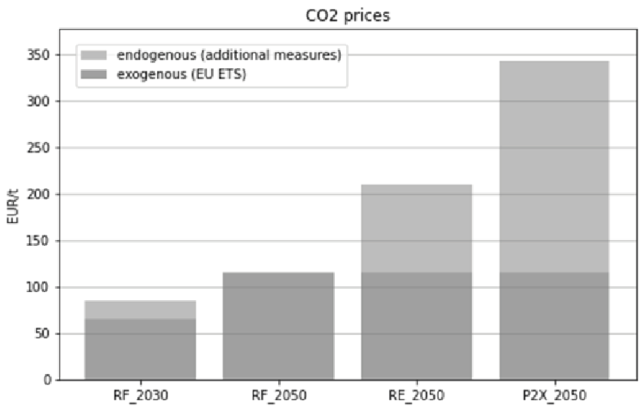


Figure 86. Endogenous emission allowance (CO_2) price divided into the exogenous EU Emissions Trading System (ETS) section and surplus which can be interpreted as additional measures. "**RF_2030**": 2030 Reference scenario; "**RF_2050**": 2050 Reference scenario; "**RE_2050**": 2050 Renewable Electricity scenario; "**P2X_2050**": 2050 Power-to-X scenario.

<u>BSAM results: Unit-specific deep dive</u>

During the current decade, new natural gas capacity is expected to be brought into market operation in Greece as shown in **Table 44**. Specifically, the new CCGT plant of Mytilineos Group will start operating in the second half of 2022, the fuel switch of the "Ptolemaida 5" lignite unit to gas is expected to be completed by 2028 and, a newly planned CCGT unit may enter the market by 2027 (IPTO, 2021). **Table 59** summarises the simulated electricity generation from these gas plants in the "**IPTO-Baseline**" and "**IPTO-Green Deal**" cases as presented in **Section 3.3.2.2**.

Table 59. Electricity generation from new natural gas plants (TWh).

Plant name	IPTO-Baseline (2030)		IPTO-Green Deal (2030)		IPTO-Baseline (2050)	
	TWh	Operational days	TWh	Operational days	TWh	Operational days
"Ptolemaida 5-ST"	0.75	204	0.87	224	5.30	325
"Mytilineos Group CCGT"	4.01	324	3.10	325	4.00	343
"New CCGT"	3.79	323	3.46	331	3.17	325

We observe that even though a transition to increasingly higher levels of RES penetration is planned (as shown in **Table 43**), the operation of the new gas plants is not expected to be disrupted by this occasion between 2030 and 2050. In fact, the "Ptolemaida 5" plant is expected to experience a significant increase in its contribution. This can be justified by the significant natural gas capacity which will be shut down after 2035 according to new "National Resource Adequacy Assessment" report of IPTO, as shown in **Table 44**, giving the opportunity to the rest of the units to contribute more. Specifically, for the case of the "Ptolemaida 5" plant, simulations showed that in 2030 it operated only for 204 days, while the other newly built units operated from more than 320 days. This is due to the fact that "Ptolemaida 5" in 2030 is a retrofitted steam turbine unit (fuel change from lignite to natural gas by 2028), making it less cost competitive with respect to its combined cycle competitors. However, when the planned shutdown of natural gas capacity is materialised post 2035, the role of "Ptolemaida 5" in 2050 is transformed to a base unit, with 325 days of operation throughout the year.

The above observations can also be validated by the profit per unit of supplied electricity for all new gas plants (i.e., their profits divided by their electricity generation), which is expected to increase in 2050 compared to 2030, as presented in **Table 60**. This finding highlights the profit-maximising behaviour of agents who tend to pass the projected increases in carbon and natural gas prices (**Table 42**) to the electricity wholesale market, in order to maintain their profitability level. An interesting case is again the "Ptolemaida 5" plant, which due to its low utilisation rate in 2030, it entails high costs for cold starts. Furthermore, the power plant has the opportunity to bid as a peaker, with a slightly increased profit margin compared to its competitors. When its utilisation rate is increased in 2050, the profit margin as well as the profit per unit of supplied electricity is levelled with that of the other newly built units.

Table 60. Profit per unit of supplied electricity of newly built natural gas plants (million €/TWh).

Plant name	IPTO-Baseline (2030)	IPTO-Green Deal (2030)	IPTO-Baseline (2050)
"Ptolemaida 5-ST"	60.10	56.46	118.97
"Mytilineos Group CCGT"	29.40	32.09	135.99
"New CCGT"	29.63	30.47	143.51

The only case where the contribution of natural gas plants, in terms of energy produced, is expected to decline, is when more ambitious VRES capacity expansions are planned (**Table 43**), as suggested by the "**IPTO-Green Deal**" case. In such a case the profit per unit of supplied electricity is affected based on the plants' utilisation rate. Specifically, for the "Ptolemaida 5" plant in 2030, which had a low utilisation rate in the "**IPTO-Baseline**" case, its profit per unit of supplied electricity is reduced in the "**IPTO-Green Deal**" case due to less cold start occurrences following its higher utilisation rate and a decreased profit margin to avoid being left out of the market due to competition. On the contrary, the "Mytilineos Group CCGT" and "New CCGT" plants, whose energy output is reduced in the "**IPTO-Green Deal**" case, causes their profit per unit of supplied electricity to rise, due to slightly increased profit margins chosen by the power plants.

Based on the above and considering the overall contribution of natural gas to the electricity mix, as shown in cluster **GR-C1** (**Section 3.3.3.1)**, the new natural gas plants are not expected to be shut down due to profitability in the near future, under the assumptions of the "**RF**" scenarios. Thus, considering also their generation output as shown in **Section 3.3.3.1** the stranded asset scenario of newly built natural gas units is not expected to be materialised (**RQ2**). However, regarding the sustainability of the EU ETS carbon price policies (**RQ4**), it can be surmised that alone they are not enough to drastically limit the contribution of natural gas to the electricity mix. Instead, they pose a challenge to just transition, since the cost is passed to the wholesale market and subsequently to the consumers. Therefore, carbon pricing should be combined with appropriate instruments (e.g., economic incentives, regulations, targets, etc.) for VRES capacity expansion, possibly by utilising the economic income for the financing of new VRES projects. A more holistic approach for the assessment of the EU ETS instrument is presented in following paragraphs.

Economy-wide effects

<u>WEGDYN results</u>

Regarding the due date of natural gas plants operation (**RQ2**), WEGDYN can neither inform whether specific technologies should be banned, or shut-down, nor about the timing of such a decision, but it can deliver the economy-wide effects if a certain development path is pursued that excludes certain technological options. Hence, this modelling approach generates alternatives and provides a discussion supporting input. We here adopt the model ensemble QCW (**Section 3.3.2.9**) applied to the "**Climate Neutrality**" scenario of the European CS and report resulting energy systems and corresponding economy-wide effects for Greece (results for EU27+ can be found in the European CS section (**Section 3.1**)). The three storylines imply energy system configurations that already operate almost without gas-fired generation by 2030 (**Figure 79**). By 2050, all three storylines incorporate green H_2-fired electricity generation of less than 1 TWh in the Greek energy system. This shift away from any fossil-fired capacity does not only address the strong reduction requirements to fulfil Greece's contribution to climate mitigation objectives, but also the current reliance on fossil imports and connected insecurity of energy supply in the aftermath of the Russian invasion of Ukraine.

From an anthropogenic point of view, sustainability (**RQ4**) can be defined as the ability of humans to maintain a flourishing society at a certain rate or level. The interaction of individuals characterise the working of societies, the structure of this interaction that can be observed and measured in various ways. A particular analytical structure is the energy system, which is currently unsustainable due to a multitude of unintended and harmful side effects connected to it. CO_2 emissions are one side effect and economic theory suggests that pricing emissions is one possible policy instrument to qualify individuals to make reasonable decisions of production and consumption based on price signals that also reflect the social costs of carbon. This also means that decision makers are primarily interested in sustainable structures (purpose) but also in measures and instruments (the means) that bring about structural change. Measures and instruments can be qualified by their contribution to achieve societal objectives, inter alia in terms of efficiency (i.e., lowest cost), effectiveness (i.e. assuring goal attainment) or various other criteria (e.g. resilience, distributional effects or synergies with other societal objectives such as air quality). However, it is unusual to assess the sustainability of instruments rather than to assess the sustainability of a system.

In **Figure 87** we report the level of CO_2 allowance prices prevailing in a trading system across EU27+ regions (and thus effective for Greece) covering all the domestic industrial process and combustion-based CO_2 emissions ("production-based principle"). The trading system is set up to reduce the absolute amount of allowances such to achieve the 2030 and 2050 emission targets of the European "**Climate Neutrality**" scenarios. Hence, the resulting allowance prices are consistent with energy system configurations connected to the three storylines, i.e., **MDR**, **GDI** and **PPO**. Consequently, remaining emissions by 2050 are lower than available allowances and prices drop to zero. At the aggregate level, absolute decoupling of emissions and GDP is achieved in all storylines with, compared to **MDR**, beneficial effects in the **GDI** storyline in 2030 and worse effects otherwise. We discuss the sources of these differences in cluster **GR-C4 (Section 3.3.3.4)**. Note that the 2050 GDP levels are smaller than in 2030 (but still larger than in 2020), because additional revenues from EU ETS boost the national GDP in 2030, but not anymore in 2050 (due to climate-neutrality by then).

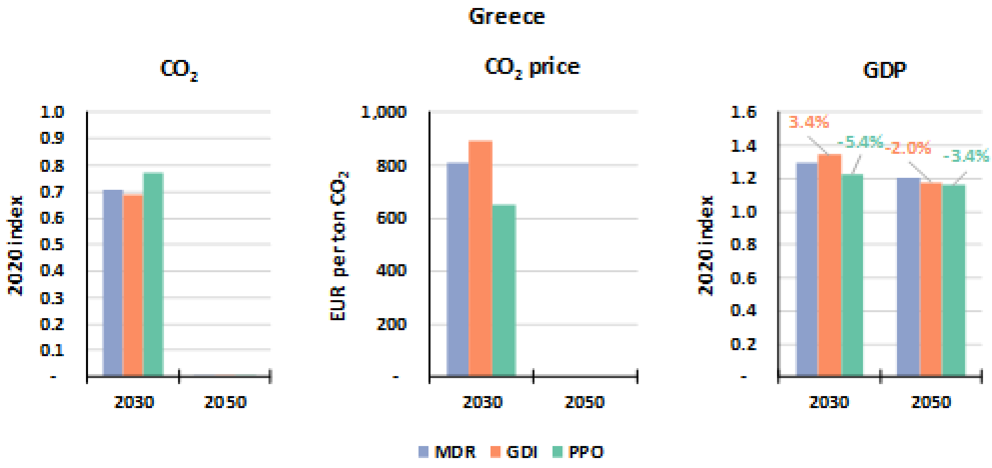


Figure 87. Greek Carbon Dioxide (CO_2) emission reductions (left), EU allowance prices (middle) and Gross Domestic Product (GDP) effects (right) across the three storylines under study; bar labels indicate the percentage difference to the GDP level of the Market-driven (MDR) storyline (blue bars) in the respective period.

RQ4 implicitly asks for a mix of policy options that goes beyond (existing) pricing instruments. On the basis of the current modelling results, one insight concerns the possibility and eventually materialising benefits of integrating emissions into a continental trading scheme, which are currently un-, or insufficiently covered by pricing instruments (sectors either subject to but currently exempt from the EU ETS or unpriced/regulated under the effort sharing decision). Additional coverage potential for Greece is small because more than 90% of energy-related emissions are already priced[17]. However, the leverage potential is still moderate to high because only one third of emissions is priced with effective rates above 60 EUR per tonne of CO_2 and increasing the scope of the EU ETS is shown in (Landis et al., 2021) to have the potential for generating further substantial efficiency gains. On top, using the revenues of carbon pricing is an essential acceptance leverage, for instance, by using the additional funds to shape the energy system (green spending), or to ameliorate undesired distributional effects (climate dividend per capita payments; (Sommer et al., 2022)).

Further options refer to complementing non-pricing instruments. For instance, demand-side measures (e.g., improved standards for new buildings, stimulus for renovation of the existing building stock, spatial planning “Fit for 55”, increased home office, product design and recycling, etc.) can potentially lower the required renewable energy in the first place. In addition, information campaigns and participatory processes can be used to integrate the needs of citizens in shaping local- to national-scale pathways, an instrument mostly reflected by the logic of the **PPO** storyline. The **MDR** storyline clearly shows economic benefits of electricity trade, which would require strengthened international cooperation and respective joint ventures necessitating accelerated approval processes of related transmission infrastructure. This acceleration raises legal questions

[17] https://www.oecd.org/tax/tax-policy/effective-carbon-rates-greece.pdf

about how to guarantee that the balancing with other societal objectives is not undermined (e.g., environmental quality, property rights, etc.). Finally, governments can establish coordination and discussion platforms to help identify potential national industry champions based on revealed technological and comparative trade advantages. This information can be the basis for directed fiscal impulses like green public procurement, or education and training programmes for green jobs, all of which the quantification of the **GDI** storyline does not explicitly cover.

A note on CO_2 pricing

While WEGDYN covers all EU27+ CO_2 emissions (ETS and non-ETS, combustion and industrial processes), EMMA and BSAM capture "only" combustion-based CO_2 emissions in the Greek electricity generation. Hence, all three applied models focus on different impact channels and a different emissions coverage on the CO_2 allowance market. Also note that the absolute values of the presented CO_2 prices are only indicative in the context of the variously modelled systems and implications for the real world must be interpreted with great care. For instance, CO_2 prices in WEGDYN rise to levels ten times higher than observed today in the ETS market, not only because the emissions coverage is assumed to increase to 100% of EU27+ CO_2 emissions, but also because other measures and instruments may not (yet) be implemented or be effective by 2030 (e.g., H_2-based steel, or a certain share of insulated buildings), which drives allowances prices up to keep the overall EU27+ region within the set emission reduction targets for 2030.

*3.3.3.3. **GR-C3**: Implications on the stability of the Greek power system operation*

Contributing models: BSAM

Research Questions' Overview

Large VRES penetration increases the planning complexity of the electricity system, since VRES units do not have the technical ability to contribute to direct electricity system reserves due to intermittency (Kontochristopoulos et al., 2021). Furthermore, the higher the VRES penetration, the higher the residual load volatility to be met by dispatchable power plants is (Stavrakas et al., 2021). As such, only dispatchable units (including stored energy and units operating with converted fuels) are considered capable for covering the electricity system reserve requirements. Among those units, fast and flexible power plants (i.e., plants that can quickly be brought online due to their low start-up time and do not need to remain online or offline for several hours owing to their low minimum uptime and downtime), such as hydroelectric and OCGT units, can provide flexible generation when power imbalances arise (Babatunde et al., 2020). Considering the above, in this section we answer the following RQ, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ6:** Can the gas-fired generating resources and imported electricity meet the demand (as presented in the cases of **Table 45**) and system reserve requirements in case of large VRES penetration? What would the role of fast and flexible units as system stabilisers be?

Results and Discussion

In BSAM, an "ideal" power plant is used in cases where demand and/or system reserve requirements cannot be met due to restrictions set by the operational constraints of GUs (e.g., minimum uptime, minimum downtime, etc.). This power plant has minimal operational constrains as well as high nominal capacity, which enables undisrupted simulations in BSAM, and can be viewed as an ideal electricity storage, always ready to supply electricity if it cannot otherwise be procured (Kontochristopoulos et al., 2021).

The utilisation rate of this "ideal" generator is used to answer the first part of **RQ6**. As shown in **Table 61**, the "ideal" power plant is not used at most simulated cases. This indicates that the solution of the Security Constrained Unit Commitment problem was feasible with the available generation portfolio, meaning that the demand and system reserve requirements were safely met with the generation portfolio presented in **Table 43**, **Table 44**, **Table 54,** and **Table 55**. Regarding 2050 in the "**EMMA-BSAM**" case, the use of the "ideal generator" indicates that with very high RES capacities, instances where the conventional units will not be able to cover the residual demand due to operational constraints might appear. In such a case, flexible generators would be required, yet with low contribution compared to the total generation (**Section 3.3.3.1**).

Table 61. Electricity generation from the "ideal" power plant (TWh).

Scenario	"IPTO-Baseline"	"IPTO-Green Deal"	"EMMA-BSAM"
2030	0	0	0
2050	0	N/A	0.25

This triggers the answering of **RQ6** and the role of fast and flexible units. Simulations showed that their overall contribution to the electricity mix remains low compared to the total demand that needs to be met. Specifically, hydroelectric plants generate electricity covering only 3.5-5.6% and 3.2-4.4% of electricity demand in 2030 and 2050 respectively, as shown in **Figure 88** (see also **Figure 82** in cluster **GR-C1** (**Section 3.3.3.1**)). However, this is mainly driven by the availability of water resources, rather than market needs.

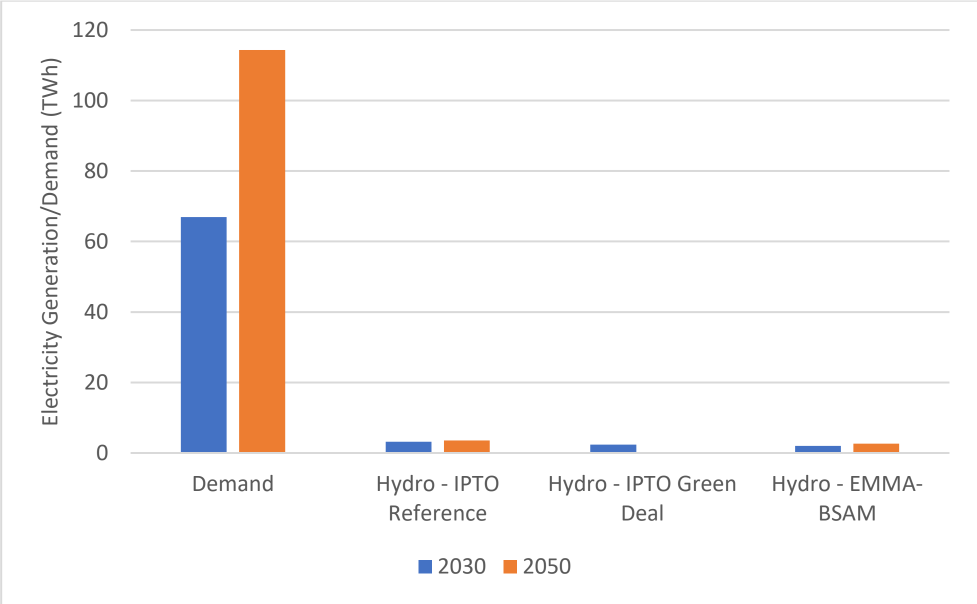


Figure 88. Electricity generation from hydroelectric generators.

OCGT generators were modelled only for 2030 in the "**IPTO-Baseline**" and the "**IPTO-Green Deal**" cases, as all three existing power plants of this technology will be shut down in 2035. For the "**EMMA-BSAM**" **case**, OCGT capacity is modelled both in 2030 and 2050, following the EMMA simulation results of **Table 55**. In all the IPTO cases, the contribution from this technology is negligible (i.e., 0.01%), so that they are barely visible in **Figure 89**. However, in the "**EMMA-BSAM**" case this contribution reaches 0.2% in 2030 and 1.73% in 2050, which validates that fast and flexible units are utilised when the residual demand is low and volatile. In any case, OCGT units seem to provide firm capacity, therefore operate for very few hours throughout the year, during which, they do not produce much energy.

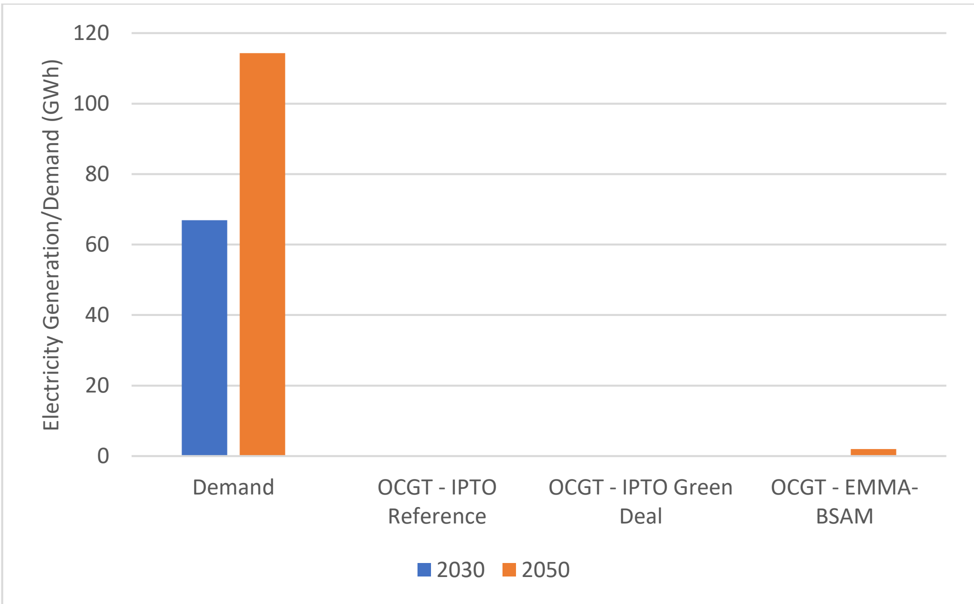


Figure 89. Electricity generation from Open Cycle Gas Turbines (OCGT) plants.

Considering the above, we can conclude that both in the medium- and long-term, fast and flexible generators are not expected to have a critical contribution to system stability. However, their availability could be of use in disruptive events of high VRES generation and consequent high residual demand. In this case, an inquiry that arises and could be evaluated by further research is how costly it is to keep those units active as insurance, even though their contribution is low.

*3.3.3.4. **GR-C4**: How does the changing supply mix affect prices and system costs?*

Contributing models: EMMA, WEGDYN and BSAM

Research Questions' Overview

Several studies project reduction in wholesale market prices as RES participation in the electricity mix grows (Peña and Rodríguez, 2019; Trujillo-Baute et al., 2018; Würzburg et al., 2013). With increasing RES penetration, the variable costs for electricity generation, reflected in the System Marginal Price (SMP), tend to diminish (Capros et al., 2018). Technological innovation can also contribute towards price reduction (van den Bergh and Savin, 2021) However, a recent study is seemingly in disagreement with this view, as it projects an increase in wholesale market prices (Koltsaklis et al., 2020), stemming from a high CO_2 emission cost projection (up to 84.3 €/tnCO_2 in 2030). Furthermore, during the COVID-19 pandemic, the decreased electricity consumption and a higher share of RES led to a lower price level on the day-ahead market compared to previous years (Halbrügge et al., 2021). Other externalities, such as the recent war between Russia and Ukraine, have affected the uncertainty of commodity availability, and as a consequence their prices. Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ8:** How will the decommissioned lignite-fired capacity and the added RES capacity affect the cost of emissions and the SMP? What is the necessary total investment cost for the added RES capacity and what is the total system cost? What are the specific economy-wide effects??

Results and Discussion

RF scenario (BSAM results)

Regarding the effect of the decommissioned lignite-fired capacity and the added RES capacity on the SMP, we observe that in the "**IPTO-Baseline**" case the average SMP (**Table 62**) is expected to increase by about 62% in 2030 compared to the pre-energy crisis period (2020) and to be double by 2050 compared to 2030 (105% increase). The increasing trends in SMP can be attributed to the rising EU ETS carbon prices and natural gas prices, which increase the variable costs of conventional power plants, as well as their profit margin window (**Table 63**). In 2030, the average SMP of the "**IPTO-Green Deal**" case is slightly lower (i.e., 3.9% decrease compared to the "**IPTO-Baseline**" **case** and 56.4% increase compared to 2020) because, even if the EU ETS carbon prices and natural gas prices are assumed to be the same for the two cases (**Table 42**), the penetration of VRES technology is higher in the "**IPTO-Green Deal**" case, thus contributing to a reduction of the average SMP. This is even more evident in the "**EMMA-BSAM**" case, where prices rise by a smaller percentage in 2030 compared to 2020 (i.e., 52.4%) and significantly fall in 2050 (almost by 19% compared to the "**IPTO-Baseline**" case) due to the increased displacement of the gas-fired electricity generation with production from VRES technologies. Since more VRES electricity is produced, the residual demand to be covered becomes much less, thus the competition between natural gas units increases, reducing their bids to remain cost competitive.

Table 62. Average system marginal price (€/MWh) per case.

Scenario	"IPTO-Baseline"	"IPTO-Green Deal"	"EMMA-BSAM"
2020 (historical)	50.80	50.80	50.80
2030	82.67	79.46	77.41
2050	169.25	N/A	137.70

Specifically, even though agents bid with the same average profit margin of 20% across cases, in the "**2050 IPTO-Baseline**" case, the most frequent non-zero[18] profit margin bid is 35%, whereas in the "**EMMA-BSAM**" case, agents' most frequent non-zero bid is 10% profit margin. This is also evident from the aggregated profit of all power plants across scenarios (**Table 63**) which follows a decreasing trend with increasing VRES shares. This indicates that if the share of VRES sharply increases, it could in fact be a driver for cost reduction, additional to the drop that is expected due to the low operational costs of VRES. However, if the clean energy narrative does not prevail, then the decisive factor for limiting the SMP will be the pricing mechanisms in place that define the evolution of natural gas and carbon prices.

Table 63. Profit of all agents aggregated in billion €.

Scenario	"IPTO-Baseline"	"IPTO-Green Deal"	"EMMA-BSAM"
2030	1.00	0.88	0.78
2050	4.50	N/A	2.69

An interesting finding is that the frequency of electricity price change is much higher for all the cases in 2050 compared to those in 2030. This means that the hours within a year where the SMP is almost stable, are more frequent in 2030 than in 2050 as shown in **Figure 90.** This fact can be correlated with the increased residual demand in 2050, which causes generators to regularly alter their bid levels.

[18] Bid at zero profit margin is possible when a plant needs to keep generating to comply with its operational constraints.

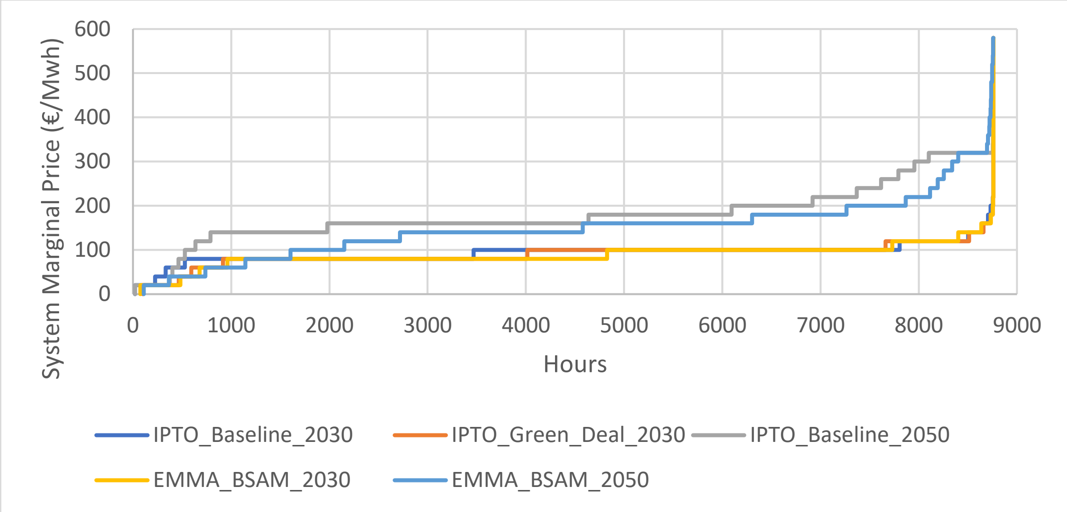


Figure 90. Price duration curve.

With regards to the cost of emissions (**Figure 91.**), the results follow the same trend to the SMP. In the "**IPTO-Baseline**" case the average cost of emissions is expected to become more than double by 2050 compared to 2030 (108% increase). This is owing to the EU ETS carbon prices and the thermal generating resources not being displaced by VRE. In this respect, in the "**IPTO-Green Deal**" case, we observe a drop by 11.8% in the total emissions cost compared to the "**IPTO-Baseline**" case in 2030, due to lower power generation from natural gas units. This downward trend also follows the "**EMMA-BSAM**" cases, where in 2030 we observe a cost reduction of 14.8% in comparison to the "**IPTO-Baseline**" case. In 2050, the cost of carbon emissions increases by 55.8% compared to 2030 in the "**EMMA-BSAM**" case. This cost increase is owing to the increase of carbon prices by 43.7% from 2030 until 2050 (**Table 42**). The Greek NECP mentions that the revenue from the auctioning of emissions allowances will be allocated in development actions such as development of clean forms of energy (including energy communities), energy efficiency improvements in public/private buildings, supporting energy crops, promoting circular economy, etc (Greek Ministry of Environment and Energy, 2019). Therefore, the CO_2 income follows the market needs, with lower revenues stemming from higher RES penetration, but higher revenues stemming from increasing natural gas and CO_2 prices, where more effort on RES expansion is needed to limit the cost of electricity generation.

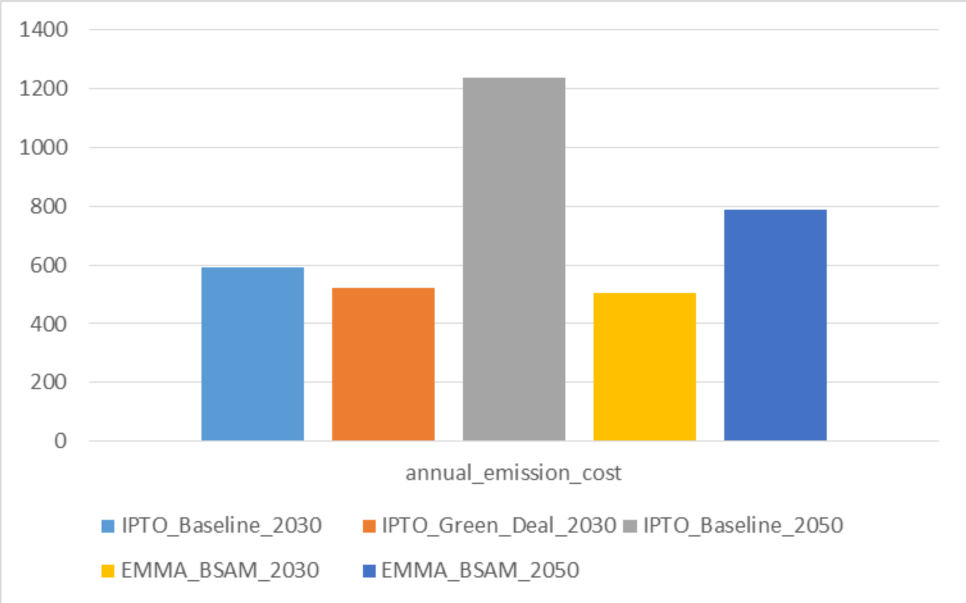


Figure 91. Annual cost of carbon emissions (million €).

Scenario-comparative simulations (EMMA results)

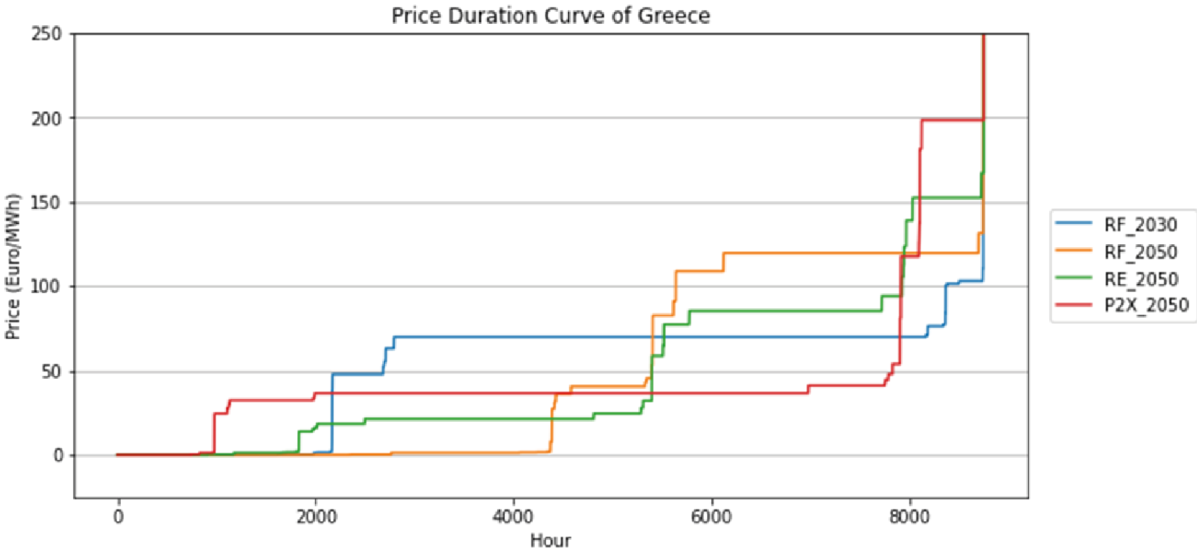


Figure 92. Price duration curve of the Greek electricity market by scenario. For readability, the upper limit of the y-axis is limited to 250 €/MWh. Highest prices reach 3000 €/MWh according to the price cap specified by the respective market regulation.

The absence of cheap baseload generation drives the electricity price from 45 €/MWh in 2020 (actual) to 60 €/MWh in 2030 (simulated)[19]. Nevertheless, this is not conclusively imputable to the regulatory phase out of lignite capacities. In fact, the projected CO_2 price (**Figure 86** in cluster **GR-C2** (**Section 3.3.3.2**)) would

[19] The average marginal price under the assumptions of BSAM (without VRES price setting hours) is 76 €/MWh in the **RF 2030** scenario and, hence, comparable to their results.

cause electricity generation from lignite units to be costly. For example, an EU ETS price of 65 €/tCO_2 increases the marginal cost of lignite by about 56 €/$MWh_{electric}$ (42% efficiency and 0.36 t/$MWh_{thermal}$). The electricity price is projected to decrease after 2030 despite the increasing electricity demand because investment costs for intermittent renewables decrease as well. According to **Figure 93,** price effects depend on the scenario-specific technology mix:

- **2030 Reference scenario ("RF_2030"):** The price distribution of the Greek electricity market is mostly characterised by around 2400 hours of nearly zero electricity prices, and a plateau at around 72 €/MWh. In hours with nearly zero prices intermittent renewable sources are price setting, whereas 72 €/MWh reflects the variable generation costs of CCGT units.
- **2050 Reference scenario ("RF_2050"):** Intermittent renewable sources are setting the price about half the year. After that, two plateaus emerge at 40 €/MWh (about 1000 hours) and 119 €/MWh (around 3000 hours). These prices reflect the marginal generation costs of coal power plants with CCS and CCGT, respectively.
- **2050 Renewable Electricity scenario ("RE_2050"):** Renewables are less frequently price setting, mainly due to the additional flexibility provided by electrolysers and storage technologies. Most of the year the system is solely supplied by renewable sources where intermittent renewables, electrolysers and H_2-fired CCGT set the price. Finally, natural gas-fired CCGT provide peak-load capacity when the power demand is highest at just over 150 €/MWh.
- **2050 Power-to-X scenario ("P2X_2050"):** The price jumps are caused by the same technologies as in the "**RE_2050**" scenario. Nevertheless, the additional H_2 demand that characterises the "**P2X_2050**" scenario causes the H_2 price and the endogenous CO_2 price to be higher. Therefore, not only are electrolysers more often price setting, but they also buy electricity at higher prices. Because of the higher CO_2 and H_2 prices (**Figure 93**) the marginal cost of natural gas and H_2-fired units increases.

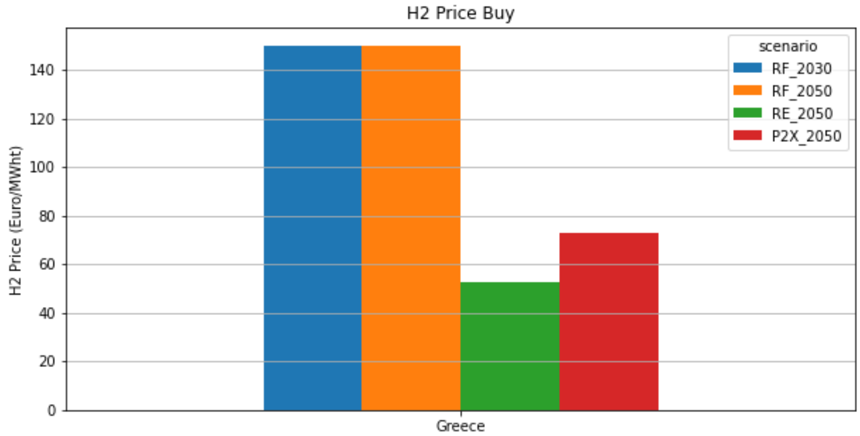


Figure 93. Hydrogen prices (incl. 20 EUR/MWh markup for storage and transportation) in Greece of all the scenarios under study. Because the there is no domestic hydrogen production in the Reference scenario, the modelled price equals the assumed import price.

Total investment costs in intermittent renewable technologies, for the "**RF_2030**" scenario, are 1.37 bn € and increase to 2.3 bn € in the "**RF_2050**" scenario. Compared to the "**RF_2050**" scenario, investment costs in the "**RE_2050**" scenario remain constant, whereas they increase in the "**P2X_2050**" scenario by 64%. In all the scenarios the portion of intermittent renewable investment costs to the total investment cost ranges from 87% to 95%. The scenario differences in terms of power sector emissions and carbon prices are discussed in cluster **GR-C2** (**Section 3.3.3.2**).

Economy-wide effects (WEGDYN results)

Applying the QCW model ensemble results in emission allowance prices as shown in **Figure 87** of the cluster **GR-C2** (**Section 3.3.3.2**). The corresponding merit order in the Greek electricity system is shown in **Figure 80,** and resulting effects on GDP in **Figure 87** of the **GR-C2** section. Here we focus on the components of GDP, which are shown in **Figure 94**. Compared to the **MDR** storyline, the positive GDP effect in 2030 for the **GDI** storyline is driven by current consumption (public and private), due to productivity gains in the electricity market raising private income (**Figure 95**) and additional earnings from the CO_2 certificate market (**Figure 96**). The same drivers have an opposite sign for the 2050 effects in the **GDI** storyline. Both 2030 and 2050 GDP effects are negative in the **PPO** storyline compared to the **MDR** storyline. Lower earnings from allowance prices lead to lower public consumption, and larger energy system unit-cost reflect productivity losses negatively affecting private income available for consumption. There are small employment gains in the **GDI** storyline relative to the **MDR** storyline, but exclusively for skilled workers in 2030 (**Figure 97)**. The **PPO** storyline implies larger unemployment compared to the **MDR** storyline but for unskilled workers in 2030.

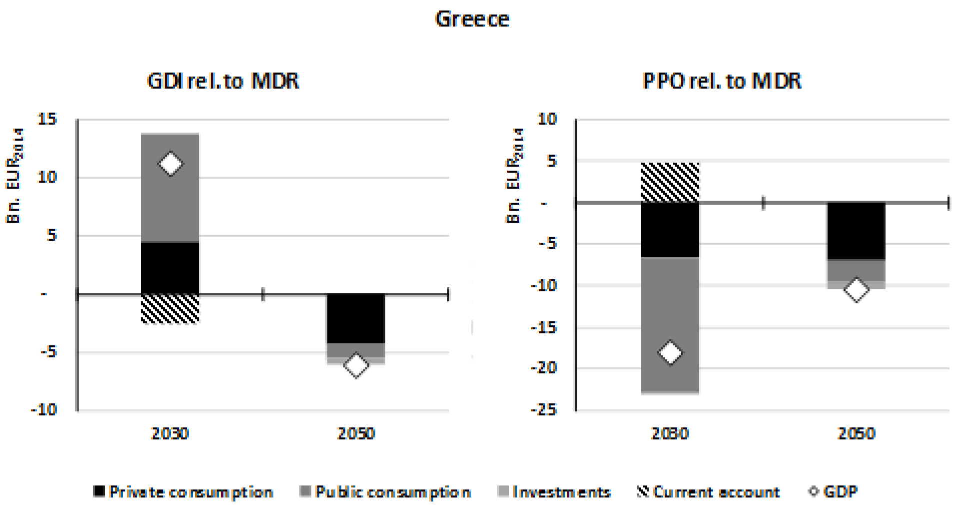


Figure 94. Greece private income decomposition for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

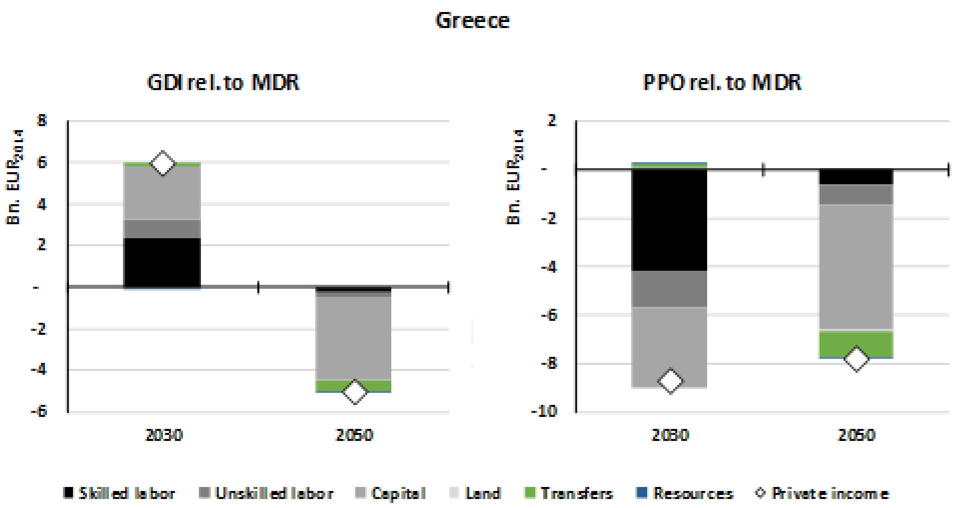


Figure 95. Greece public budget decomposition for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

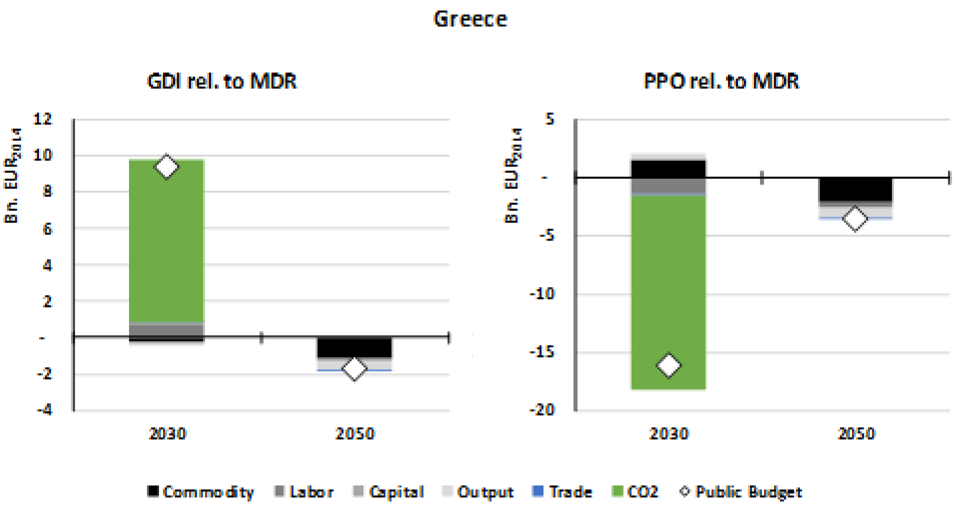


Figure 96. Greece percentage-point change in unemployment rate for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

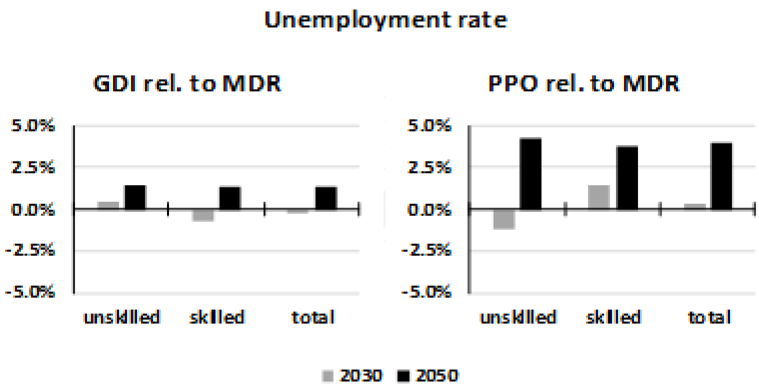


Figure 97. Greece percentage-point change in unemployment rate for the Government-directed (GDI, left) and People Powered (PPO, right) storylines relative to the Market-driven (MDR) storyline.

Figure 98 summarises the effects on Greek welfare and its negative relationship to average energy system costs (LCOE), both dimensions relative to the **MDR** storyline. Higher unit costs imply larger welfare losses, which emphasises the economic benefit of transmission for the Greek economy present in the **MDR** storyline especially in the long run and the climate neutral future by 2050. Only the **GDI** storyline leads to medium term welfare gains induced by additional CO_2 market revenues for the Greek government and temporary productivity gains in the electricity system. Note, however, that the aggregate EU27+ welfare effect of the **PPO** storyline is positive (see European CS section (**Section 3.1**)), which means that European transfer mechanisms would in principle allow for Pareto improvements.

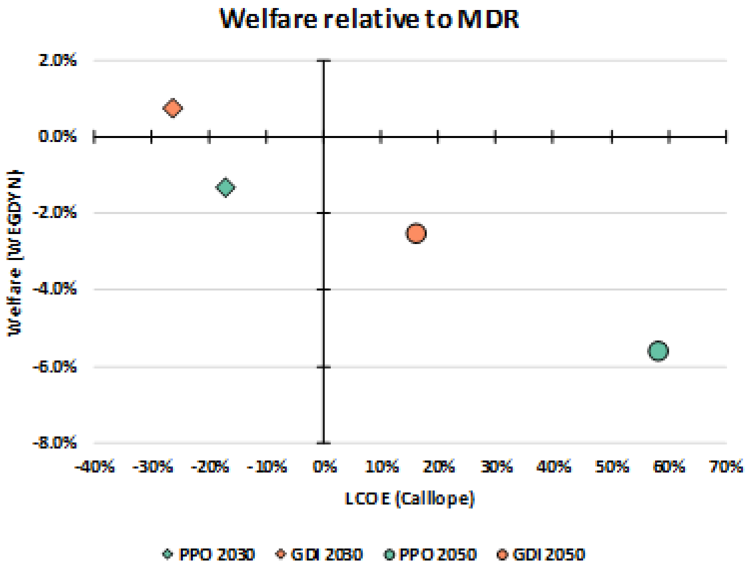


Figure 98. Greece welfare (ordinate; WEGDYN) and Levelized Costs of Energy (LCOE; abscissa; Calliope) relative to the MDR storyline.

3.3.4. Distributed generation, storage & curtailment

*3.3.4.1. **GR-C5**: About the role of intermittent renewables and storage*

Contributing models: EnergyPLAN, and EMMA

Research Questions' Overview

In the case of high RES penetration in the electricity system, storage systems are needed (Nanaki and Xydis, 2018) to manage VRES generation. Storage systems could help absorb more RES electricity, enabling RES, which have high intermittency (Tröndle et al., 2019) to become the main source of energy (Greek Ministry of Environment and Energy, 2019). Considering the above, in this section we answer the following RQ, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ13:** How much RES capacity and storage (“**RE_2050**”: 22.4 TWh (8.5 GW), “**P2X_2050**”: 42.4 TWh (28.1 GW)) are needed to reach a 100% renewable energy electricity mix (“**RE_2050**” and “**P2X_2050**” scenarios) without excessive curtailment? How does RES capacity relate to RES generation and storage needs? What is the cost of each additional percent of RES generation injected to the system?
- **RQ22:** What are the energy and power storage needs considering the reserve capacity requirements in a RES-based Greek interconnected system?

Results and Discussion

Besides VRES and storage options, the main flexibility in the EnergyPLAN scenario comes from power stations using gas and biomass. These can in principle be replaced with interconnection to other countries, but this is not investigated in the scenario. Furthermore, DH and cooling are included to lower electricity demands and increase the energy efficiency of the scenario. H_2 is used to create e-fuels for transport and industry and to provide flexibility.

According to EMMA simulations, in the "**RF_2030**" scenario, the dispatchable generation stock mostly consists of CCGT, OCGT, hydro reservoir, and run-of-river, and a small proportion of CCGT with CCS. In the "**RF_2050**" scenario CCGT with CCS is exchanged for coal with CCS. As shown in **Table 64,** onshore wind and PV provide the main proportion of generation in the "**RE_2050**" and "**P2X_2050**" scenarios. Only a small portion is produced by other dispatchable plants, which contain natural gas-powered plants.

Table 64. System buildouts across scenarios and models.

		EnergyPlan ("Climate Neutrality 2050")	**EMMA ("RE_2050")**	**EMMA ("P2X_ 2050")**
Wind onshore	Capacity [GW]	17.5	11.1	28.8
	Generation [TWh]	38.51	26.1	67.6
Wind Offshore	Capacity [GW]	5	0	0
	Generation [TWh]	14.47	0	0
PV	Capacity [GW]	18.3	50.7	62.7
	Generation [TWh]	34.51	79.1	97.9
Batteries	(Discharging) Capacity [GW]	3	14.3	13.5
	Volume [TWh]	0.01	20.5	17.7
PHS	(Discharging) Capacity [GW]	1	1.5	1.5
	Volume [TWh]	0.01	1.2	0.9
Other dispatchable generation	Capacity [GW]	14.5	1.2	1.2
	Generation [TWh]	18.30		
System	Curtailment [% of demand]	1.5	2.76	3.48
	Final electricity consumption [TWh]	114.9	137.3	190.9

*3.3.4.2. **GR-C6:** Investigating variable renewable energy sources penetration and curtailment issues in Greece*

Contributing models: BSAM and EMMA

Research Questions' Overview

With increasing VRES shares, when the system's safe operation limits are expected to be violated, a portion of VRES-generated electricity needs to be curtailed. While curtailment is a proven method for managing excess VRES generation (Solomon et al., 2019), and is possible to help reducing total system costs (Brouwer et al., 2016), it entails financial burdens for producers who do not utilise the full potential of their systems thus should not be applied extensively (Michas et al., 2019). In fact, according to the EU regulation 2019/943 on the internal market for electricity (European Parliament and the Council, 2019), the annual VRES curtailment must not exceed the limit of 5% (system limit). Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ18:** With the achievement of the VRES capacities presented in the cases of **Table 43** and **Table 54** (i.e., IPTO resource adequacy assessment projections and EMMA-BSAM simulations), what is the expected level of curtailment without storage technologies?
- **RQ17:** What is the maximum RES penetration (defined as system limit) that could be accommodated within the Greek electricity system with acceptable levels of curtailment? Curtailment should not surpass the 5% threshold, according to the EU regulation.
- **RQ20:** What is the optimal wind/PV ratio to achieve maximum RES penetration with low curtailment?

Results and Discussion

RF Scenario (BSAM results)

To answer the above set of RQs with BSAM, the scenarios presented in **Table 57** were run, but without any storage capacity. In terms of curtailment (**RQ18**), simulations suggest that both the total VRES capacity as well as the proportion of WT and PV installations with respect to the total VRES capacity have an impact on the electricity that is curtailed, as shown in **Table 65**.

Table 65. Annual curtailment levels without battery storage capacity[20].

Year	Scenario	Case	PV generation (%)	WT generation (%)	Curtailment (%)
2021	Current situation	-	8.18	16.80	0
2030	"RF"	"IPTO-Baseline"	18.59	26.32	0.19
		"IPTO-Green Deal"	23.55	28.06	2.85
		"EMMA-BSAM"	14.08	46.28	2.88
2050		"IPTO-Baseline"	20.14	28.83	0.53
		"IPTO-Green Deal"	-	-	-
		"EMMA-BSAM"	42.34	26.41	20.59

The increase in VRES capacity (**Table 43)** between the "**IPTO-Baseline**" and "**IPTO-Green Deal**" cases for 2030 (about 21%), leads to a significant increase in VRES penetration equal to 6.7%, surpassing the resulting 2050 VRES penetration levels of the "**IPTO-Baseline**" case, but with an accompanied increase in curtailment, equal to 2.66%. However, when this capacity increase is more than doubled in 2030 in the "**EMMA-BSAM**" case (**Table 54**), an additional 8.75% increase in RES penetration is observed compared to the "**IPTO-Green Deal**" case, but with curtailment remaining almost the same. This is because in the **"IPTO-**

[20] Please note that the increased generation from wind and solar resources in the EMMA-BSAM case for 2030 is due to the inclusion of demand for electricity exports equal to 9.43TWh in 2030 and 32.16TWh in 2050, which is an output of simulations with the Calliope model.

Baseline" and **"IPTO-Green Deal**" cases the VRES capacity mix features slightly more PV capacity, which have generation peaks during the noon and are idling during the night. On the contrary, the "**EMMA-BSAM**" case for 2030 features WT as the dominant technology, which have a more evenly distributed generation profile, therefore the curtailment is reduced due to better matching of supply and demand.

This picture is highly different in 2050, where the VRES capacity increase between the **"IPTO-Baseline**" and "**EMMA-BSAM**" cases of about 175%, achieves RES penetration equal to about 69%, but with an astonishing percentage of curtailed energy, equal to 20.59%. The high curtailment levels in the "**EMMA-BSAM**" case can be accounted to the very high preponderance of PV related to WT (i.e., 78.3% of PV capacity in the total VRES capacity), whose generation profile is characterised by high peaks during the noon hours, which may lead large shares of renewable electricity not being able to be matched with demand, if no storage exists. This implies that to reach efficiently higher VRES shares, both the volume as well as the distribution of VRES capacity needs to be taken into account. The answers to **RQ17** and **RQ20** in the following paragraphs shed more light on the effect of technology distribution.

To answer **RQ17**, a sensitivity analysis to the VRES growth was conducted for the "**IPTO-Baseline**" and "**IPTO-Green Deal**" cases in order to identify the level of VRES penetration, where the limit of 5% annual curtailment is breached. For this reason, VRES capacity was increasingly modelled in BSAM until the curtailment threshold was breached. The results of the conducted sensitivity analysis are presented in **Table 66.**

Table 66. Variable renewable energy sources (VRES) curtailment depending on the VRES penetration.

Year	Scenario	Case	Capacity increase (%)	PV (MW)	WT (MW)	VRES penetration (%)	Curtailment (%)
2030	"RF"	"IPTO-Baseline"	0	7342.0	6619.0	44.9	0.19
			20	8810.4	7942.8	52.9	1.94
			35	9911.7	8935.6	57.9	4.66
			36.5	10021.8	9034.9	58.4	4.97
			37	10058.5	9068.0	58.5	5.08
		"IPTO-Green Deal"	0	9763.0	7149.0	51.6	2.85
			5	10251.1	7506.5	53.5	4.02
			8.5	10592.9	7756.7	54.8	4.94
			10	10739.3	7863.9	55.3	5.35
2050	"RF"	"IPTO-Baseline"	0	11229.0	10171.0	49.0	0.53
			27	14260.8	12917.2	59.5	4.79
			27.5	14317.0	12968.0	59.7	4.91
			28	14373.1	13018.9	59.8	5.01

In the “**IPTO-Baseline**” case, the system limit is reached when 58.4-59.7% of the demand is met by VRES. Such a case would require 36.5% more VRES capacity in 2030 (i.e., 19056.7 MW) and 27.5% more VRES capacity in 2050 (i.e., 27105 MW), than the capacity mentioned in the IPTO’s “National Resource Adequacy Assessment” report (IPTO, 2021) and the LTS50 document (Greek Ministry of Environment and Energy, 2020) respectively. In the “**IPTO-Green Deal**” case, which features higher preponderance of PV in the VRES capacity mix compared to the “**IPTO-Baseline**” case (**Table 43**), the system’s limit is reached at a lower VRES penetration level, when 54.8% of the demand is met by VRES. Such a case would require a total of 18349.6 MW of VRES capacity, which corresponds to 8.5% increase with respect to the capacity mentioned in the Greek IPTO’s National Resource Adequacy Assessment report. From these results, it is obvious that lower PV shares in the VRES capacity mix result in higher VRES penetration levels without breaching the system’s curtailment limits and therefore can accommodate higher VRES capacity without the need for storage capacity in order to maintain curtailment within limits.

However, there is an optimal PV and WT distribution to the VRES capacity mix (**RQ20**), beyond which, an increase in WT share would result in less demand being met by VRES when the curtailment limits start to be breached. This configuration corresponds to 67.5% WT and 32.5% PV in the VRES capacity mix. The corresponding PV and WT capacities achieving VRES penetration at the curtailment limit in 2030 are shown in **Table 67**.

Table 67. Optimal Photovoltaic (PV) and Wind Turbine (WT) shares for maximisation of renewable energy sources penetration.

Year	PV (MW)	WT (MW)	VRES penetration (%)	Curtailment (%)
2030	6806	14135	69.9	4.89

It is obvious that the levels of VRES penetration are significantly increased before the curtailment level is breached. In fact, 11.5% and 15.1% more renewable electricity can be integrated to the electricity mix with such a configuration of PV and WT, compared to the “**IPTO-Baseline**” and “**IPTO-Green Deal**” cases for 2030. This is also validated by the results of the “**EMMA-BSAM**” case for 2030, where the VRES mix consists of almost 67% WT, and the VRES penetration level significantly increases compared to the other two cases as shown in **Table 65**. This highlights the importance to account for VRES capacity distribution in parallel with capacity expansion.

RE 2050 and P2X 2050 scenarios (EMMA results)

Figure 99 presents the simulated level of curtailment (**RQ18**) in all the simulated scenarios (i.e., “**RF_2030**”, “**RF_2050**”, “**RE_2050**”, and “**P2X_2050**”**),** considering the capacity needs calculated by EMMA (**Figure 84**), as well as the existence of storage and energy conversion technologies.

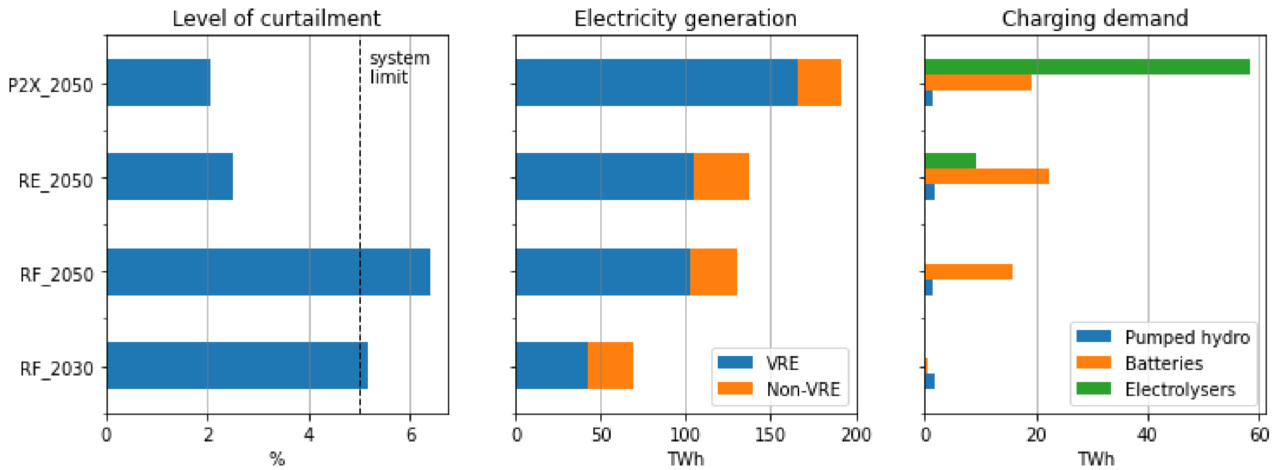


Figure 99. Level of curtailment with the EU regulation system's limit of 5%, electricity generation of VRE and non-VRE plants and yearly charging of storage technologies for all scenarios. "**RF_2030**": 2030 Reference scenario; "**RF_2050**": 2050 Reference scenario; "**RE_2050**": 2050 Renewable Electricity scenario; "**P2X_2050**": 2050 Power-to-X scenario.

VRE generation more than doubles from the "**RF_2030**" scenario (43.1 TWh) to the "**RF_2050**" scenario (103 TWh) and the level of curtailment[21] increases from 5.2% to 6.4%. Nevertheless, it decreases to about 2% in the "**RE_2050**" and "**P2X_2050**" scenario, although VRE generation remains constant compared to the "**RF_2050"** scenario ("**RF_2050**" scenario: 105.2 TWh) or even increases ("**P2X_2050**" scenario: 165.5 TWh).

The added flexibility in form of batteries and H_2 storage (electrolysers plus H_2-fired units) mitigates the necessity to curtail VRE generation. This becomes most apparent when comparing the "**RF_2050**" and "**RE_2050**" scenario. As the VRE generation remains constant and the cumulated charging of storage technologies (pumped hydro storage, batteries and electrolysers) doubles from the "**RF_2050**" (17 TWh) to the "**RE_2050**" scenario (33.1 TWh), the level of curtailment decreases by 4%.

The **P2X 2050** scenario is characterised by the addition of H_2 demand from the industry sector that can be met either by imports or by converting electricity to H_2. The level of curtailment decreases by 4.5% compared to the **RF** scenario while the VRE generation increases by 60.7 %. Although the exact quantification is driven by the assumption that hydrogen storage and transportation cost sum up to 20 €/MWh, results show that a flexible hydrogen demand can be used to substantially reduce curtailed electricity generation.

3.3.5. RES business models

*3.3.5.1. **GR-C7**: Assessing the performance of different policy schemes towards the adoption of small-scale photovoltaic systems under diverse socio-political storylines*

Contributing models: ATOM and QTDIAN

[21] Please note that differences in curtailment in BSAM and EMMA simulations exist due to diverging input assumptions, such as the demand and VRES generation profiles.

Research Questions' Overview

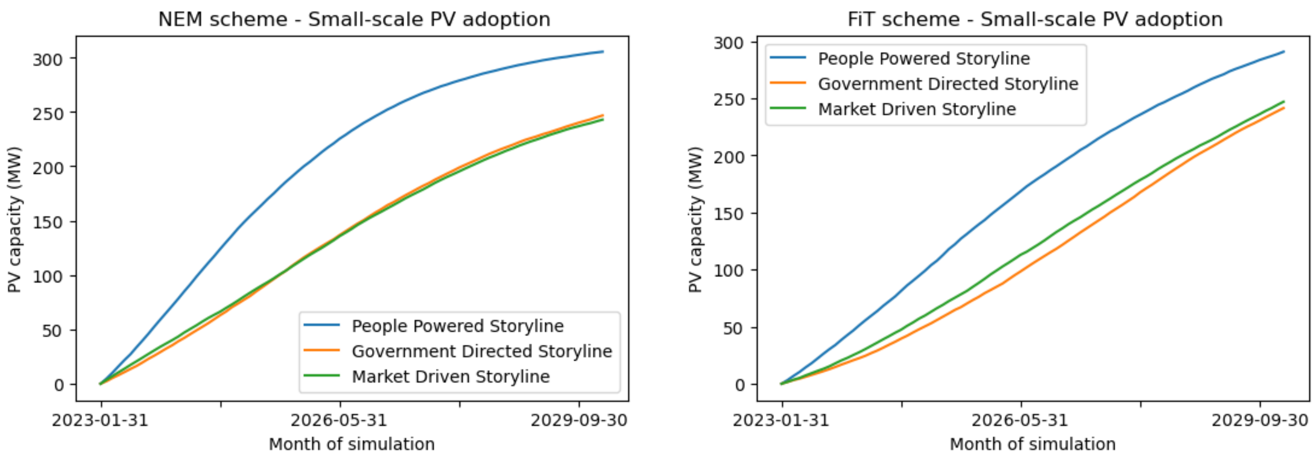
Recent policies, as the Renewable Energy Directive (2018/2001/EU) (European Parliament, 2018) and the Energy Union Strategy (COM/2015/080) (European Commission, 2015) emphasise the role of citizens as self-consumers (i.e., prosumers) and members of renewable energy communities to meet the EU goal of providing "Clean Energy for All Europeans" (European Commission, 2019c). Furthermore, the recently published "RePowerEU" energy strategy, which aims to disentangle Europe from Russian gas as soon as possible, while protecting citizens from painful, and increasing energy price shocks, places a particular emphasis on multiplying rooftop PV development through mandatory solar PV installations on new buildings (European Commission, 2022). On top of that, the earlier "Renovation Wave Strategy" emphasises that to fully reap the potential of a renovation wave, an integrated approach combining on-site renewable solutions and rooftop solar in particular is necessary (European Commission, 2020d). In this research cluster, we explore and quantify the diffusion of small-scale solar PV among Greek households as well as how the correlated behavioural uncertainty of prosumers could impact the diffusion course toward 2030, under different socio-political storylines for the currently operational policy schemes (**Section 3.3.2.9**).

We answer the following RQs:

- **RQN1:** How could different socio-political storylines impact the participation of citizens in the energy transition towards 2030 through the adoption of small-scale PV systems under the currently available policy schemes in Greece?
- **RQN2** How the different socio-political storylines could influence the citizens' behavioural uncertainty with regards to the diffusion of small-scale PV systems under the currently available policy schemes in Greece?

Results and Discussion

ATOM shows that the average expected PV capacity addition (**Figure 100**) from the current NEM scheme during the period 2023–2030 is estimated at around 300 MW under the **PPO** storyline and at around 250 MW for the **GDI** and **MDR** storylines. The average expected PV capacity addition from the current FiT scheme is estimated at around 280 MW under the **PPO** storyline and at about 240 MW for the **GDI** and **MDR** storylines, correspondingly.

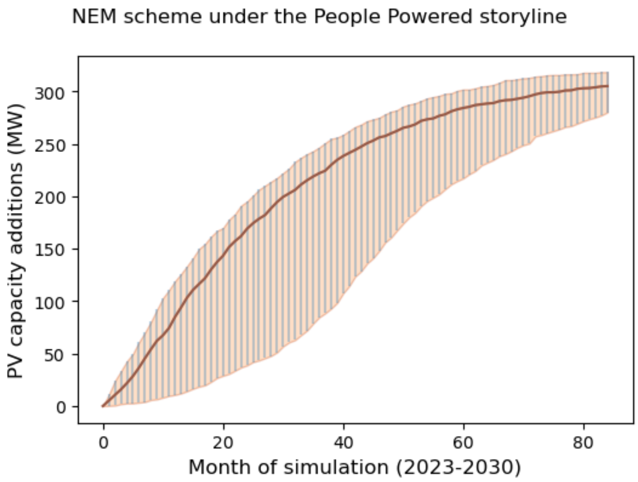


i. Net-Metering ii. Feed-in-Tariff

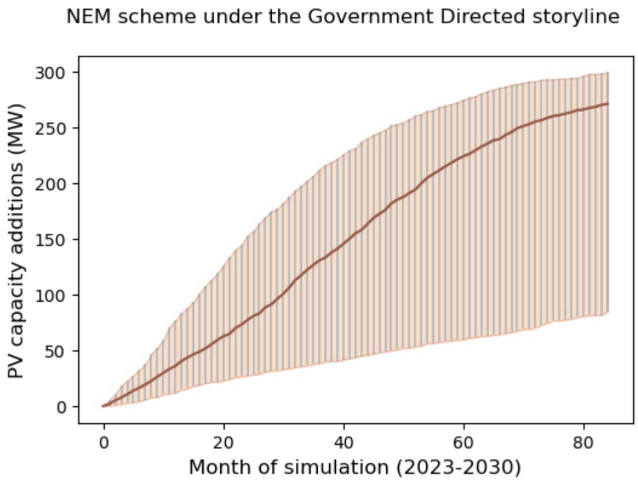
Figure 100. Average expected adoption of small-scale Photovoltaics (PV) systems under the different socio-political storylines for the existing operational schemes; **i.** Net-Metering (NEM) and **ii.** Feed-in Tariff (FiT).

Considering that the currently installed capacity of small-scale PV in Greece is 352 MW, a combination of both support schemes, preferably under the **PPO** storyline, is necessary to reach a level of aggregated adoption close to the target of 1 GW by 2030. It should be pointed out that the NEM and FiT schemes aim to target different audiences. On the one hand, the NEM scheme is more suitable for citizens/households that are occupants of their self-owned houses, as the produced electricity is deducted from the consumed electricity, while no compensation mechanism is prescribed for the excess electricity after the final settlement of the three year netting period. On the other hand, FiT is a fixed payment whose value is decoupled from the market conditions and citizen's/households' consumption patterns, and, thus, it could be more suitable for houses that are not self-occupied, or seasonally inhabited. Furthermore, as presented in **Table 56** the "initial beliefs" parameter, which is mostly influenced by the expected annual income, is notably higher for the NEM scheme. This is a result of the calibration phase, as the existing tariff in Greece is 87 €/MWh, while the competitive electricity consumption tariffs and other regulated charges under the current most common residential tariff (i.e., "G1" tariff) in Greece are 245 €/MWh, which is almost 3 times higher than the tariff offered under the FiT scheme.

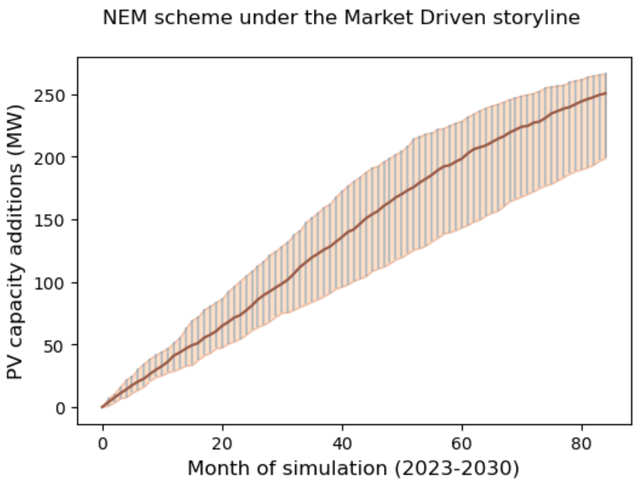
Under the **PPO** storyline, an interesting finding is that even for the group of risk averse agent, aleatoric uncertainty gap between the willing to invest and risk-averse scenarios narrows after the 40th month (April of 2026) of simulation (Figure 101), indicating that the initial high willingness to participate in the energy system pays a key role in the successful roll-out of a policy scheme that promotes prosumerism. This means that even though the NEM scheme has not yet achieved the expected diffusion in Greece, a radical change in people's behavioural profiles and a stronger promotion of a more decentralised power generation system, such as via information campaigns, could result to significant uptake of small-scale PV under the NEM scheme. Furthermore, our results show that, even though the **MDR** and **GDI** storylines result to approximately the same PV capacity addition, under the **MDR** storyline, the NEM scheme is more robust in terms of its effectiveness by decreasing behavioural uncertainty related to the agents' decision-making process. This is mainly due to the rise in electricity prices in Greece, which result in higher profitability of investing in small-scale PV under the NEM scheme.



(a) People Powered (PPO) storyline



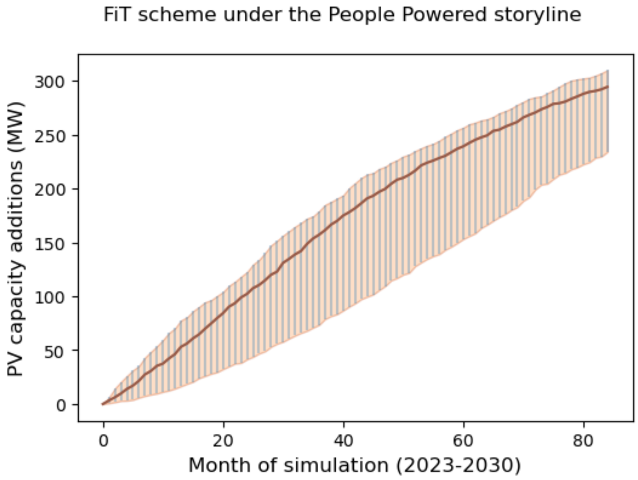
(b) Government Directed (GDI) storyline



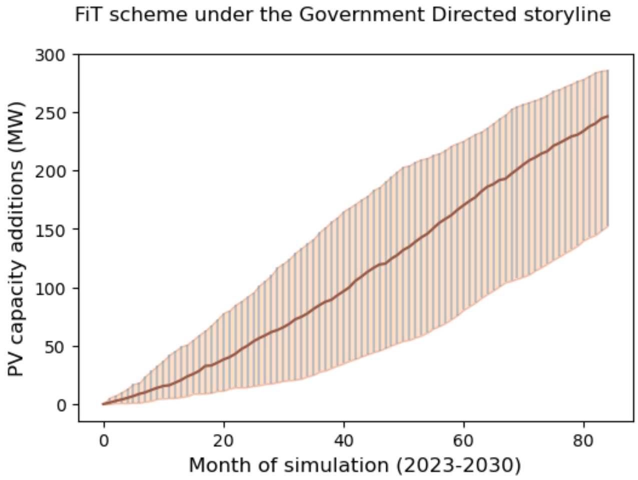
(c) Market Driven (MDR) storyline

Figure 101. Simulation results on the Photovoltaics (PV) capacity addition expected from the existing Net-Metering (NEM) scheme in Greece over the period 2023–2030 under the different socio-political storylines explored. The brown curve represents the average expected adoption, while upper and lower bounds represent adoption trends for willing to invest (i.e., optimistic scenarios) and risk-averse consumers (pessimistic scenarios), respectively.

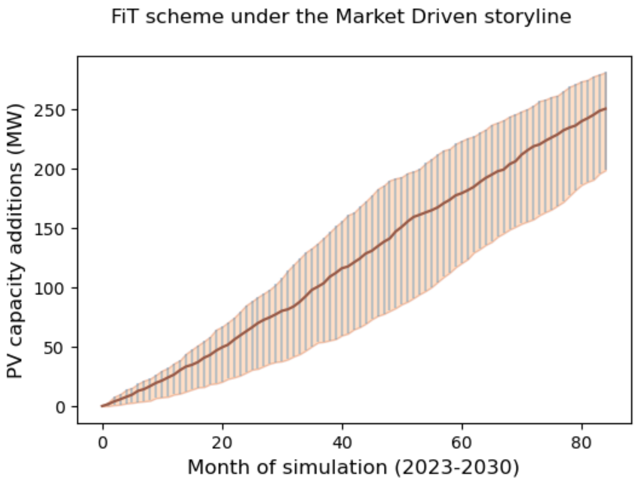
Regarding the FiT scheme (**Figure 102**), we observe that the behavioural uncertainty under the **PPO** and **MDR** storylines follows a similar course and results to similar uncertainty gap. However, the average expected PV addition is about 40MW higher in the **PPO** scenario. This is attributed to the fact that investing in the FiT scheme is considered as an investment opportunity totally disconnected from the consumption patterns of the agents and the concepts of prosumerism and energy citizenship. Therefore, even in the **PPO** storyline the profitability of the investment is the factor that mainly drives agents' decisions. Results also indicate that under the **GDI** storyline the behavioural uncertainty is almost two times higher than under the two other storylines.



i. People Powered (PPO) storyline



ii. Government Directed (GDI) storyline



iii. Market Driven (MDR) storyline

Figure 102. Simulation results on the Photovoltaics (PV) capacity addition expected from the existing Feed-in Tariff (FiT) scheme in Greece over the period 2023–2030 under the different socio-political storylines explored. The brown curve represents the average expected adoption, while upper and lower bounds represent adoption trends for willing to invest (i.e., optimistic scenarios) and risk-averse consumers (pessimistic scenarios), respectively.

3.3.6. Direct and indirect electrification & energy efficiency

*3.3.6.1. **GR-C8**: Direct and indirect electrification and energy efficiency in transport*

Contributing models: DESSTINEE and EnergyPLAN

Research Questions' Overview

Road transport electrification is expected to play a significant role to enable the decarbonisation of this final energy use, whilst leading to higher yearly and hourly power usage which may alter the shape and amplitude of load curves. DESSTINEE projects final electricity consumption for road transport will range between 30 and 42 PJ in 2050 in the "**RE_2050**" and "**P2X_2050**" scenarios, respectively. Electrification rates will vary according to vehicle category, due to the technical and long travel distance feasibility of battery electric units.

Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ28:** What are the additional electricity consumption patterns resulting from the electrification of the transport sector ("**RF_2030**": 278,254 EVs, "**RF_2050**": 6,029,000 EVs, "**RE_2050**": 8,011,000 EVs, "**P2X_2050**": 7,607,000 EVs)? How could "smart charging" (e.g., charging overnight, etc.) influence these patterns?
- **RQ34:** What is the role of indirect electrification in the fuel basket for road transport?
- **RQ35:** Could heavy goods vehicles be effectively decarbonised using H_2?

Results and Discussion

EnergyPLAN results

For the electrification of the transport sector, an additional electricity demand (**RQ28**) of 22.22 TWh is added to the electricity demand in Greece. Of this 6.22 TWh is "smart charge" EVs, while the remaining is used for heavy transport, public transportation, etc. Furthermore, 27.63 TWh of electricity is used for the H_2 production needed to provide the necessary e-fuels. With "smart charge", curtailment is around 1% of the total electricity demand, whilst without "smart charge", curtailment increases to 3%.

DESSTINEE results

Fuel penetration across different vehicle categories was modelled in DESSTINEE on the basis of current travelled distance and number of units informed by EUROSTAT (Eurostat, 2021b), assumptions on fuel economy and age profiles for the units, and inputs from the National CS narrative (Stavrakas et al., 2021). It must be mentioned that the National CS narrative as well as additional information supplied from the Greek NECP (Greek Ministry of Environment and Energy, 2019) and LTS (Greek Ministry of Environment and Energy, 2020) documents report the number of cars, motorbikes, and light duty vehicles as a single group and buses and trucks as part of another group of vehicles (and fleet composition). Assuming that the current shares of vehicle categories (retrieved from (Eurostat, 2021a)) among the two big groups keep constant in the future, the number of cars and motorbikes, buses, light duty, and heavy duty vehicles were forecasted. The increase in the number of units, in comparison to 2015, is applied to the travel distance reported for each vehicle type (as retrieved from (Eurostat, 2021b)), defining future energy service demand (see **Table 68**).

Table 68. Travelled distance (national totals) by vehicle categories, across scenarios.

Travelled distance (million km)	"RF_2030"	"RF_2050"	"RE_2050"	"P2X_2050"
Passenger cars and motorbikes	47,833	56,392	53,328	54,123

Buses	1,101	1,457	1,289	1,367
Light duty vehicles (vans)	6,692	7,890	7,461	7,572
High duty vehicles (trucks)	9,770	14,376	12,720	13,487

In addition, fuel economy standards from the Continental CS are employed for the estimations (see cluster **EU-C7** in **Section 3.1.4.6**). This allows the quantification of the travelled distance by fuel type and vehicle category, and the yearly fuel consumption profile. **Figure 103** displays the shares of travelled distance according to fuel and transport mode for the different scenarios here-considered, whilst **Table 69** reports the power consumption for road transport and how these figures relate with the current total electricity consumption and the share in power usage for the different time horizons.

Table 69. Power consumption for road transport, under different scenarios, and in comparison with total values for 2015 and the corresponding time horizon.

Scenario	"RF_2030"	"RF_2050"	"RE_2050"	"P2X_2050"
Power consumption road transport (PJ)	4.5	37.3	42.7	30.7
Percentage of road power consumption in electricity usage in 2015	2.5	20.5	23.5	16.9
Percentage of road power consumption in electricity usage (time horizon)	2.7	13.9	15.8	12.4

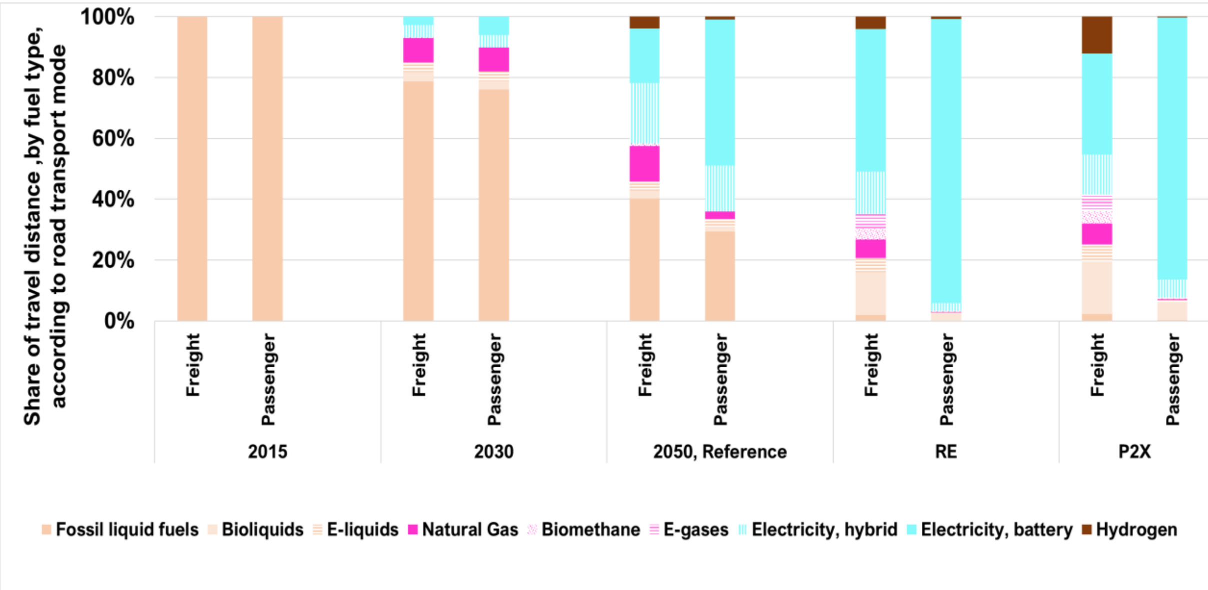


Figure 103. Shares of travelled distance according to fuel and transport mode for the different scenarios.

Hourly electricity demand in DESSTINEE is modelled by accounting for default profiles for power consumption for road transport, which is a blending of different regimes including "Work", "Home", and "Smart". These regimes are further described in cluster **EU-C13** (**Section 3.1.6.3**). Under "Work", it is assumed that EVs will be charged in parallel with occupants being at their respective employment. "Home" considers charging in households and "Smart" that the units are plugged when the electricity prices (or demand) are low.

Figure 104, **Figure 105**, **Figure 106**, **and Figure 107** display an hourly based profile for a typical winter day associated with the different decarbonisation scenarios and time horizon. The effects of road transport electrification can be appreciated, especially at the 2050 time horizon, for which the electric shares in the fleet become relevant. Particularly, the amplitude of the evening peak is modelled to increase as a consequence of the effect of "Home Charging". "Smart charging" (**RQ28**) is evidenced by the power consumption that occurs during the first hours of the day.

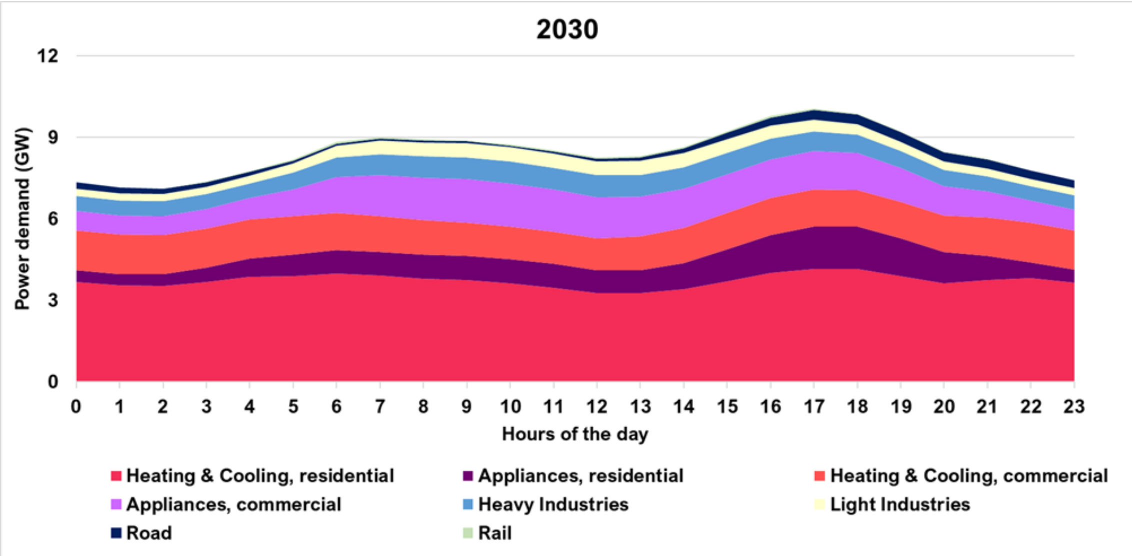


Figure 104. Hourly power demand profiles for the 2030 Reference ("**RF_2030**") scenario.

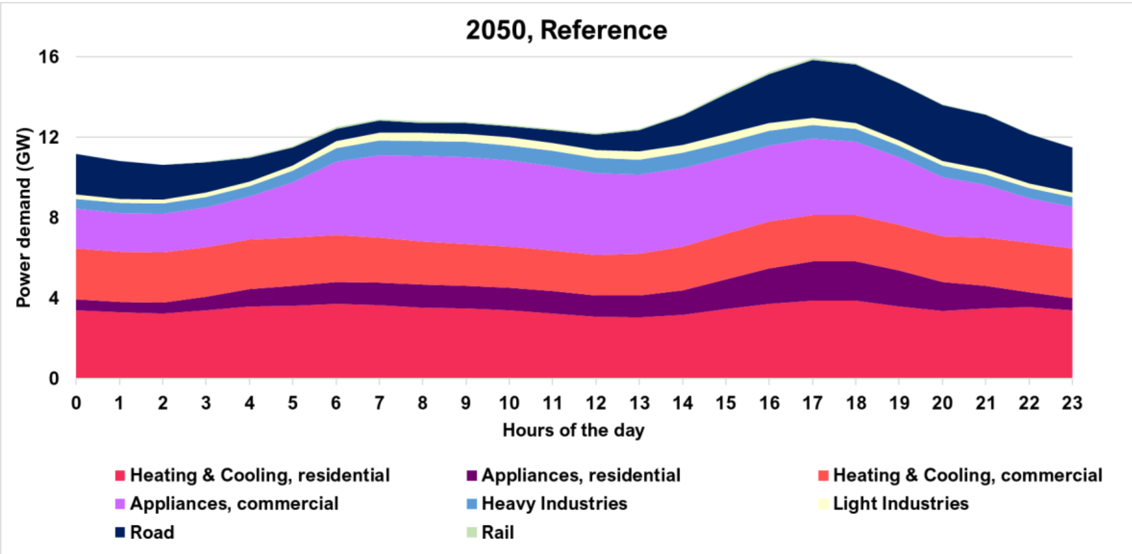


Figure 105. Hourly power demand profiles for the 2050 Reference ("**RF_2050**") scenario.

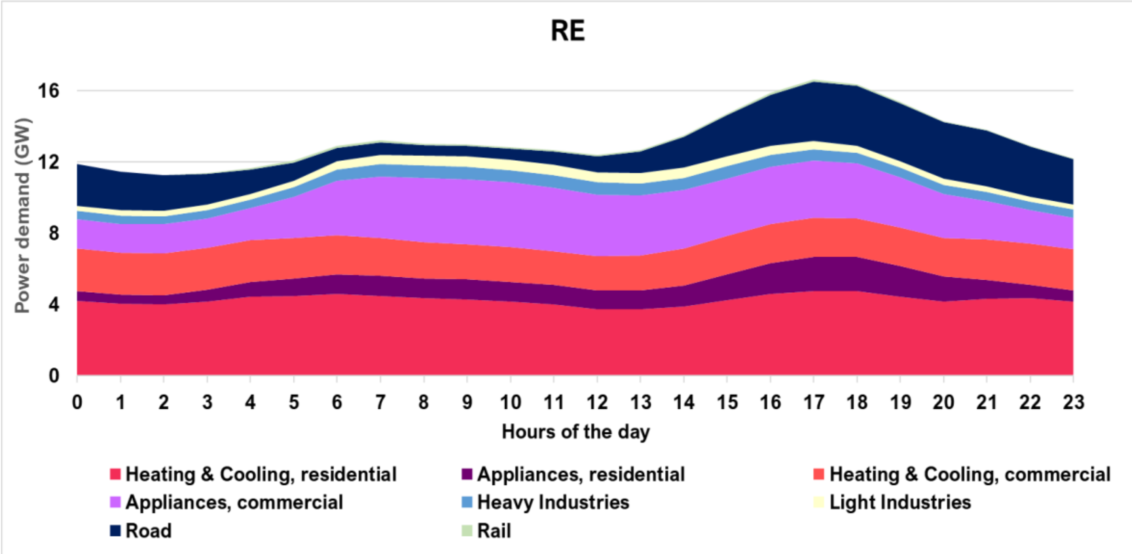


Figure 106. Hourly power demand profiles for the 2050 Renewable Electricity ("**RE_2050**") scenario.

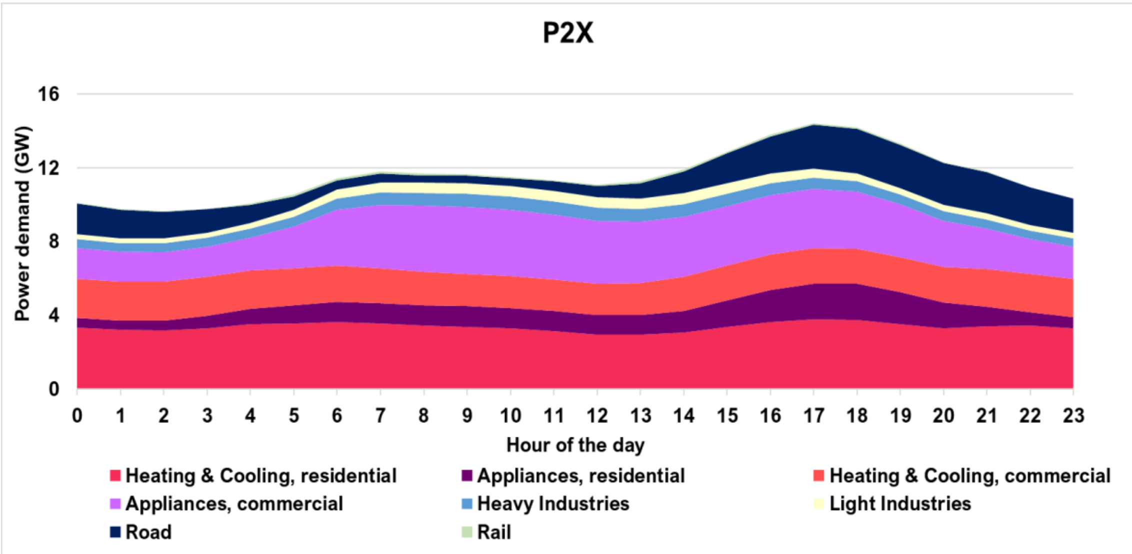


Figure 107. Hourly power demand profiles for the 2050 Power-to-X ("**P2X_2050**") scenario.

*3.3.6.2. **GR-C9**: Heating decarbonisation*

Contributing models: DESSTINEE and DREEM

Research Questions' Overview

Trends for final power consumption for heating will rely on the evolution of thermal energy service, assumptions for the shares of electricity in the heating fuel basket, and especially on how much of that heat is produced using heat pumps. Thermal energy service demand is the function of the building surface, renovation rates, and consequent variations in building-useful energy. Greece already significantly relies on electricity as secondary fuel for heat provision (including space, water heating, and cooking). Based on information from the JRC IDEES (Mantzos et al., 2017) and ODDYSEE-MURE database (Lapillonne et al., 2021), around 25% of the thermal energy demand in households was supplied by electricity in 2015. Whilst these shares are expected to increase in the coming years, this necessarily may not be translated straightforwardly into rises in final power consumption given the substitution of direct heaters by heat pumps and building envelope efficiency improvements. We answer the following RQ, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ38:** What are the additional electricity demand patterns and the effect on peak load demand resulting from the electrification of the heating and cooling sector?

Results and Discussion

For this cluster, DREEM and DESSTINEE are employed, with both models soft-linked. DREEM is used to provide renovation rates and the useful energy per building surface for different types of buildings. These results enable the definition of the increase for the average national building envelope's efficiency in DESSTINEE, which complement default projections on the evolution of building covered areas, heating and cooling degree days, and assumptions on technical indicators for combustion devices and heat pumps. This allowed the calculation of heat and cooling service demands. Fuel baskets from the National CS narrative, for the different scenarios were accounted for, estimating the electricity consumption for the final energy uses discussed in **RQ38**. It must also be highlighted that between nowadays and 2050, a reduction in the number of households is expected to occur in Greece, derived from negative population growth (Capros et al., 2016). We have assumed that the area per household would remain constant and that both cooling and HDD would be affected by climate change.

We are discussing two sets of results. At first, we focus on the observed trends for households, and secondly, we present the main results for commercial buildings.

Figure 108 presents the evolution of thermal energy services in households and thus the total amount of heat being consumed by residential buildings. Decreasing trends are a consequence of the aforementioned demographic trends, in combination with more efficient thermal usage in buildings (derived from renovation). The thermal service supplied by electricity is expected to increase, both in absolute and relative figures by 2050.

Despite the growing trends for thermal energy services, final power consumption (**Figure 109**) is modelled to decrease (except for the "**RE_2050**" scenario) particularly because we are assuming that heat pumps will play a key role in space and water heating, reaching 42% by 2050. In our modelling exercise, coefficient performances ranging between 2.5-3.5% are assumed thus allowing lower energy consumption than direct heating (with efficiency close to 1). Especially, between 2030 and 2050, both deployment shares and coefficients of performance for heat pumps are assumed to increase.

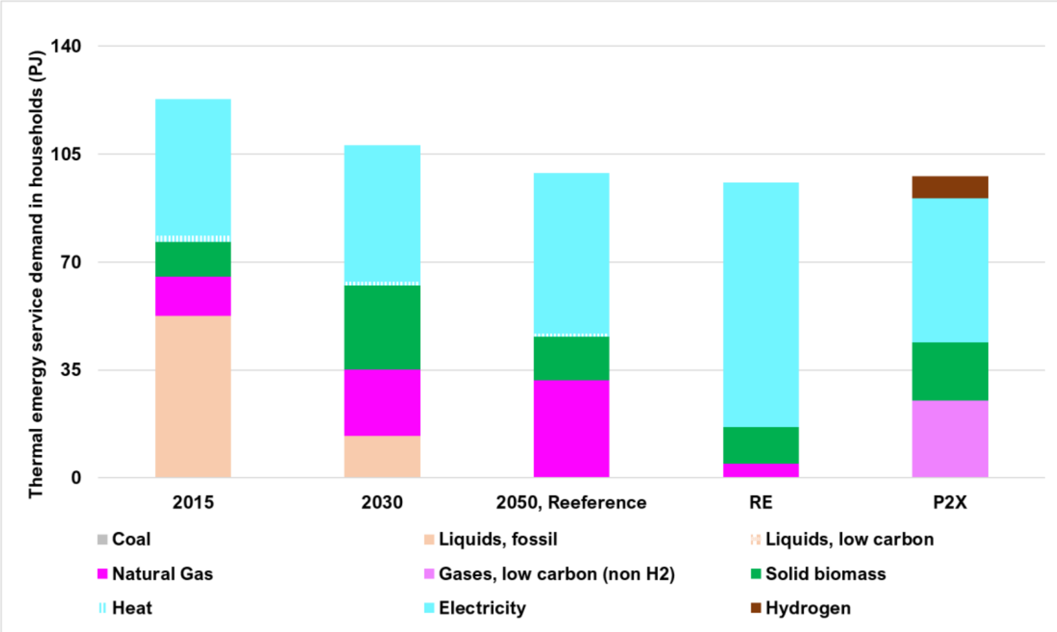


Figure 108. Thermal energy service demand in households, modelled for the different scenarios.

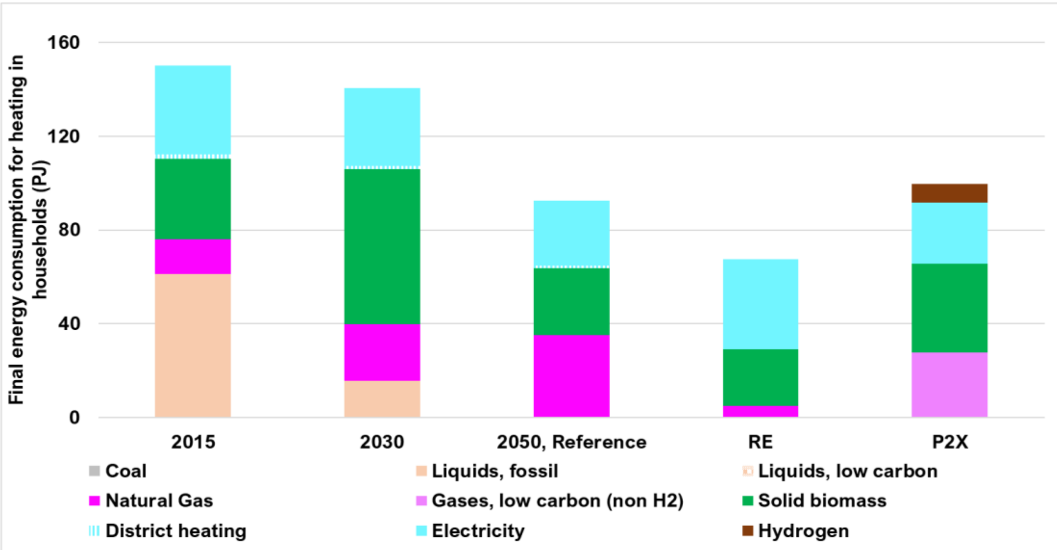


Figure 109. Final energy consumption for heating in households, modelled for the different scenarios.

For commercial facilities, the penetration of electricity as an energy carrier is followed. However, as shown in **Figure 110** and **Figure 111**, both thermal energy service and FEC exhibit an upward trend. This obeys the evolution of commercial building area, modelled to increase on the basis of projections for sectorial value-added.

In terms of the impact on peak demand, as shown in **Figure 105**, **Figure 106**, **Figure 107**, **Figure 108** and **Figure 110**, electricity consumed for heating purposes significantly contributes to electricity usage- in particular during winter days. However, given the initial electrification shares, the evolution of the commercial area, and the efficiency trends here-discussed, the amplitude and shape of the hourly demand curve do not appear to be major when analysing the whole building sector. This is a reflection of the yearly trends, being the base and peak usage for "**RES**" ("**RE_2050**"), the largest when comparing across the different scenarios.

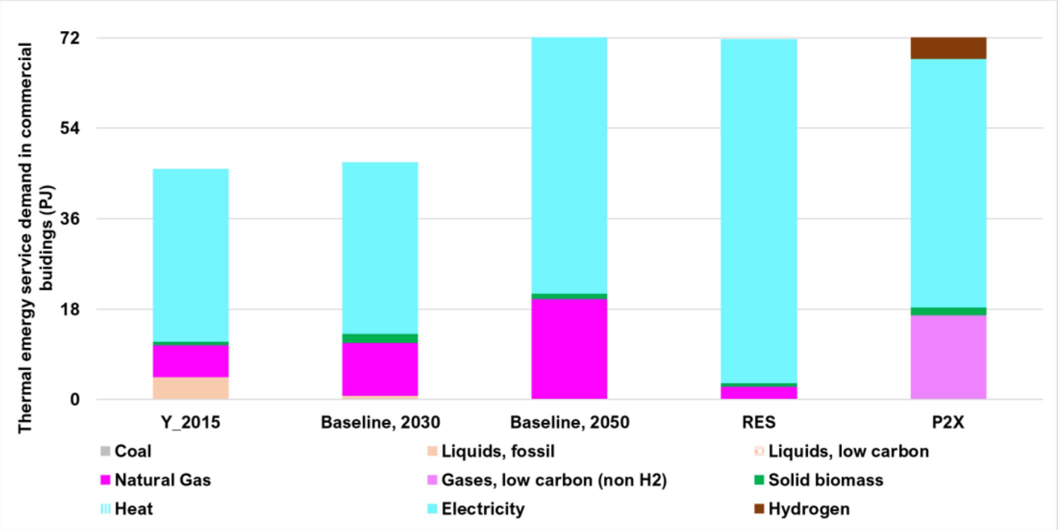


Figure 110. Thermal energy service demand in commercial buildings, modelled for the different scenarios.

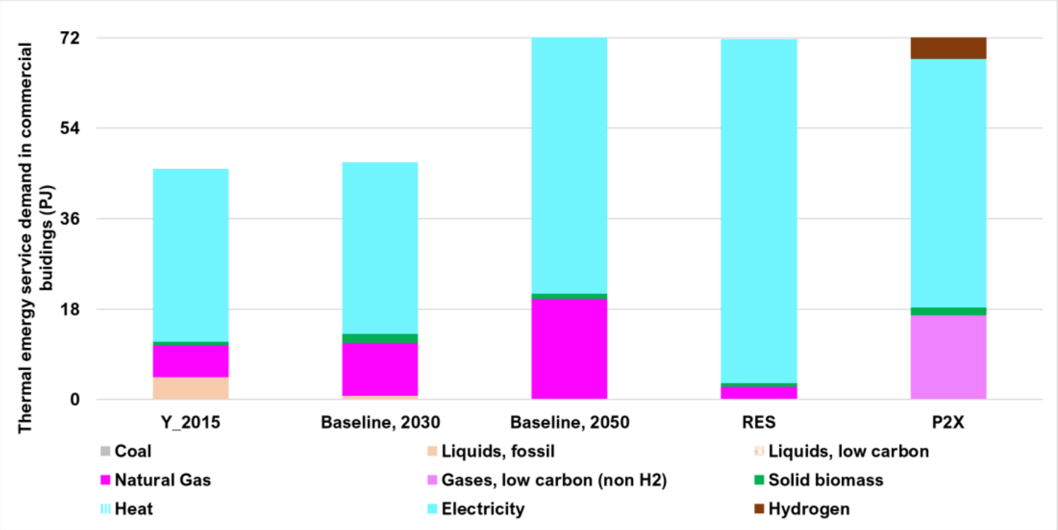


Figure 111. Final energy consumption for heating in commercial buildings, modelled for the different scenarios.

*3.3.6.3. **GR-C10**: Investigating energy transition pathways in the residential sector in Greece*

Contributing models: DREEM

Research Questions' Overview

In the EU buildings consume around 40% of the FEC, highlighting the great importance to reduce the sector's consumption and improve its environmental footprint. In this direction, several strategies, regulations, and directions have been established focusing on the key role of energy-efficiency actions (Buildings Performance Institute Europe (BPIE), 2020). Moreover, the importance of energy efficiency actions is further underlined by the latest developments in Ukraine, which have caused several concerns regarding high energy prices and energy security (European Commission, 2022). Due to the latter, the EU has developed the "REPowerEU" plan, which along with the "Fit for 55" package, that was introduced in 2021, change the future of fossil fuels (oil products and natural gas) in the building sector radically (European Commission, 2022). The targets of: **(i).** reducing the EU's dependence on Russian natural gas, **(ii).** focusing on energy efficiency, **(iii).** gradual phasing out of fossil fuel boilers, as well as **(iv).** creating a new parallel ETS on heating fuels in the building sector, lead to more pressure on investing to fossil fuel alternatives (e.g., electrification, etc.) in the coming years (European Commission, 2022, 2021b).

The building sector in Greece, and especially the residential sector, which consumes around 25% of the FEC, is considered more than critical for the achievement of Greece's energy transition and security (IEA, 2020b). The current NECP sets as an objective that by 2030 12-15% of the total number of dwellings in the country, i.e., up to 60000 households per year, will be upgraded in terms of energy efficiency (in part or in full), while targeting in the increase of the natural gas consumption, and, thus, the country's energy dependency (Greek Ministry of Environment and Energy, 2019). One can simply understand that this new EU energy policy context described above cannot leave the energy policy landscape in Greece unaffected. Considering the critical challenges towards the energy transition of the Greek residential sector we seek to answer the following RQs:

- **RQN3:** Is the current NECP target of 60000 renovations per year able to lead to the decarbonisation of the Greek residential sector by 2050?
- **RQN4:** Should Greece proceed with the current national planning, investing in natural gas as a transition fuel, also increasing national energy dependence in fossil fuels?

Results and Discussion

To explore the energy transition towards 2050 in the residential sector in Greece, six scenarios are simulated. The first four scenarios (Scenarios 1-4) are based on the current NECP renovation rate of 60,000 renovations/year and their specifications are presented below:

i. **Scenario 1: "Baseline"**
   - **(2023-2030):** Annual natural gas penetration according to NECP 2030 targets (15.1% of total consumption). Annual heat pump penetration in order to achieve 300% increase in heat pump installations. The remaining households will be only renovated through envelope/window upgrades.
   - **(2031-2035):** Substitution of new natural gas boilers with heat pumps.
   - **(2036-2050):** Phase-out of remaining natural gas boilers with heat pumps.

ii. **Scenario 2: "Investing in heat pumps & phasing out natural gas #1":**
   - **(2023-2050)**: 60000 oil boilers substitutions with heat pumps.

- **(2036-2050)**: Phase-out of existing natural gas boilers with heat pumps.

iii. **Scenario 3: "Investing in heat pumps & phasing out natural gas #2":**

- **(2023-2050):** 60000 oil boilers substitutions with heat pumps.
- **(2031-2050):** Phase-out of existing natural gas boilers with heat pumps.

iv. **Scenario 4: "Complete independence from natural gas as soon as possible":**

- **(2023-2050):** 60000 oil boilers substitutions with heat pumps.
- **(2026-2050):** Phase-out of existing natural gas boilers with heat pumps.

For the two remaining scenarios (Scenarios 5 & 6), a reverse engineering process is applied to specify renovation rate necessary for the residential sector to be decarbonised by 2050 and 2040, respectively. In each one of these scenarios, we also distinguish between two pathways: the first pathway refers to the current national planning, which based on the latest version of the Greek NECP, assumes that investing in new natural gas infrastructures to use natural gas as intermediate transition fuel will take place after all, increasing national dependence on fossil fuels. The second pathway investigate a different road than the current national planning by promoting the electrification of heating in the residential sector and investments in heat pumps. Further assumptions and specifications of these two scenarios and their respective pathways are presented below:

v. **Scenario 4: "Decarbonisation by 2050"**

100000 household renovations (energy-efficiency upgrades in the building envelope and in the heating/cooling system) per year:

(a) Investing in natural gas

- **(2023-2030)**: Annual natural gas penetration according to the NECP 2030 targets (15.1% of total consumption). For the remaining households, it is assumed that they substitute oil boilers with heat pumps.
- **(2031-2050)**: Phase out of existing natural gas boilers with heat pumps.

(b) Investing in electrification

- **(2023-2050):** Substitution of oil and natural gas boilers with heat pumps.

vi. **Scenario 5: "Decarbonisation by 2040"**

145000 household renovations (energy-efficiency upgrades in the building envelope and in the heating/cooling system) per year:

(a) Investing in natural gas

- **(2023-2050):** Annual natural gas penetration according to NECP 2030 targets (15.1% of total consumption). For the remaining households, it is assumed that they substitute oil boilers with heat pumps.
- **(2031-2050):** Phase-out of existing natural gas boilers with heat pumps.

(b) Investing in electrification

- **(2023-2050):** Substitution of oil and natural gas boilers with heat pumps.

For all the five scenarios under study:

All dwellings that have their heating technology substituted are also renovated through envelope/window upgrades:

- **In dwellings built before 1981:** exterior wall insulation & window replacements.
- **In dwellings built during the period 1981-2000:** exterior wall insulation.

Finally, following the target for creating a new parallel ETS on heating fuels in the building sector, two potential cases for the evolution of the ETS price are investigated: **(i).** constant ETS price at 30€/tnCO_2 for the whole period of the transition (2025-2050, we assume that this parallel ETS in the EU building sector will come into effect in 2025), **(ii).** changing ETS price with the following trend: 2025 at 30€/tnCO_2, 2026-2030 at 50€/tnCO_2, and 2031-2050 at 100€/tnCO_2.

With regards to the simulation of the scenarios 1-4, our modelling results show that the current NECP target of 60000 household renovations per year (1.5% annual renovation rate), cannot lead to decarbonisation by 2050. As shown in **Figure 112**, our findings indicate that in none of these scenarios the consumption of oil products and/or natural gas is eliminated by 2050. Another interesting finding is that when investing in natural gas as a transition fuel ("**Scenario 1**") more energy derived from fossil fuels (oil products and natural gas) is consumed in 2050 compared to the scenarios 2-4.

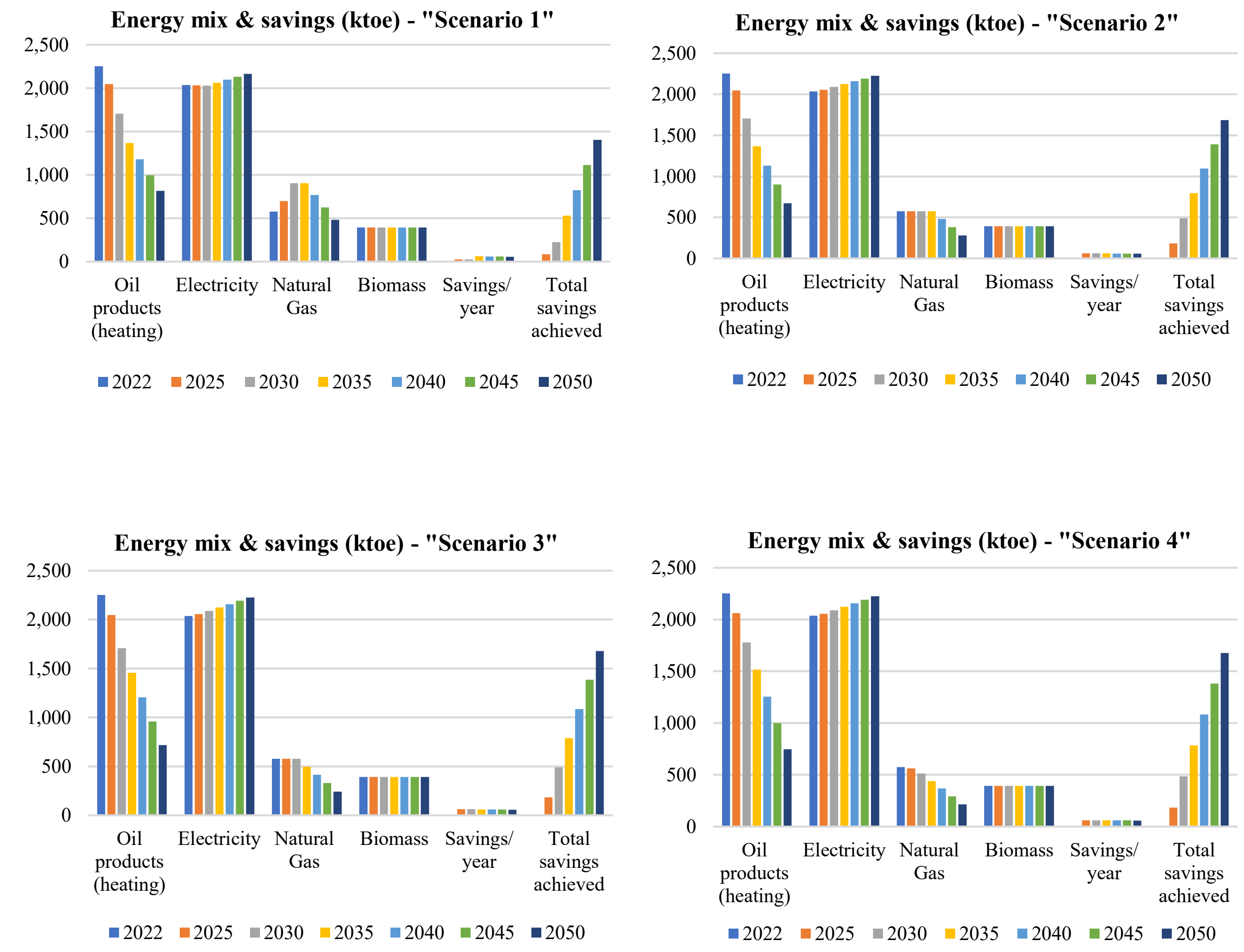


Figure 112. Energy mix towards 2050 in the Greek residential sector – Cross-scenario comparison.

Regarding "**Scenario 5**" and "**Scenario 6**", our findings suggest that to decarbonise the Greek residential sector by 2050 (**Table 70** and **Figure 113**), 100000 households should be renovated each year (2.5% annual renovation rate), while to decarbonise it by 2040, 145000 households should be renovated each year (3.5% annual renovation rate).

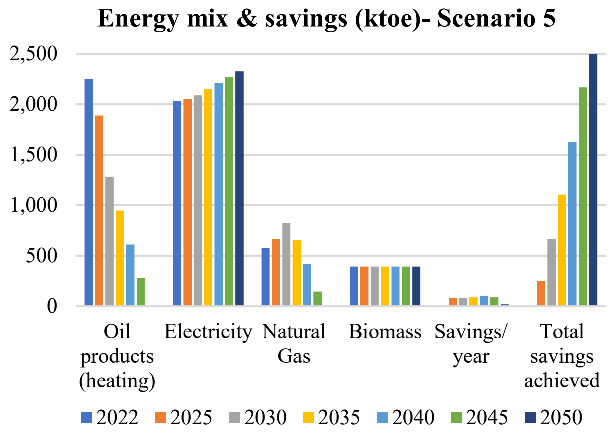
Table 70. Energy mix towards 2050 in the Greek residential sector: "**Scenario 5**" focusing on investing in new natural gas infrastructure by 2030.

Consumption by fuel (ktoe)	**2022**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Oil products (heating)	2252.5	1889.7	1285.0	947.7	610.4	277.9	0.0
Electricity	2035.6	2054.8	2086.7	2151.0	2211.6	2272.3	2325.5
Appliances and Cooling	1338.3	1319.1	1287.0	1242.5	1194.4	1146.3	1107.5
Electric Heating System	696.0	696.0	696.0	696.0	696.0	696.0	696.0
Heat Pumps	1.3	39.7	103.6	212.4	321.2	429.9	521.9
Natural Gas	576.0	669.1	824.2	658.7	417.9	146.7	0.0
Biomass	393.0	393.0	393.0	393.0	393.0	393.0	393.0
Savings/year	0.0	83.5	83.5	87.7	103.5	88.2	20.5

Total savings achieved	0.0	250.6	668.2	1106.8	1624.2	2167.2	2544.0

Table 71. Energy mix towards 2050 in the Greek residential sector: "**Scenario 6**" focusing on investing in new natural gas infrastructure by 2030.

Consumption by fuel (ktoe)	2022	2025	2030	2035	2040	2045	2050
Oil products (heating)	2252.5	1728.0	853.8	426.5	0.0	0.0	0.0
Electricity	2035.6	2077.3	2146.8	2240.5	2325.5	2325.5	2325.5
Appliances and Cooling	1338.3	1302.6	1243.1	1179.5	1107.5	1107.5	1107.5
Electric Heating System	696.0	696.0	696.0	696.0	696.0	696.0	696.0
Heat Pumps	1.3	78.7	207.7	364.9	521.9	521.9	521.9
Natural Gas	576.0	634.8	732.8	330.4	0.0	0.0	0.0
Biomass	393.0	393.0	393.0	393.0	393.0	393.0	393.0
Savings/year	0.0	141.3	141.3	147.2	121.3	0.0	0.0
Total savings achieved	0.0	424.0	1130.7	1866.7	2530.1	2530.1	2530.1



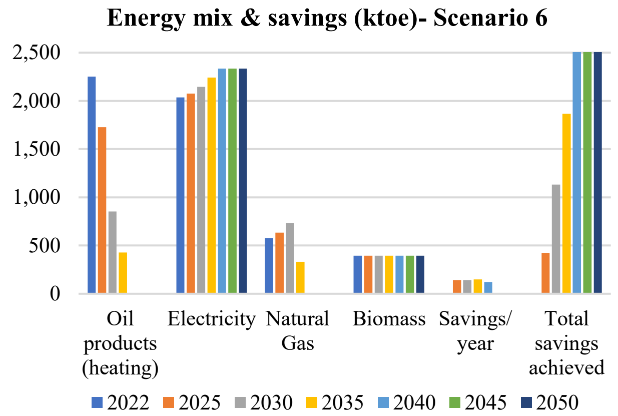


Figure 113. Energy mix towards 2050 in the Greek residential sector: Scenarios **5** and **6** focusing on investing in new natural gas infrastructure by 2030.

Furthermore, it appears that towards the decarbonisation process, investing in electrification and heat pumps leads to less harmful environmental footprint as more tonnes of CO_2 are avoided as presented in **Table 72** and **Figure 114**, while it also leads to lower costs at both the household and the national level, compared to investing in natural gas as presented in **Table 73** and **Table 74**. Finally, when scenarios 5 and 6 are compared, striving to be ambitious and decarbonising the residential sector by 2040 also leads to a less harmful environmental footprint and lower total costs than decarbonising by 2050.

Table 72. Carbon Dioxide (CO_2) avoided due to interventions by 2050.

tnCO_2 avoided due to interventions	2025	2030	2035	2040	2045	2050
"Scenario 5a"	1.448 M	9.094 M	23.367 M	44.748 M	74.021 M	**110.44 M**
"Scenario 5b"	1.734 M	11.174 M	29.202 M	55.102 M	88.736 M	**126.95 M**

“Scenario 6a”	2.326 M	14.841 M	38.197 M	71.892 M	109.79 M	**148.03** M
“Scenario 6b”	2.507 M	16.155 M	41.392 M	76.730 M	114.62 M	**152.86 M**

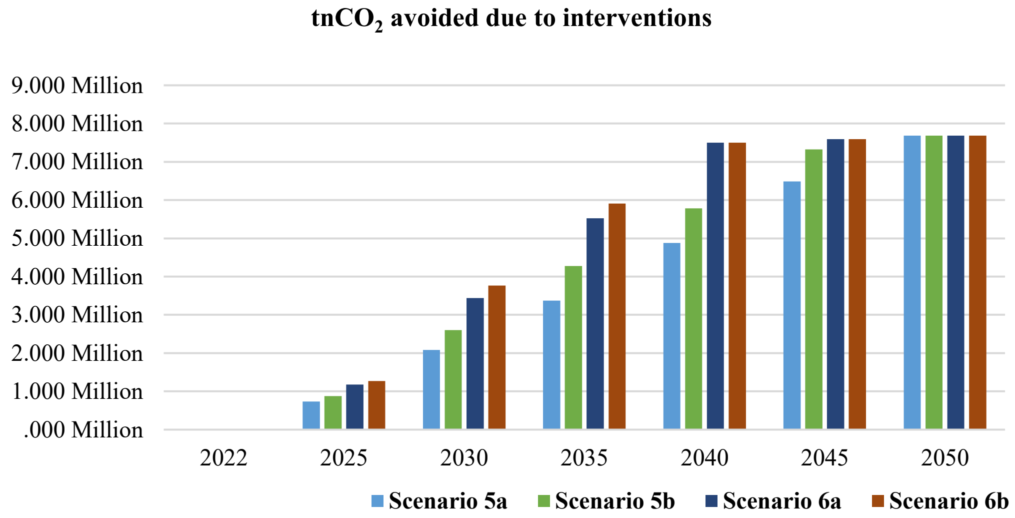


Figure 114. Tonnes of Carbon Dioxide ($tnCO_2$) avoided due to interventions by 2050.

Table 73. Cross-scenario comparison at the household level.

	2022	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Total**
Potential extra charge on bill/household and fuel costs per household without interventions (ETS 30) (€)	2295	2462	2641	2678	2714	2751	2788	**76661**
Potential extra charge on bill/household and fuel costs per household without interventions (ETS 30-100) (€)	2295	2462	2681	2817	2854	2891	2927	**79654**
“Scenario 5a”								
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	2295	2651	2540	2309	1982	1599	1216	**61608**
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	2295	2651	2570	2392	2041	1632	1230	**62893**
“Scenario 5b”								
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	2295	2621	2449	2142	1809	1417	1212	**58404**
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	2295	2621	2476	2210	1853	1436	1227	**59437**
“Scenario 6a”								
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	2295	2753	2448	2020	1493	1221	1184	**55177**

Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	2304	2753	2471	2067	1508	1236	1199	**55913**
"Scenario 6b"								
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	2295	2734	2390	1949	1419	1221	1184	**54133**
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	2295	2734	2412	1989	1434	1236	1199	**54792**

Table 74. Cross-scenario comparison at the national level.

	2022	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**Total**	**Money saved (€)**
Potential extra charge on bill/household and fuel costs per household without interventions (ETS 30) (€)	9909 m.	10632 m.	11406 m.	11564 m.	11722 m.	11,80 m.	12038 m.	**331062 m.**	
Potential extra charge on bill/household and fuel costs per household without interventions (ETS 30-100) (€)	9909 m.	10632 m.	11578 m.	12167 m.	12325 m.	12483 m.	12641 m.	**343987 m.**	
"Scenario 5a"									
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	9909 m.	11450 m.	10971 m.	9971 m.	8561 m.	6905 m.	5249 m.	**266055 m.**	65007 m.
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	9909 m.	11450 m.	11100 m.	10330 m.	8814 m.	7048 m.	5314 m.	**271603 m.**	72384 m.
"Scenario 5b"									
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	9909 m.	11320 m.	10577 m.	9251 m.	7813 m.	6118 m.	5232 m.	**252220 m.**	78842 m.
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	9909 m.	11320 m.	10694 m.	9543 m.	8001 m.	6201 m.	5297 m.	**256680 m.**	87306 m.
"Scenario 6a"									
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	9909 m.	11890 m.	10571 m.	8722 m.	6448 m.	5275 m.	5113 m.	**238283 m.**	92779 m.
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	9909 m.	11890 m.	10672 m.	8925 m.	6512 m.	5339 m.	5178 m.	**241461 m.**	102526 m.
"Scenario 6b"									
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30) (€)	9909 m.	11808 m.	10322 m.	8418 m.	6127 m.	5275 m.	5113 m.	**233773 m.**	97290 m.
Potential extra charge on bill/household and fuel costs per household with interventions (ETS 30-100) (€)	9909 m.	11808 m.	10416 m.	8591 m.	6191 m.	5339 m.	5178 m.	**236619 m.**	107368 m.

Overall, our study aims to shed light on energy transition pathways in the Greek residential sector, which is one of the most energy-consuming sectors in Greece. By doing so, we aim to provide useful conclusions and recommendations to policymakers and other relevant end-users from the field of policy and practice, especially in view of the latest evolutions in the energy markets as well as the forthcoming amendment of the Greek NECP. Our findings highlight the need for more ambitious targets for the achievement of the decarbonisation targets set by the EU, as well as the need for greater focus on investing in electrification rather than natural gas.

*3.3.6.4. **GR-C11**: Investigating energy transition pathways in the residential sector in Peloponnese*

Contributing models: DREEM

Research Questions' Overview

As mentioned in cluster **GR-C10** (**Section 3.3.6.3**) the decarbonisation of the Greek building sector, and especially the residential, which consumes around 25% of the FEC, is considered more than critical for the achievement of Greece's energy transition and security (IEA, 2020b). The current NECP sets as an objective that by 2030 12-15% of the total number of dwellings in the country, i.e., up to 60000 homes per year, will be upgraded in terms of energy efficiency (in part or in full), while targeting in the increase of the natural gas consumption, and, thus, the country's energy dependency (Greek Ministry of Environment and Energy, 2019).

In the light of the above, scenarios of energy transition in the residential sector in the Peloponnese region towards 2050 are examined. Two are the main reasons we chose Peloponnese region for this analysis. First, because of the plan for interconnecting the region to natural gas distribution networks for the first time, which given the current circumstances raises questions regarding its viability. Second, because it is the only region that consists of regional units in three out of the four climate zones in Greece, bringing together different climatic conditions.

Considering the critical challenges towards the energy transition in the residential sector in Peloponnese region we seek to answer the following RQs:

- **RQN5:** What is the optimal mixture of technologies for the most cost-effective decarbonisation in the residential sector in the Peloponnese region?
- **RQN6:** Should the region proceed with the current national planning, investing in natural gas as a transition fuel, also increasing its energy dependence?

Results and Discussion

To explore the energy transition towards 2050 in the residential sector in the Peloponnese region, three scenarios are simulated. These scenarios are based on the current NECP renovation rate of 60000 household renovations/year at the national level adapted to the region under study, meaning that 2775 households are annually renovated. Scenario specifications are presented below:

i. **Scenario 1: "Natural gas as a transition fuel"**

- **(2023-2030):** Annual natural gas penetration according to the NECP 2030 targets (10% of total consumption). Annual heat pump penetration in order to achieve 300% increase in heat pump installations.
- **(2031-2035):** Substitution of new natural gas installations with heat pumps.
- **(2036-2050):** Phase-out of the remaining natural gas installations with heat pumps.

ii. **Scenario 2: "Investing in electrification and natural gas & phasing out natural gas"**

- **(2023-2030):** Annual natural gas penetration at the half of the NECP 2030 targets (5% of total consumption). For the remaining households, it is assumed that they substitute oil boilers with heat pumps.
- **(2031-2035):** Substitution of new natural gas installations with heat pumps.
- **(2036-2050):** Phase-out of the remaining natural gas installations with heat pumps.

iii. **Scenario 3: "Investing in electrification"**

- **(2023-2050):** Substitution of oil boilers with heat pumps.
- **(2026-2050):** Phase-out of the remaining natural gas installations with heat pumps.

For all the three scenarios under study:

All dwellings that have their heating technology substituted are also renovated through envelope/window upgrades:

- **In dwellings built before 1981:** exterior wall insulation & window replacements.
- **In dwellings built during the period 1981-2000:** exterior wall insulation.

Simulation results from the DREEM model show that the current NECP renovation rate of 60000 renovations of households per year (1.5% annual renovation rate), cannot lead to decarbonisation by 2050. As shown in **Figure 115**, our findings indicate that in none of these scenarios consumption of oil products and/or natural gas is eliminated by 2050. More specifically, "**Scenario 1**" leads to 27.2 ktoe of fossil fuel consumption (oil products and natural gas), "**Scenario 2**" leads to 17.9 ktoe of fossil fuel consumption, while "**Scenario 3**" leads to the lowest fossil fuel consumption (7.7 ktoe). Only by investing in electrification from the beginning ("**Scenario 3**") decarbonisation levels can be reached as the fossil fuel consumption is eliminated by almost 91%.

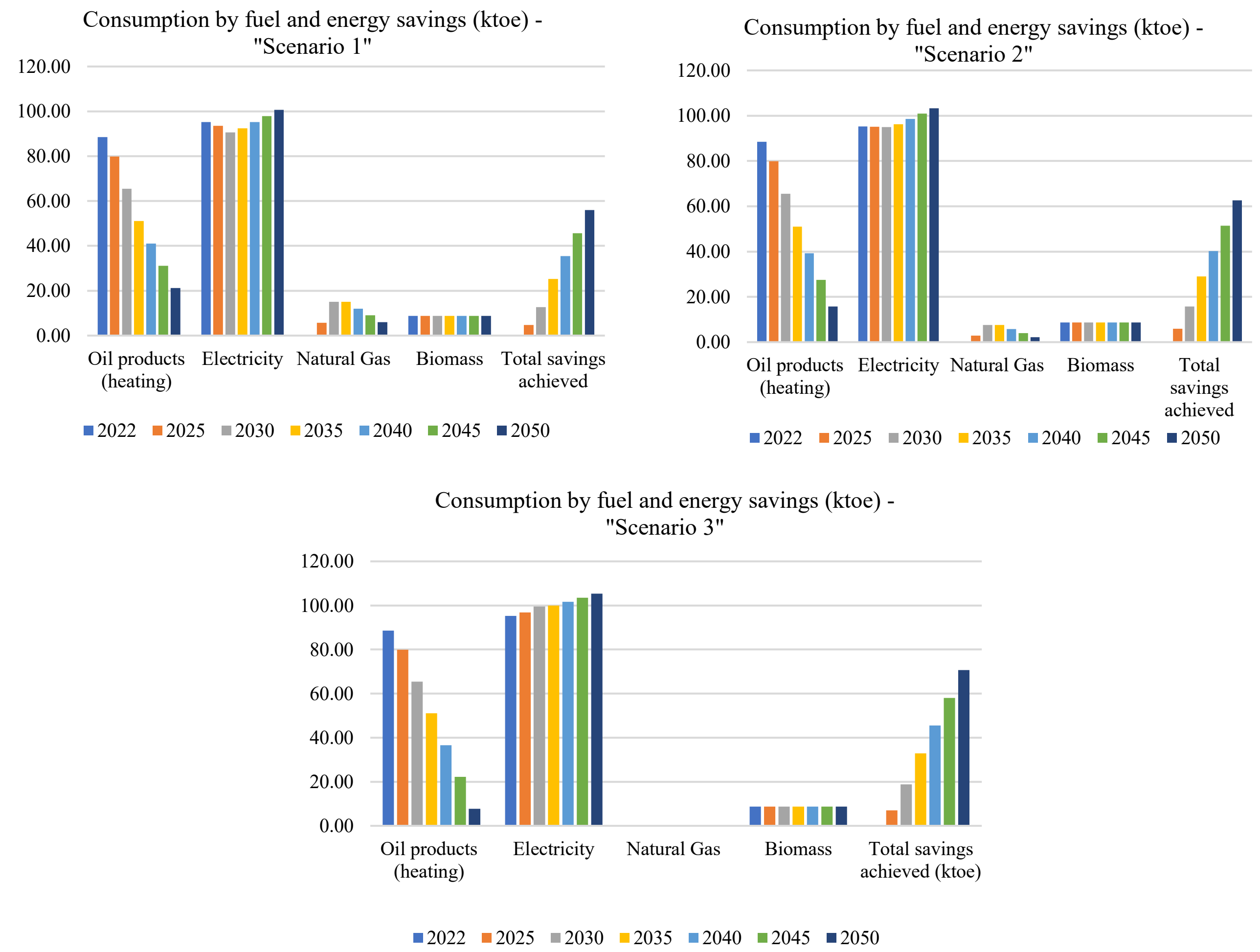


Figure 115. Energy mix towards 2050 in the residential sector in the Peloponnese region – Cross-scenario comparison.

In terms of the environmental footprint of each scenario under study, CO_2 emissions are used as an indicator. As shown in **Figure 116**, "**Scenario 3**" leads to the lowest level of CO_2 emissions, namely 47218 $tnCO_2$ by 2050, while in "**Scenario 2**" 74614 $tnCO_2$ are emitted in 2050 and in "**Scenario 1**" 98807 $tnCO_2$. Moreover, investing in electrification ("**Scenario 3**") leads to more total tonnes of CO_2 avoided during the transition (3.19M $tnCO_2$ avoided by 2050), while investing in natural gas with a lower penetration rate, allowing for the higher penetration of heat pumps ("**Scenario 2**" compared to the "**Scenario 1**") leads to higher avoidance of CO_2 emissions (2.77M $tnCO_2$ by 2050 and 2.38M $tnCO_2$, respectively).

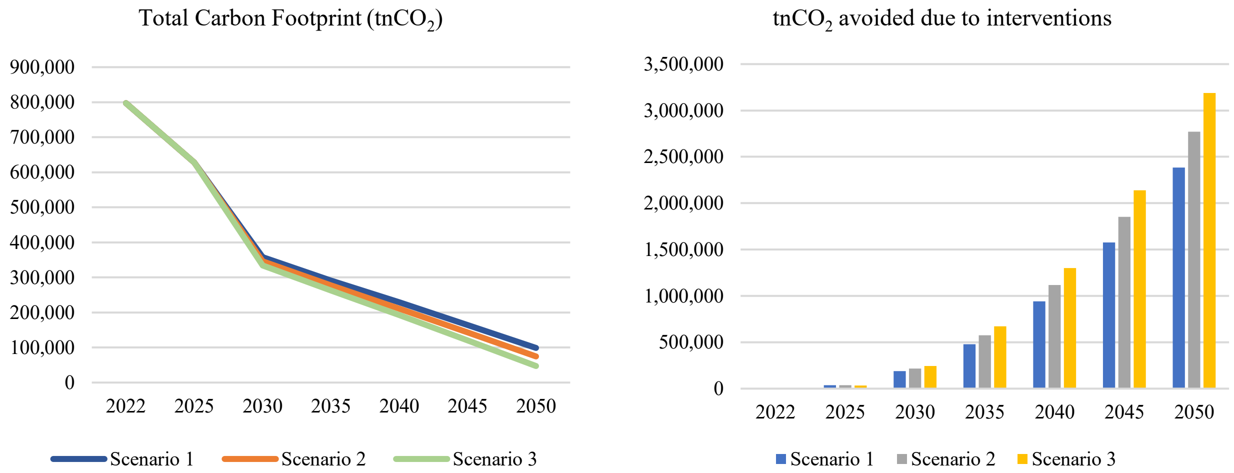


Figure 116. Environmental footprint ($tnCO_2$) and total amount of $tnCO_2$ avoided towards 2050 - Cross-scenario comparison.

Assuming the building sector will be included in a parallel ETS, as also mentioned in cluster **GR-C10** (**Section 3.3.6.3**), two potential cases for the evolution of the ETS price are investigated: **(i).** a constant ETS price at 30€/$tnCO_2$ for the whole period of the transition (2025-2050, we assume that this parallel ETS in the EU building sector will come into effect in 2025), **(ii).** a changing ETS price with the following trend: 2025 at 30€/$tnCO_2$, 2026-2030 at 50€/$tnCO_2$, and 2031-2050 at 100€/$tnCO_2$. **Figure 117** suggests that in both potential cases, when investing in electrification, ETS costs are reduced. When comparing the three scenarios under study, "**Scenario 1**" leads to total ETS costs of €392.7M by 2050, while "**Scenario 2**" leads to €348.6M, while "**Scenario 3**" leads to €302.0M, reducing the cost by 11.2% and 23.1%, respectively, compared to "**Scenario 1**".

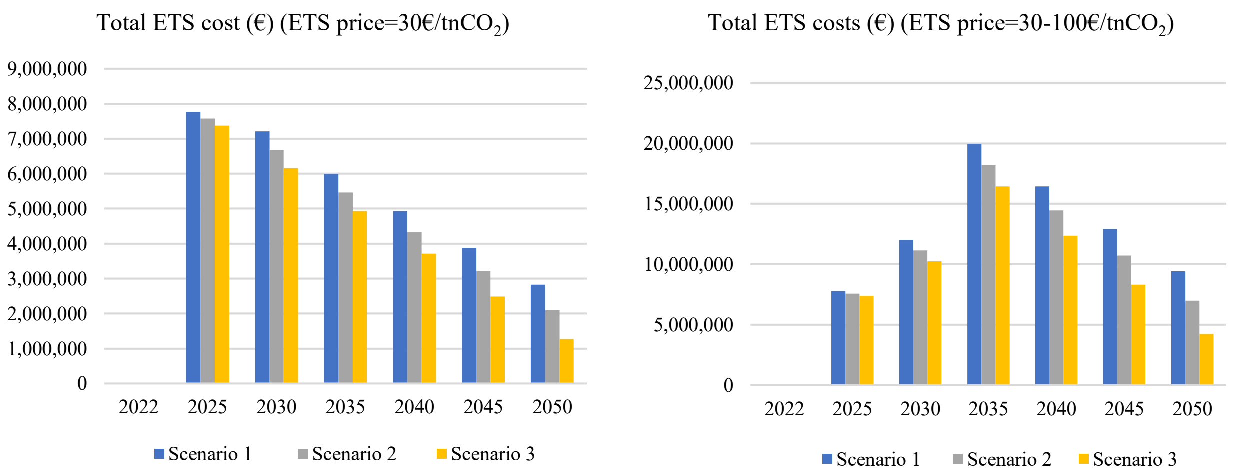


Figure 117. Emissions Trading System (ETS) relevant costs for the two potential cases of ETS price - Cross-scenario comparison.

Except for the ETS costs, the implementation of each of the three scenarios include different fuel and renovation costs. As shown in **Table 75** and **Table 76**, focusing on investing in electrification compared to investing in natural gas leads to lower annual fuel costs, increasing the annual fuel cost savings. “**Scenario 1**” leads to a total of €2015.2M of fuel cost savings towards 2050, “**Scenario 2**” saves €2256.0M of fuel costs in the same period, while “**Scenario 3**” in total saves €2527.3M.

Table 75. Energy transition in the residential sector in the Peloponnese region: Fuel costs – Cross-scenario comparison.

Fuel costs (€)	2022	2025	2030	2035	2040	2045	2050
No renovations	384.4M	399.6M	424.8M	427.8M	430.7M	433.7M	436.7M
“Scenario 1”	384.4M	389.3M	392.3M	365.1M	341.1M	313.9M	283.6M
“Scenario 2”	384.4M	388.3M	387.9M	358.2M	330.5M	299.6M	265.5M
“Scenario 3”	384.4M	387.3M	383.5M	351.3M	318.7M	282.8M	243.6M

Table 76. Energy transition in the residential sector in the Peloponnese region: Fuel cost savings – Cross-scenario comparison.

Fuel cost savings (€)	2022	2025	2030	2035	2040	2045	2050
“Scenario 1”	-	10.3M	32.5M	62.7M	89.6M	119.8M	153.1M
“Scenario 2”	-	11.3M	36.9M	69.6M	100.2M	134.1M	171.2M
“Scenario 3”	-	12.3M	41.3M	76.5M	112.0M	150.9M	193.1M

Finally, in terms of renovation costs, as also shown in **Figure 118**, the scenarios that focus more on investing in electrification instead of natural gas include higher costs. More specifically, “**Scenario 2**” is more expensive than “**Scenario 1**”, while “**Scenario 3**” is more expensive compared to the other two scenarios. These differences are mainly attributed to the period 2022-2030, as this is the period that the scenarios are using different pathways.

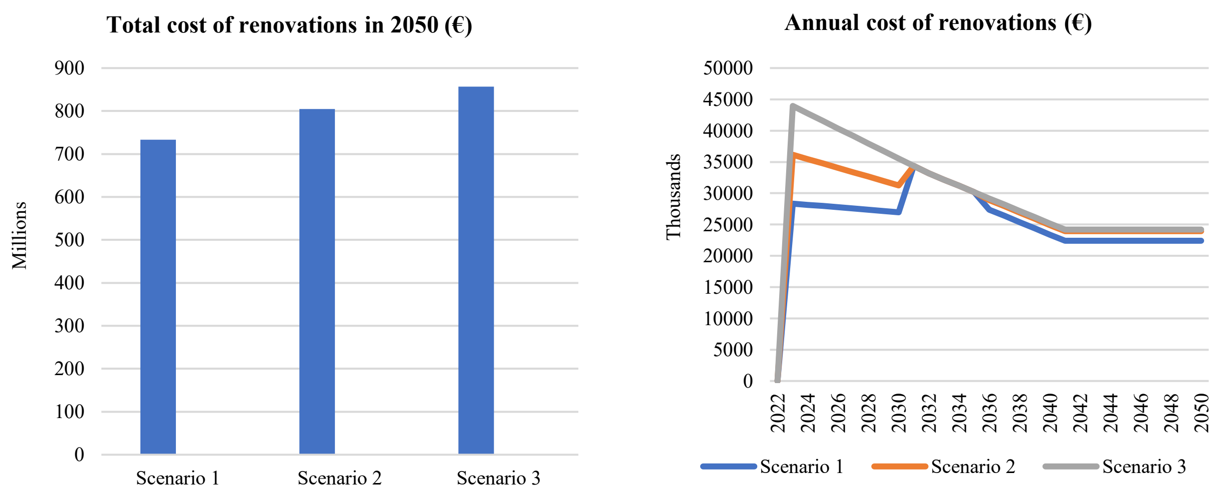


Figure 118. Energy transition in the residential sector in the Peloponnese region: Total and annual costs of renovation – Cross-scenario comparison.

To extract a robust and useful comparison regarding the financial viability of each energy transition scenario we aggregated the individual costs (ETS, fuel, and renovation costs), first at the household, and then at the regional level. **Figure 119** presents the potential extra charge at the household level if the total cost of each scenario is equally divided among all the households in the Peloponnese region, also considering the two potential cases for the ETS price under study. In both cases, all scenarios lead to reduced annual costs per household by 2050 compared to not proceeding with any renovation. Furthermore, after 2030, investing in electrification ("**Scenario 3**") leads to lower annual costs, while as shown in **Table 77** decreases the total cost during the transition period at both the household and the regional level.

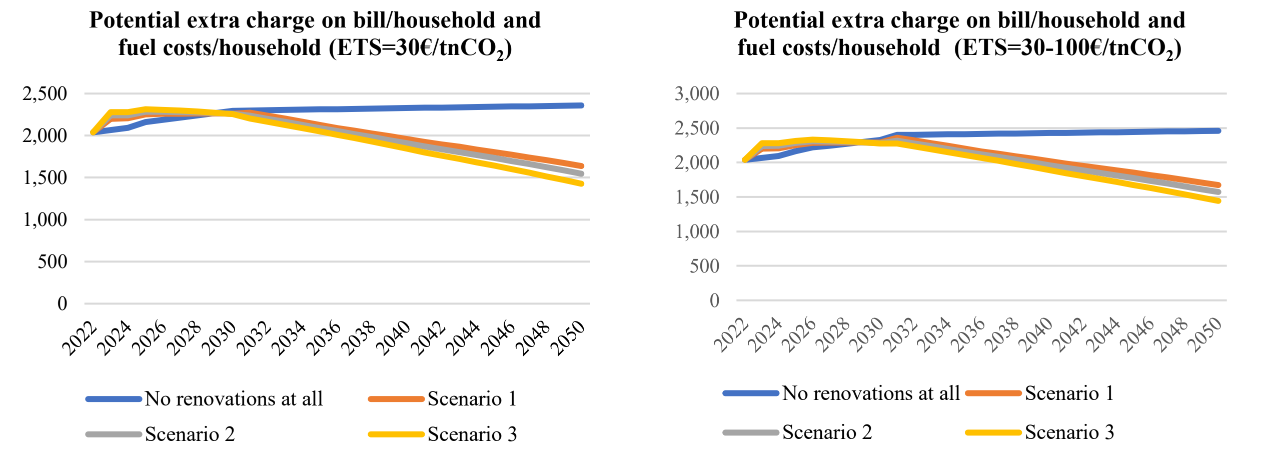


Figure 119. Potential extra charge on bill/household and fuel costs/household for the two potential cases of the Emissions Trading System (ETS) price – Cross-scenario comparison.

Table 77. Total cost savings at both the household and the regional level for the two potential cases of the Emissions Trading System (ETS) price – Cross-scenario comparison.

Total costs in 2050 (ETS, fuel & renovation)	Household level (ETS=30€/tnCO_2)	Regional level (ETS=30€/ tnCO_2)	Household level (ETS=30-100€/ tnCO_2)	Regional level (ETS=30-100€/ tnCO_2)
No renovations	66141	12472.9M	68290	12878.1M
"Scenario 1"	58978	11122.0M	60308	11372.8M
"Scenario 2"	57595	10861.1M	58767	11082.3M
"Scenario 3"	56762	10704.1M	57768	10893.8M

Overall, our findings indicate that investing in electrification increases the financial, environmental, and, thus, social benefits regarding the energy transition towards 2050 in the residential sector in the Peloponnese region. Investing in electrification leads to lower total (ETS, fuel, and renovation) costs at both the household and the regional level, in comparison to investing in natural gas as a transition fuel. Moreover, none of the scenarios under study lead to complete decarbonisation levels. Therefore, we implemented a reverse engineering approach, to explore the proper annual renovation rate so as to decarbonise the residential sector in the Peloponnese region in each one of the scenarios under study. Modelling outcomes of this process are presented in **Table 78**.

Table 78. Annual number of household renovations required at the regional level to achieve decarbonisation in each scenario under study and comparison to the existing annual renovation rate at the national level suggested by the current version of the National Energy and Climate Plan (NECP).

	Annual number of renovations required to achieve decarbonisation	**Comparison to the existing national annual renovation rate**
"Scenario 1"	4115	1.48 · existing renovation rate (~2.2%)
"Scenario 2"	3700	1.33 · existing renovation rate (~2.0%)
"Scenario 3"	3285	1.18 · existing renovation rate (~1.8%)

Again, investing in electrification right from the start ("**Scenario 3**") is the most attractive scenario, as it requires the lowest renovation rate- closer to the existing one suggested by the current version of the NECP. It is followed by "**Scenario 2**", which requires almost 420 more household renovations annually, while "**Scenario 1**", which is the possible to happen, considering the current national planning for investing in natural gas as a transition fuel, is again the less efficient one, as it requires the renovation rate to be increased by almost 1.5 times in order to achieve decarbonisation levels in the Peloponnese region.

*3.3.6.5. **GR-C12**: Investigating energy transition pathways in the residential sector in coal and carbon-intensive regions in Greece: The case of the Megalopolis municipality*

Contributing models: DREEM

Research Questions' Overview

The socially fair and inclusive clean energy transition of coal regions in Europe is envisaged as a top priority of the EU, while a wide array of funding is available at the EU level to finance the transition in these regions. In Greece, the goal of the complete lignite phase-out by 2028 was initially reflected in the forecasts of the NECP (NECP, Government Gazette B' 4893/31-12-2019) (Greek Ministry of Environment and Energy, 2019). The Megalopolis region is characterised as a coal and carbon-intensive region in Greece. The operation of the open-pit lignite mine and the "Megalopolis III" and "Megalopolis IV" lignite-fired units are the dominant economic activities in the region, while a remarkable percentage of the local workforce is employed there. According to the NECP, the lignite mine as well as the lignite units were planned to be withdrawn by 2023. Nevertheless, recent developments over the past three years, i.e., the unprecedented COVID-19 pandemic and Russia's invasion of Ukraine, have ignited discussions about the potential postponement of the decommissioning of the lignite activities to ensure energy security at a national level.

Regarding the residential sector in Megalopolis, which numbers 3545 households, a DH system is covering 30% of the demand for heating and hot water of the building stock of the municipality (Greek Ministry of Environment and Energy, 2019). According to the existing plan, a gas distribution network is under construction and Megalopolis residents will be exempted from connection fees, while the cost of replacement of existing heating systems with gas heating ones will be subsidised. However due to the latest developments and amid an energy price crisis, the EC has developed the "REPowerEU" plan, aiming at diminishing the dependence of the EU national energy systems on Russian natural gas. Thus, the existing plan for the energy transition in the residential sector in the Megalopolis municipality may have to be revised, as the decision to invest in new natural gas infrastructure could cause a lock-in effect, exposing households to high energy costs for the next decades.

In this context, energy transition scenarios towards 2050 in the residential sector in the Megalopolis municipality are examined, aiming at answering the following RQ:

- **RQN7:** When it comes to the transition in the residential sector in the Megalopolis municipality, should we stick to the existing plan and invest in new natural gas infrastructure, or should we invest in electrification right from the start?

Results and Discussion

To explore the energy transition towards 2050 in the residential sector in the Megalopolis municipality, three scenarios are simulated. These scenarios are based on the current NECP renovation rate of 60000 household renovations/year at the national level (~1.5%), adapted to the local level under study, meaning that 52 households should be annually renovated in the Megalopolis municipality. Scenario specifications are presented below:

i. **Scenario 1: "Baseline"**

- **(2023-2028):** Annual natural gas penetration to substitute DH (lignite phase-out target towards 2028). Annual heat pump penetration in order to achieve 300% increase in heat pump installations by 2030. *In this period the renovation rate is around 2.5% to cover for the delignitisation target, which is 250% over the EU and the national plan*.
- **(2028-2040):** Annual natural gas penetration to reach 10.0% of total consumption by 2030 (according to the current NECP targets for 2030). Annual heat pump penetration in order to achieve 300% increase in heat pump installations by 2030. *In this period the renovation rate is ~1.5% as implied by the Greek NECP*.
- **(2041-2050):** Phase-out of the remaining natural gas boilers with heat pumps. Same renovation rate as the one during the period 2030-2040. *In this period the renovation rate is ~1.5% as implied by the Greek NECP*.

ii. **Scenario 2: "Investing in electrification and natural gas & phasing out natural gas"**

- **(2023-2028):** Annual natural gas penetration to substitute DH (lignite phase-out target towards 2028). Annual heat pump penetration in order to achieve 300% increase in heat pump installations by 2030. *In this period the renovation rate is around 2.5% to cover for the delignitisation target, which is 250% over the EU and the national plan*.

- **(2029-2030):** Annual natural gas penetration to reach 10.0% of total consumption by 2030 (according to the current NECP targets for 2030). Annual heat pump penetration in order to achieve 300% increase in heat pump installations by 2030. *In this period the renovation rate is ~1.5% as implied by the Greek NECP*.
- **(2031-2050):** Phase out of existing natural gas boilers with heat pumps. *In this period the renovation rate is ~1.5% as implied by the Greek NECP*.

iii. **Scenario 3: "Investing in electrification"**

- **(2023-2028):** Annual heat pump penetration to substitute DH (lignite phase-out towards 2028). *In this period the renovation rate is around 2.5% to cover for the delignitisation target, which is 250% over the EU and the national plan*.
- **(2023-2050):** Annual heat pump penetration with the same rate as the natural gas boilers in the previous scenarios.

For all the three scenarios under study:

All dwellings that have their heating technology substituted are also renovated through envelope/window upgrades:

- **In dwellings built before 1981:** exterior wall insulation & window replacements.
- **In dwellings built during the period 1981-2000:** exterior wall insulation.

Simulation results for these three scenarios provides us with useful findings regarding the energy transition in the residential sector in the Megalopolis municipality. As shown in **Figure 120**, our findings indicate that both "**Scenario 1**" and "**Scenario 2**" lead to approximately the same FEC (61.8% and 60.7% of the initial consumption levels, respectively), while "**Scenario 3**" leads to greater reduction of the FEC (48% of the initial consumption levels).

Figure 121 presents the evolution of the energy mix by 2050 in the residential sector in the Megalopolis municipality. An interesting observation is the fact that investing in electrification right from the start ("**Scenario 3**") leads to decarbonisation levels by 2050 (fossil fuel consumption is almost eliminated), while "**Scenario 1**" and "**Scenario 2**" lead to 0.67 ktoe and 0.59 ktoe of fossil fuel consumption, respectively. Moreover, we can see that in all three scenarios, eliminating the consumption from DH is achieved.

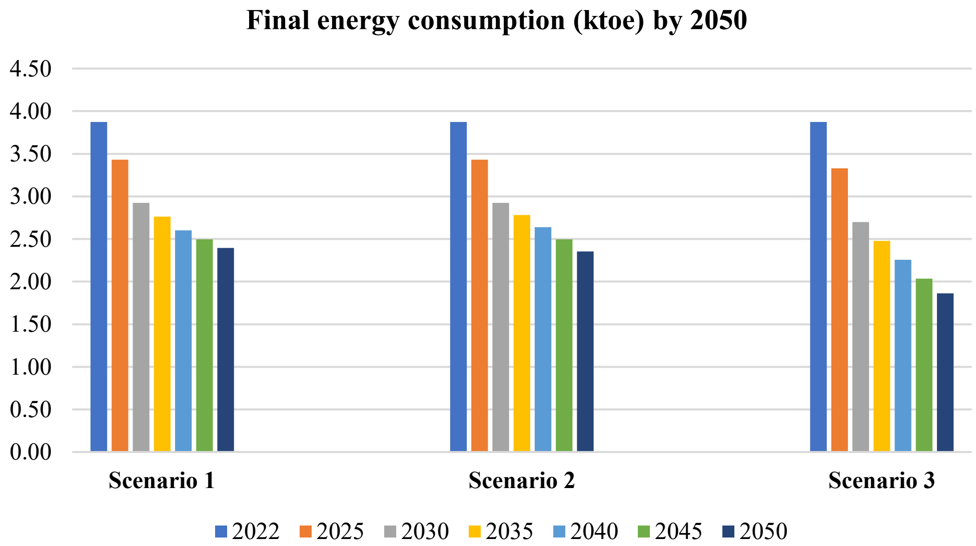
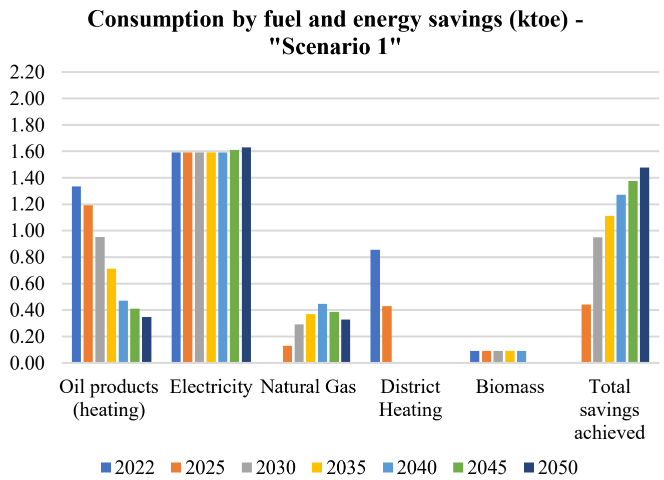
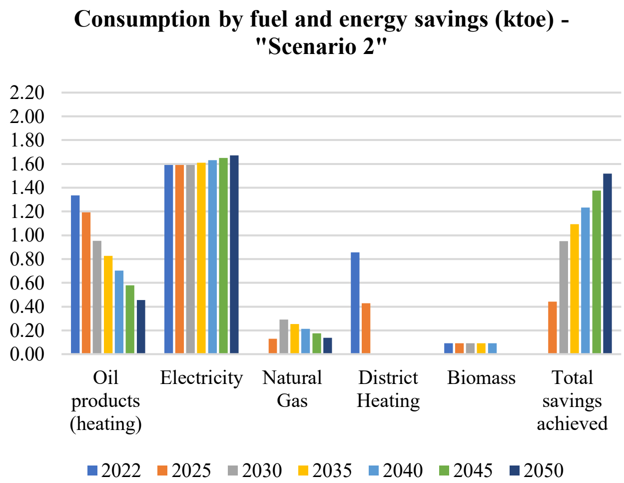


Figure 120. Evolution of the energy mix by 2050 in the residential sector in the Megalopolis municipality – Cross-scenario comparison.





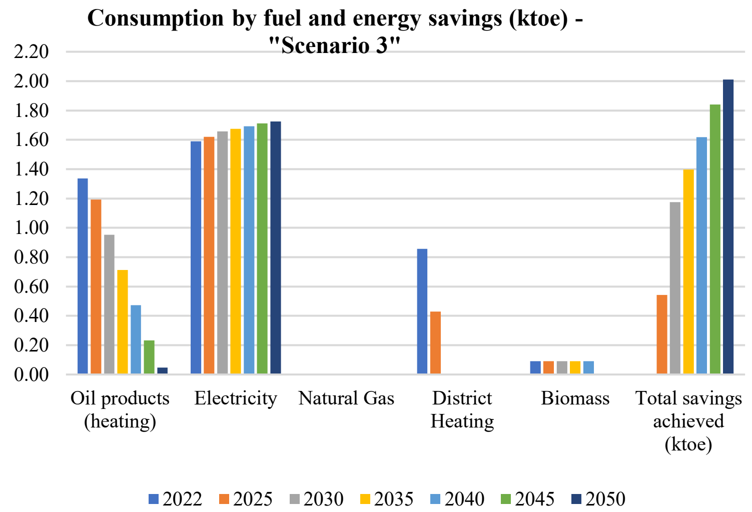


Figure 121. Consumption by fuel and energy savings (ktoe) by 2050 in each one of the transition scenarios under study – Cross-scenario comparison.

In terms of the environmental footprint in each scenario under study, CO_2 emissions are used as an indicator. As shown in **Figure 122**, "**Scenario 3**" leads to the lower levels of CO_2 emissions in 2050 (425 $tnCO_2$), while "**Scenario 1**" and "**Scenario 2**" lead to more than quadruple emissions, namely 2031 $tnCO_2$ and 1895 $tnCO_2$, respectively. Another interesting finding is that during the period 2030-2040, with these renovation rates, "**Scenario 1**" leads to lower emission levels compared to "**Scenario 2**". This is due to the fact that "**Scenario 2**" focuses on phasing out natural gas, which is a more environmentally friendly technology compared to oil boilers.

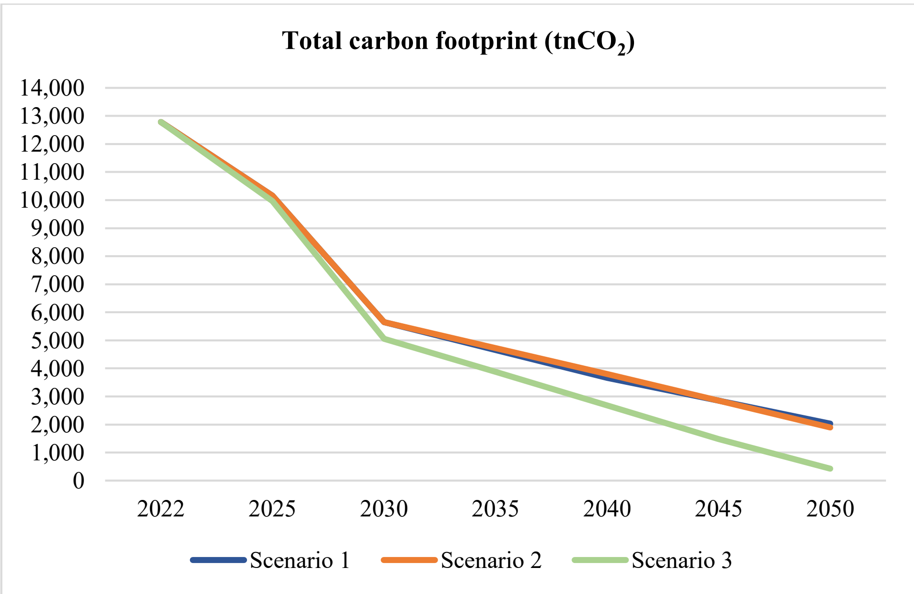


Figure 122. Environmental footprint ($tnCO_2$) by 2050 – Cross-scenario comparison.

Assuming the building sector will be included in a parallel ETS, as also mentioned in cluster **GR-C10** (**Section 3.3.6.3**), two potential cases for the evolution of the ETS price are investigated: **(i).** a constant ETS price at 30€/tnCO_2 for the whole period of the transition (2025-2050, we assume that this parallel ETS in the EU building sector will come into effect in 2025), **(ii).** a changing ETS price with the following trend: 2025 at 30€/tnCO_2, 2026-2030 at 50€/tnCO_2, and 2031-2050 at 100€/tnCO_2. **Figure 123** suggests that in both cases, when investing in electrification ("**Scenario 3**"), ETS costs are reduced. Indicatively, in the case of the increasing ETS price, if compared, "**Scenario 1**" leads in total ETS costs of €6.32M, by 2050, while "**Scenario 3**" leads to €3.87M, reducing the total cost by almost 39%. Moreover, here we can also notice that for the period 2030-2040 the annual ETS costs of "**Scenario 2**" are higher compared to "**Scenario 1**", following the trends of the CO_2 emissions described above.

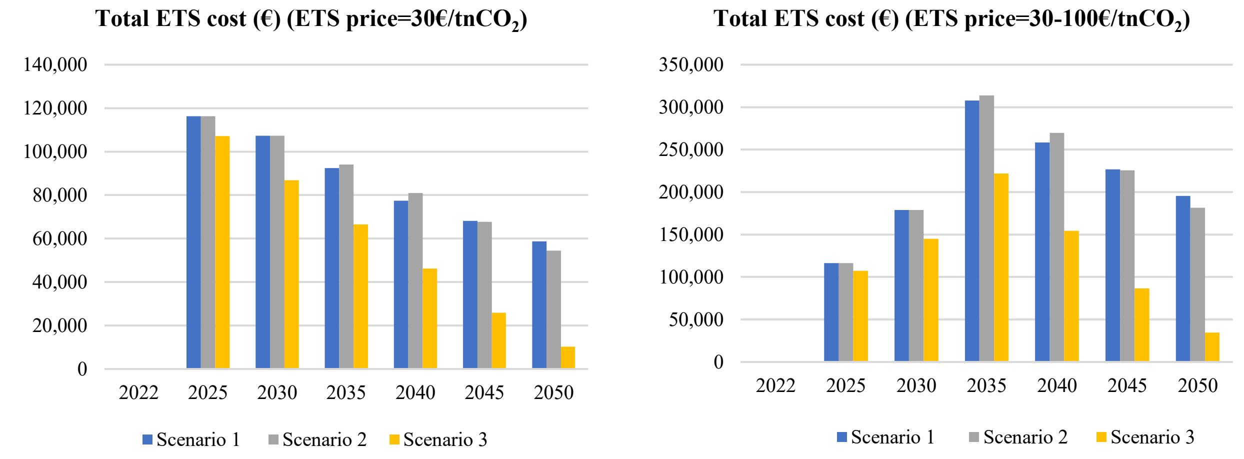


Figure 123. Total Emissions Trading System (ETS) cost for the two potential cases of the ETS price – Cross-scenario comparison.

Except for the ETS costs, the implementation of each one of the three scenarios under study includes different fuel and renovation costs. As shown in **Table 79** and **Table 80**, focusing on investing in electrification ("**Scenario 3**") compared to investing in natural gas ("**Scenario 1**" and "**Scenario 2**") leads to lower annual fuel costs and increasing annual fuel cost savings. "**Scenario 1**" leads to a total of €22.96M of fuel cost savings by 2050, "**Scenario 2**" saves €21.83M of fuel costs during the same period, while "**Scenario 3**" saves €42.13M in total.

Table 79. Energy transition in the residential sector in the Megalopolis municipality: Fuel costs – Cross-scenario comparison.

Fuel costs (€)	2022	2025	2030	2035	2040	2045	2050
No renovations	6.14M	6.37M	6.74M	6.77M	6.81M	6.84M	6.88M
"Scenario 1"	6.14M	6.33M	6.46M	6.08M	5.67M	5.40M	5.11M
"Scenario 2"	6.14M	6.33M	6.46M	6.16M	5.82M	5.44M	5.03M
"Scenario 3"	6.14M	6.17M	6.04M	5.51M	4.93M	4.29M	3.74M

Table 80. Energy transition in the residential sector in the Megalopolis municipality: Fuel cost savings – Cross-scenario comparison.

Fuel cost savings (€)	2022	2025	2030	2035	2040	2045	2050
"Scenario 1"	-	0.04M	0.28M	0.69M	1.14M	1.44M	1.77M
"Scenario 2"	-	0.04M	0.28M	0.61M	0.99M	1.40M	1.85M
"Scenario 3"	-	0.20M	0.70M	1.26M	1.88M	2.55M	3.14M

Finally, in terms of renovation costs, as shown in **Figure 124,** the scenarios that focus more on investing in electrification instead of natural gas includes higher costs. Moreover, the earlier the phase-out of natural gas, the higher the annual costs. More specifically, "**Scenario 2**" is more expensive than "**Scenario 1**", and "**Scenario 3**" is more expensive than the other two. These cost differences are mainly formulated during the period 2022-2030, as this is the period that the scenarios are using the most different pathways. However, it should be noted that infrastructure and other indirect costs are not included in the renovation costs. Only costs to be paid by consumers/households are included.

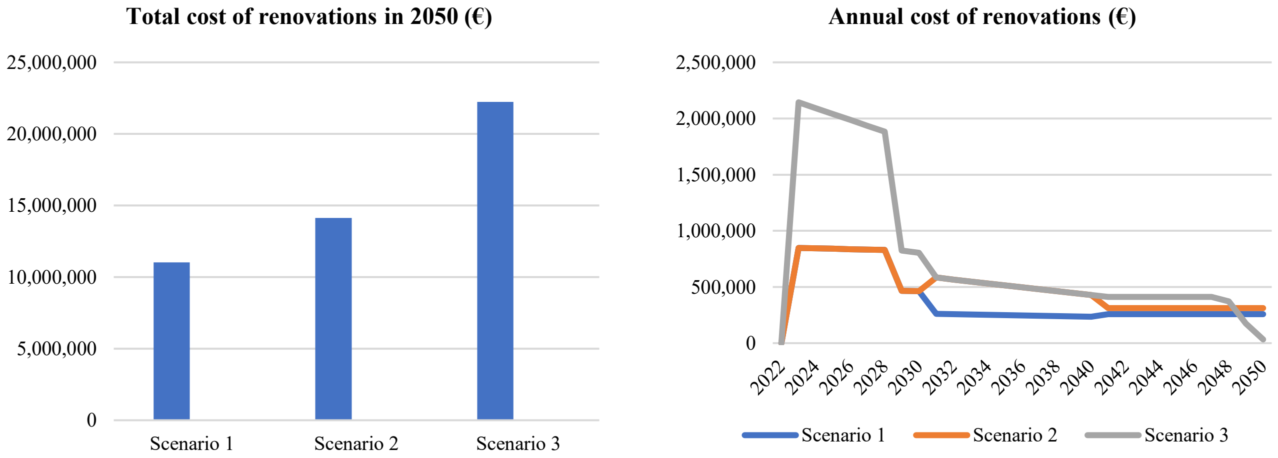


Figure 124. Energy transition in the residential sector in the Megalopolis municipality: Total and annual costs of renovation – Cross-scenario comparison.

To extract a robust and useful comparison regarding the financial viability of each energy transition scenario we aggregated the individual costs (ETS, fuel, and renovation costs), first at the household, and then at the local level. **Figure 125** presents the potential extra charge at the household level if each scenario's total cost is equally divided in each household in the Megalopolis municipality, for the two potential cases of the ETS price. In both cases, all three scenarios lead to reduced annual costs per household by 2050 compared to not proceeding with any renovation. Furthermore, after 2030, investing in electrification ("**Scenario 3**") leads to lower annual costs, while as shown in **Table 81**, the same scenario decreases the total cost during the transition period at both the household and the municipality level. Moreover, another interesting observation is that after investing in natural gas as a transition fuel ("**Scenario 1**" and "**Scenario 2**"), the earlier the phase-out, the higher the total costs at both the household and the local level.

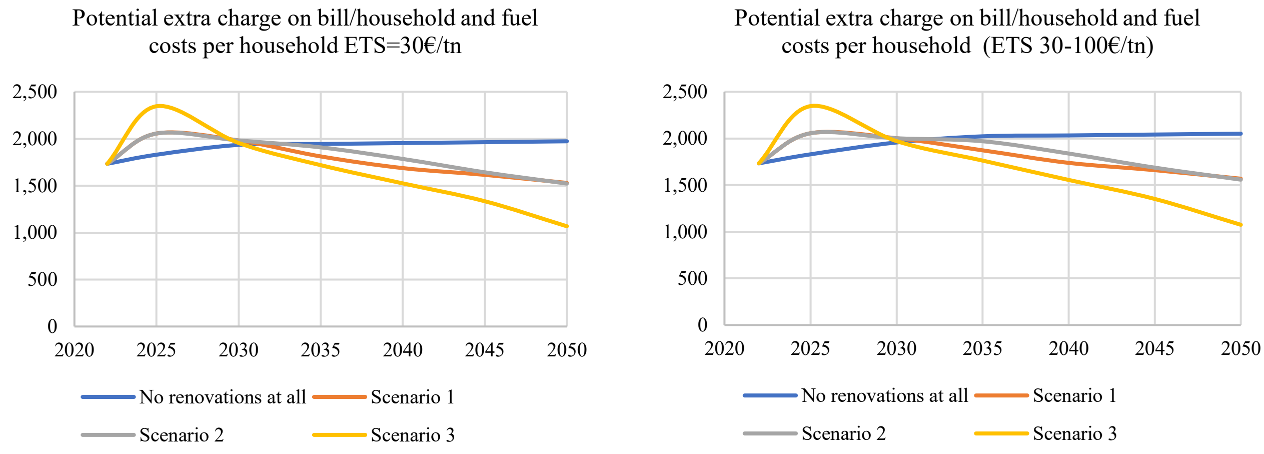


Figure 125. Potential extra charge on bill/household and fuel costs/household for the two potential cases of the Emissions Trading System (ETS) price – Cross-scenario comparison.

Table 81. Total cost savings at both the household and the municipality level for the two potential cases of the Emissions Trading System (ETS) price – Cross-scenario comparison.

Total costs in 2050 (ETS, fuel & renovation)	Household level (ETS=30€/tnCO_2)	Local level (ETS=30€/tnCO_2)	Household level (ETS=30-100€/tnCO_2)	Local level (ETS=30-100€/tnCO_2)
No renovations	55653	197.3M	57337	203.3M
“Scenario 1”	52048	184.5M	53194	188.6M
“Scenario 2”	53245	188.7M	54398	192.8M
“Scenario 3”	49580	175.8M	50256	178.1M

Overall, our findings indicate that investing in electrification leads to lower ETS and fuel costs in the long run, while renovation costs are higher in “**Scenario 3**”. Nevertheless, investing in electrification right from the start (“**Scenario 3**”) leads to lower total (ETS, fuel, and renovation) costs at both the household and the municipality level, compared to investing in natural gas as a transition fuel. Note that in our study we do not consider infrastructure and other costs, which are not accounted to households and could increase the total investment cost of using natural gas as a transition fuel. Therefore, investing in electrification right from the start is the most efficient scenario in terms of energy consumption reduction, environmental footprint, and potential extra charges on household bills. Moreover, in the long run, households’ extra charge from the replacement of existing oil boilers with gas boilers will amplify the energy poverty phenomenon in the region as it results to increased costs. Tailored energy-efficiency support programmes for such regions in transition, promoting the electrification could directly contribute to the reduction of household energy costs and indirectly to the labour market and economic growth, especially in the short term of the transition process.

3.3.7. Demand-response and digitalisation

3.3.7.1. ***GR-C13****: Assessing the benefits of electricity self-consumption coupled with demand-response innovative schemes*

Contributing models: DREEM

Research Questions' Overview

Further deployment of RES and reducing total demand are considered critical in decarbonising the electricity system (Nikas et al., 2018). However, one of the main challenges of a transition based on a high RES penetration is integrating these VRES without jeopardising security, reliability, and resilience of the electricity system (Schlachtberger et al., 2016). Key solution to this end is DSM, encompassing the entire range of management functions associated with directing demand-side activities, including programme planning, evaluation, implementation, and monitoring. Its main objective is to improve the energy system at the side of the end-user in terms of consumption and cost effectiveness (Lampropoulos et al., 2013). Different aspects of DSM range from improving energy efficiency up to sophisticated real-time control of distributed energy resources through smart devices with incentives for promoting certain consumption/production patterns (Palensky and Dietrich, 2011). By doing so, DSM adds significant economic value to all actors involved and interacting with each other in the modern energy network, while reduces carbon footprint of conventional generators at the same time (Albadi and El-Saadany, 2007).

Furthermore, regarding the future of power grids, it is often stated that residential end-users will play a more active role in the management of electric power supply and demand, transitioning from passive consumers to active co-providers called "prosumers" (Parag and Sovacool, 2016). However, end-use products and services need to be considered for such a transition (Geelen et al., 2013). To this end, to foster their role and evaluate their impact into the future energy regime, modelling of user interaction and resource management needs to be considered first through DSM modelling exercises. Indicatively, DSM modelling can support electricity distribution network operators for modelling of network peak demand, demand aggregators for estimation of potential demand-side flexibility, government agencies for assessing incentive scheme costs, or electricity retailers for understanding the impact of different technology adoption upon their demand portfolio. Thus, accurate DSM modelling could be beneficial for testing DR schemes that are primarily offered to residential customers and could provide directions for the development of products and services related to the smart-grid paradigm. Considering the above, in this section we answer the following RQ, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ54:** What are the costs and benefits of combining electricity storage with DR technologies and how are these benefits distributed between actors in the electricity supply chain? What financial incentives should be applied to attract consumers' participation?

Results and Discussion

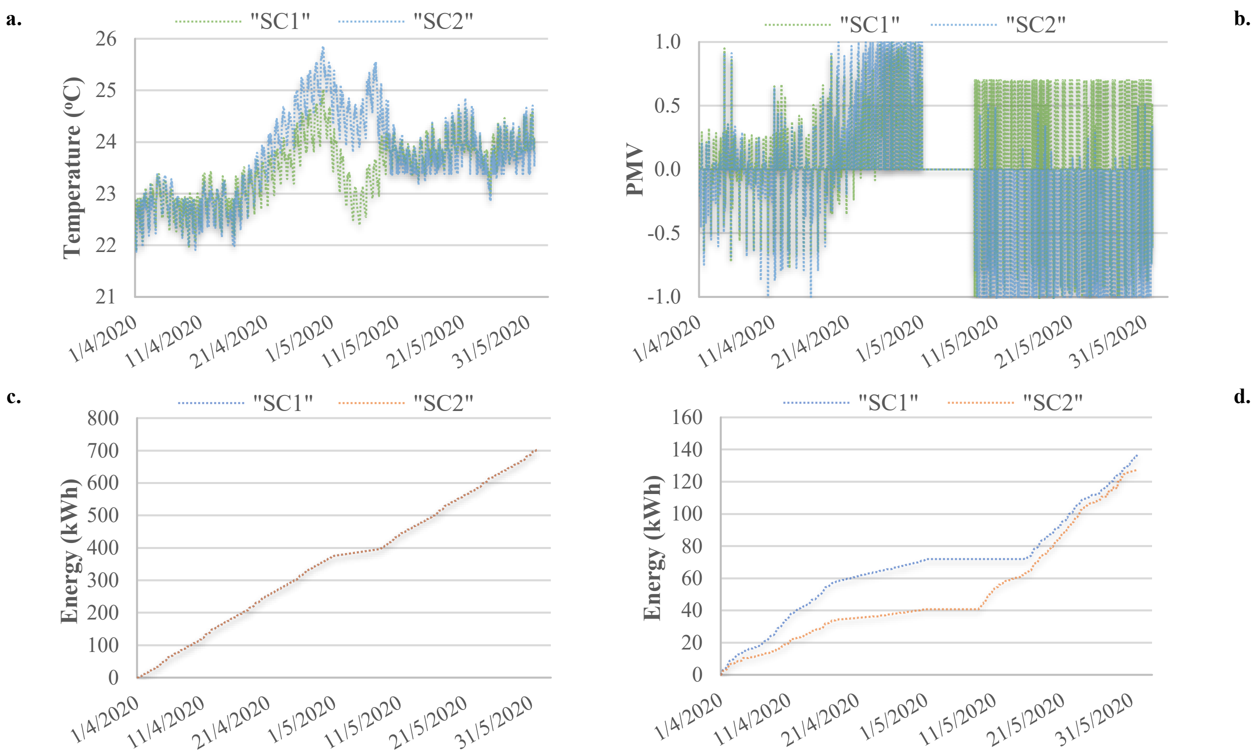
Following the DREEM-specific assumptions presented above (**Section 3.3.2.6**), the following two scenarios are tested:

iv. **Business-As-Usual ("SC1"):** The family under study consumes energy according to their daily needs, maintaining indoor temperature at comfort levels.

v. **Flexibility through provision of services to the grid ("SC2"):** The family under study invests in solar PV and electricity storage installations, a smart thermostat, and an advanced control device that regulates the dwelling's energy performance, while complying, if possible, to market dynamic DR price-based signals. The suggested control function ensures that RES self-consumption and thermal comfort of occupants are not compromised. As a result, the potential for additional revenue and benefits through the provision of services to the grid is evaluated.

Figure 126, **Figure 127**, **Figure 128**, **Figure 129**, and **Figure 130** present simulation results for both the scenarios "**SC1**" and "**SC2**", and all seasonal profiles considered. Additionally, **Table 82** summarises the benefits of demand-flexibility for consumers in the residential sector in Greece, if they invest in PV and storage installations, along with smart devices (i.e., smart thermostat and energy management control system), while motivated to comply with dynamic price-based DR signals ("**SC2**"), compared to the baseline scenario ("**SC1**").

i. **Period 1 - Mild weather**



e.

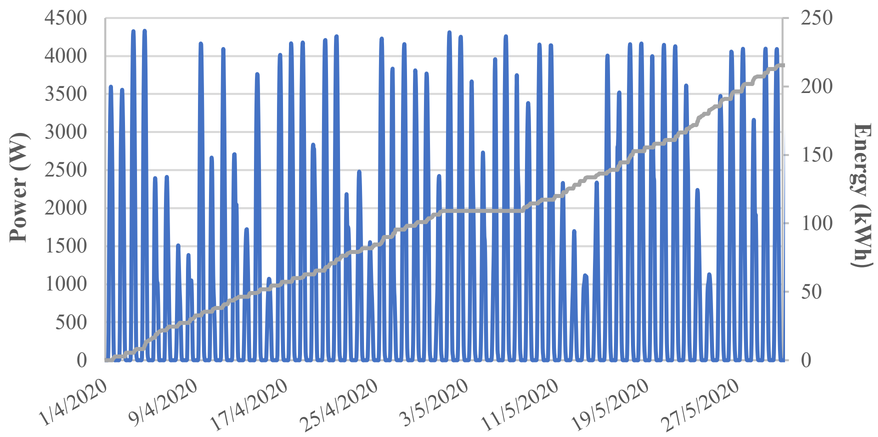
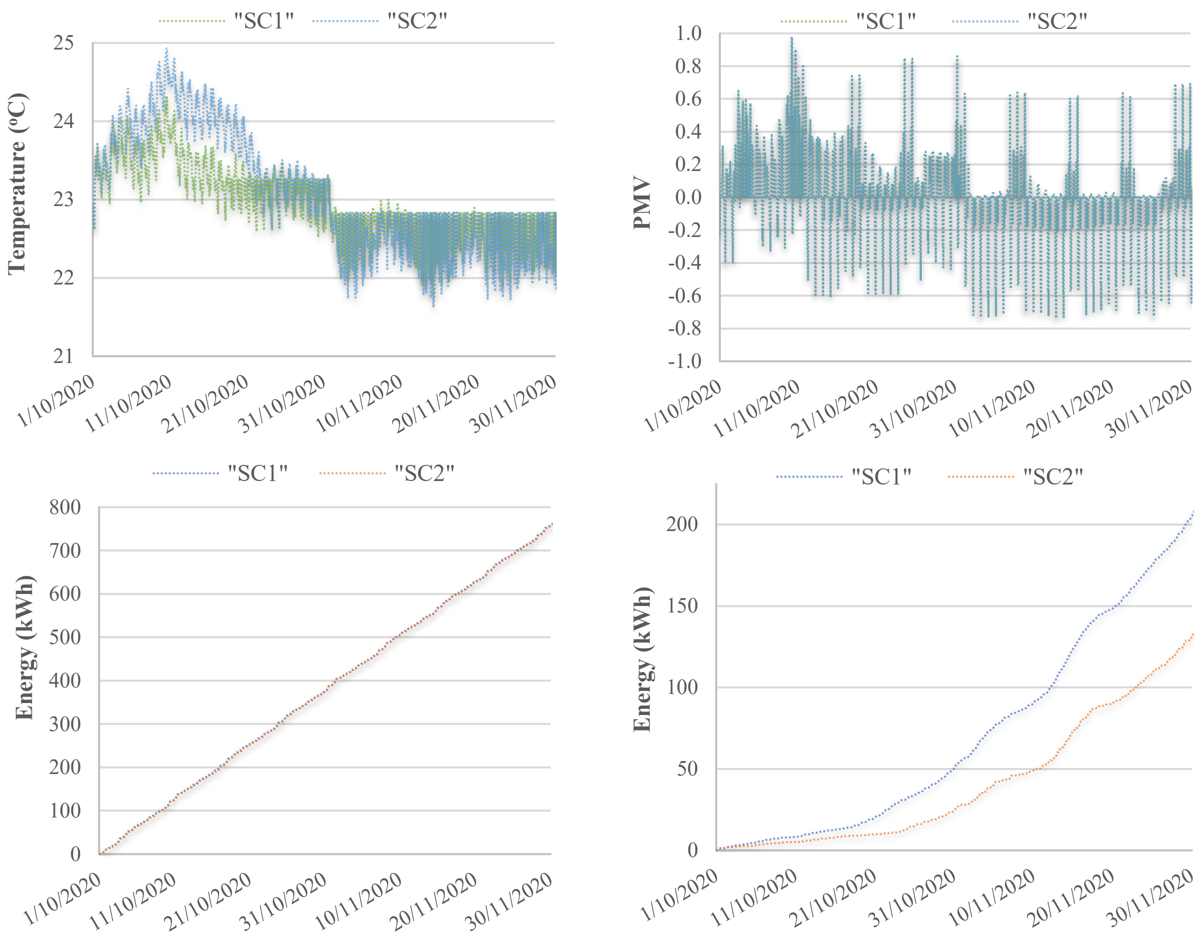


Figure 126. Simulation outcomes for the period April-May 2020, for both scenarios under study. **a.** Indoor temperature (ºC), **b.** Predicted Mean Vote (PMV)-index of thermal comfort, **c.** Cumulative energy consumption (kWh) of appliances, **d.** Cumulative energy consumption (kWh) of the Heating, Ventilation, and Air Conditioning system, and **e.** Solar power (W) generation and energy (kWh) self-consumption, owing to the Photovoltaics-battery installations for the scenario "**SC2**".

a. b.



c. d.

e.

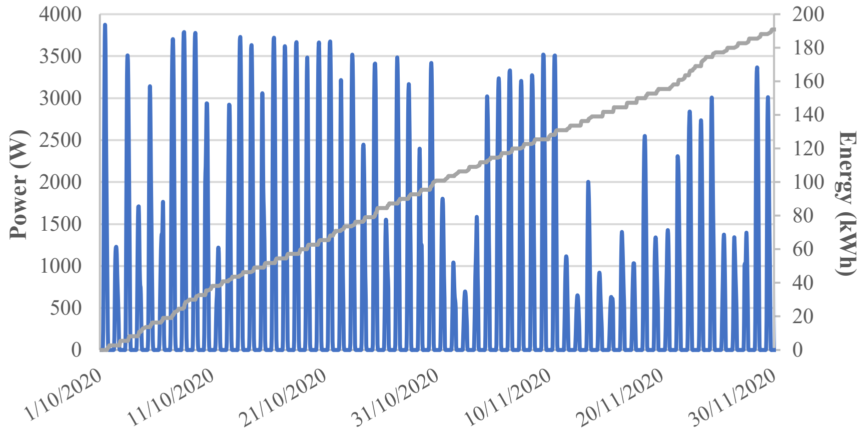
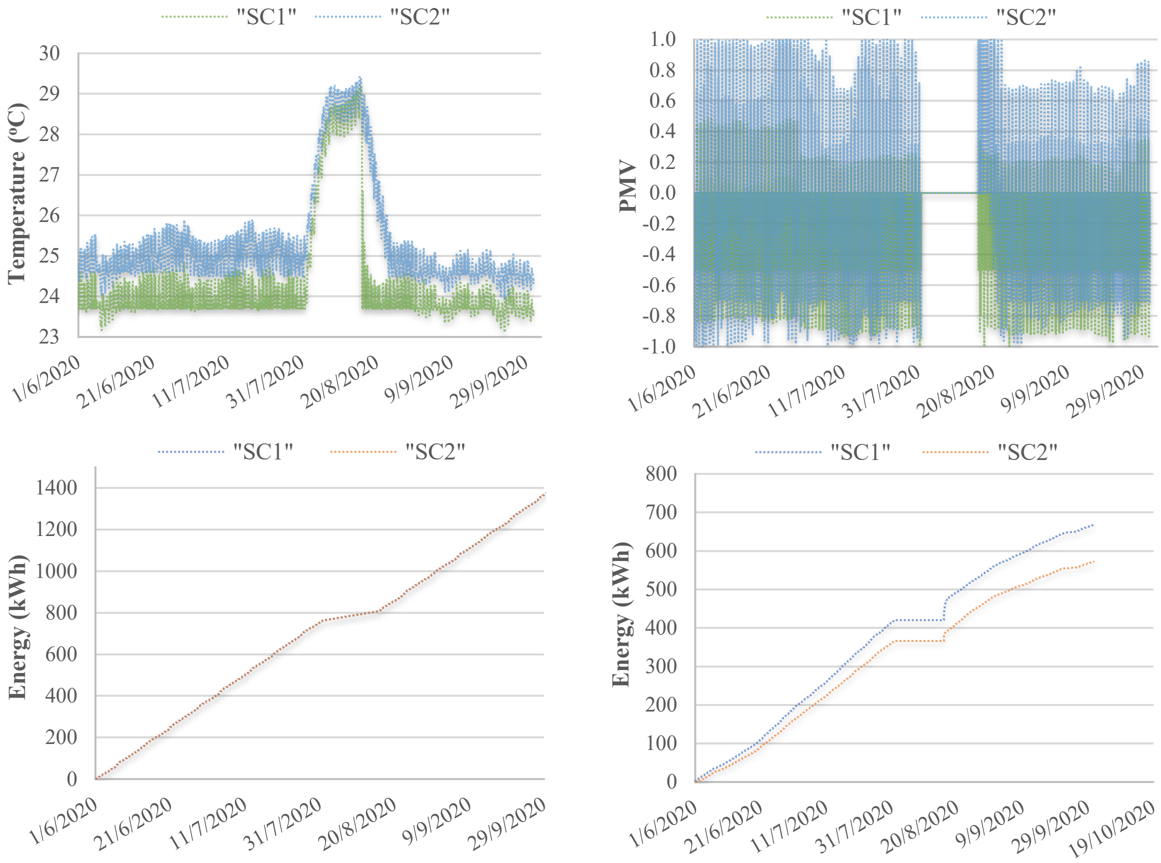


Figure 127. Simulation outcomes for the period October-November 2020, for both scenarios under study. **a.** Indoor temperature (°C), **b.** Predicted Mean Vote (PMV)-index of thermal comfort, **c.** Cumulative energy consumption (kWh) of appliances, **d.** Cumulative energy consumption (kWh) of the Heating, Ventilation, and Air Conditioning system, and **e.** Solar power (W) generation and energy (kWh) self-consumption, owing to the Photovoltaics-battery installations, for the scenario "**SC2**".

ii. Period 2 - Hot weather

a. b. c. d.



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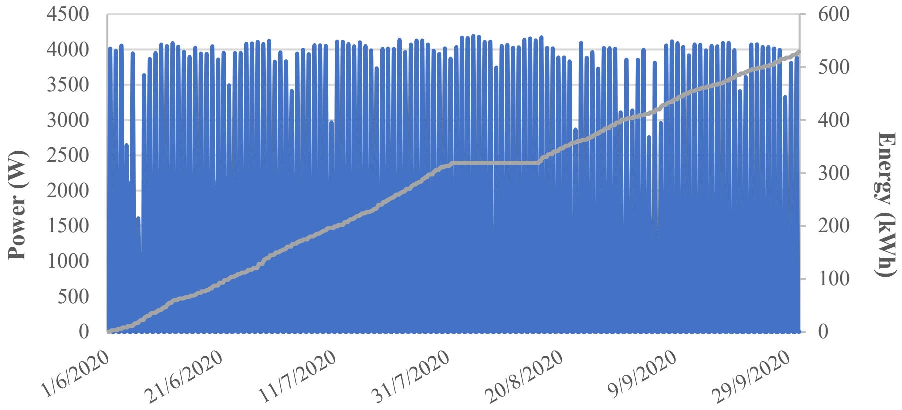
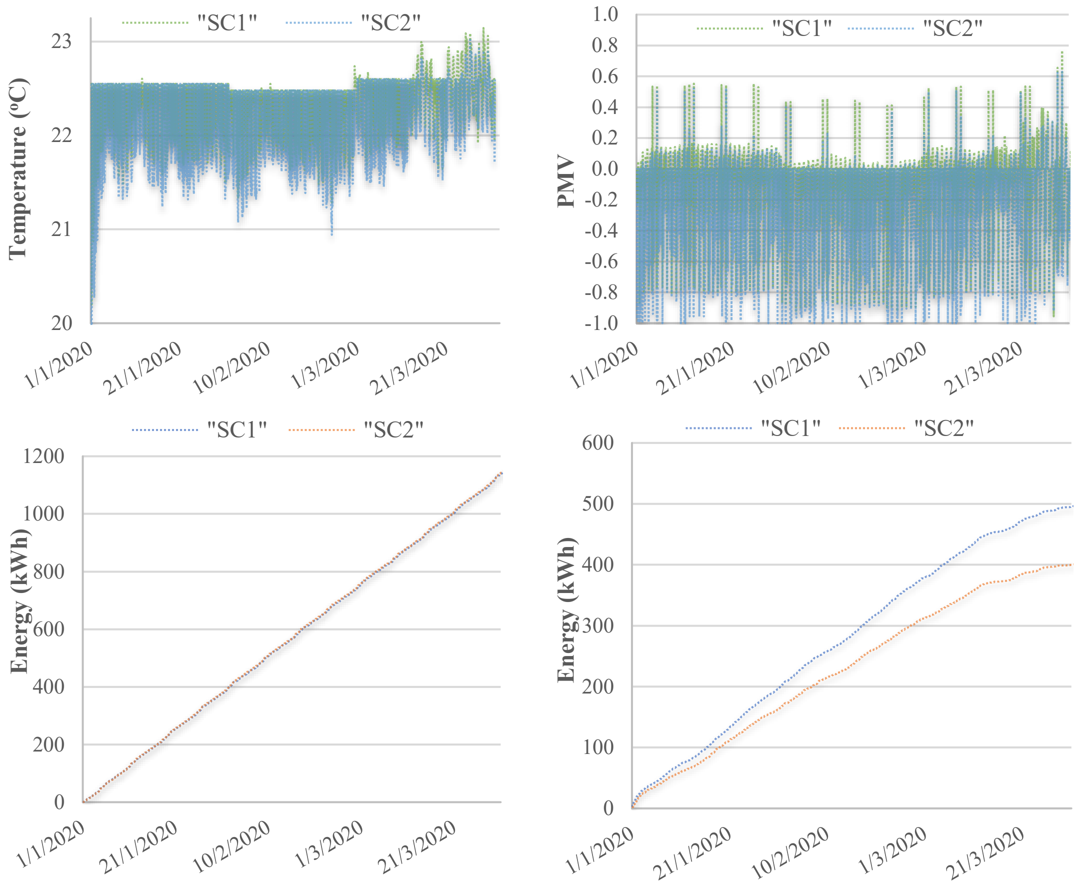


Figure 128. Simulation outcomes for the period June-September 2020, for both scenarios under study. **a.** Indoor temperature (ºC), **b.** Predicted Mean Vote (PMV)-index of thermal comfort, **c.** Cumulative energy consumption (kWh) of appliances, **d.** Cumulative energy consumption of the Heating, Ventilation, and Air Conditioning system (kWh), and **e.** Solar power generation (W), and energy self-consumption (kWh), owing to the Photovoltaics-battery installations, for the scenario "**SC2**".

iii. Period 3 - Cold weather

a. b.

c. d.



e.

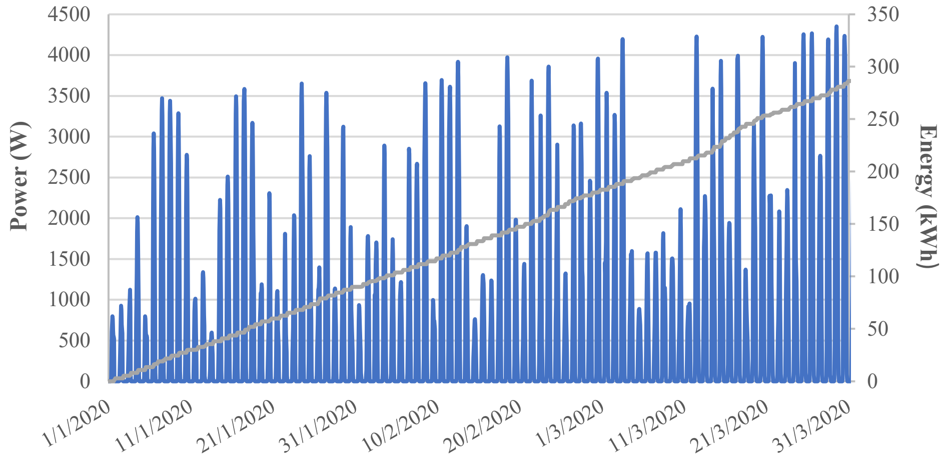
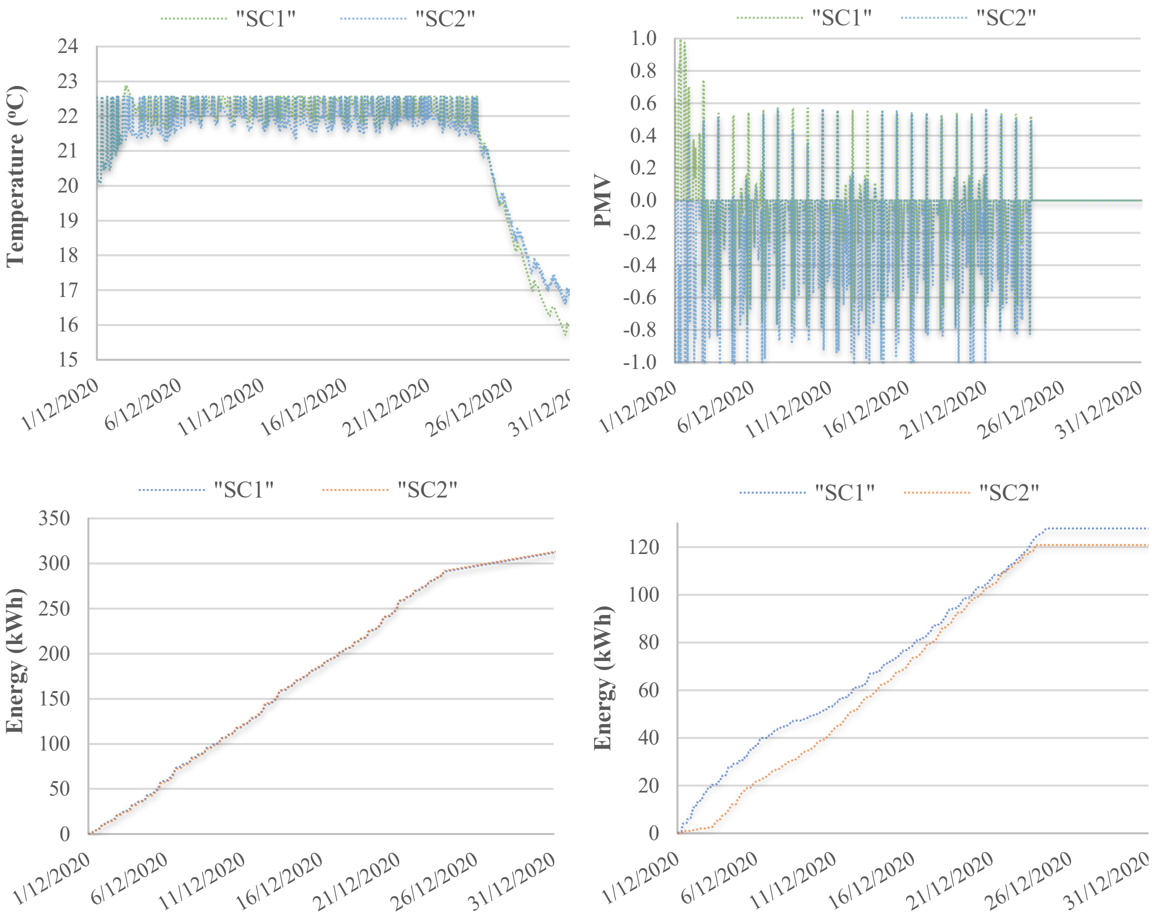


Figure 129. Simulation outcomes for the period January-March 2020, for both scenarios under study. **a.** Indoor temperature (°C), **b.** Predicted Mean Vote (PMV)-index of thermal comfort, **c.** Cumulative energy consumption (kWh) of appliances, **d.** Cumulative energy consumption of the Heating, Ventilation, and Air Conditioning system (kWh), and **e.** Solar power generation (W), and energy self-consumption (kWh), owing to the Photovoltaics-battery installations, for the scenario "**SC2**".

a. b.

c. d.



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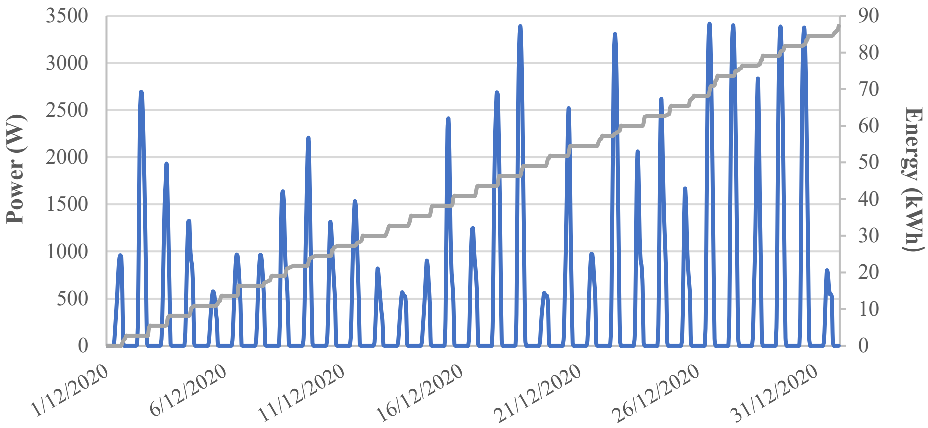

Figure 130. Simulation outcomes for the period of December 2020, for both scenarios under study. **a.** Indoor temperature (°C), **b.** Predicted Mean Vote (PMV)-index of thermal comfort, **c.** Cumulative energy consumption (kWh) of appliances, **d.** Cumulative energy consumption of the Heating, Ventilation, and Air Conditioning system (kWh), and **e.** Solar power generation (W), and energy self-consumption (kWh), owing to the Photovoltaics-battery installations, for the scenario "**SC2**".

Table 82. Quantified benefits of demand-flexibility and self-consumption for consumers in the residential sector in Greece for the building envelope under study.

Total energy savings (kWh)					**Total cost savings (€)**				
Period 1		**Period 2**	**Period 3**		**Period 1**		**Period 2**	**Period 3**	
Ap-My	**Oc-No**	**Jn-Se**	**Ja-Ma**	**De**	**Ap-My**	**Oc-No**	**Jn-Se**	**Ja-Ma**	**De**
228.3 (27.14%)	266.3 (27.18%)		386.0 (23.41%)	88.4 (20.13%)			-		
497.3 (27.31%)		626.0 (30.43%)	475.6 (22.78%)		91.9 (31.23%)		179.7 (45.08%)	143.8 (35.57%)	
		1,598.9 (26.80%)					**416.4 (37.86%)**		

Simulation results for the scenario "**SC1**" showed that the total annual electricity consumption for the case under study is 5969.3 kWh. Assuming that consumers pay the "G_1" tariff, the annual competitive electricity charges are €1098.1. On the other hand, results from scenario "**SC2**" indicate that, if the family under study invest in solar PV and storage installations, along with smart thermostat and energy management control system infrastructure and agreed to a dynamic price-based DR regime, total annual electricity consumption would be 4365.8 kWh. In this case competitive electricity charges would be €681.9, while energy savings of 1603.8 kWh and financial savings of €416.4 could be achieved. In summary, modelling findings indicate that PV self-consumption with storage and other infrastructure combined with dynamic price-based DR signals, could bring significant savings to consumers, mainly due to less electricity absorbed from the grid. This is also validated by literature studies acknowledging that the effect of load shifting is more effective if combined with PV self-consumption because of the diurnal cycle of PV, and the fact that many shiftable load follow the same diurnal cycle pattern (Salpakari et al., 2016).

However, literature studies acknowledge that PV self-consumption can be fundamentally negative for power suppliers (Eyre et al., 2017). Especially in Greece, Nikas et al. (2019) showed that allowing PV self-consumption with storage in the residential sector, could force generators to bid higher prices for their capacity, leading to an increase in the retail price of electricity. This way generators and suppliers could counterbalance revenue losses owing to self-consumption and the limited flexibility in the current Greek electricity market (Nikas et al., 2018). These results highlighted a consequential risk that must be incorporated into future policymaking, as this development could expose vulnerable social groups and customers to burdensome charges.

Additionally, successful DR mainly depends on the capabilities of end-users in altering their loads with a favourable manner for both the power suppliers and themselves (Yan et al., 2015). To this end, results from the reinforcement learning algorithm (**Figure 131**) showed that occupants, during the one-year period of simulation, could comply with 75.06% of the total signals issued, altering their demand and adjusting thermostat setpoints to less comfortable levels, with a favourable manner for both suppliers and themselves.

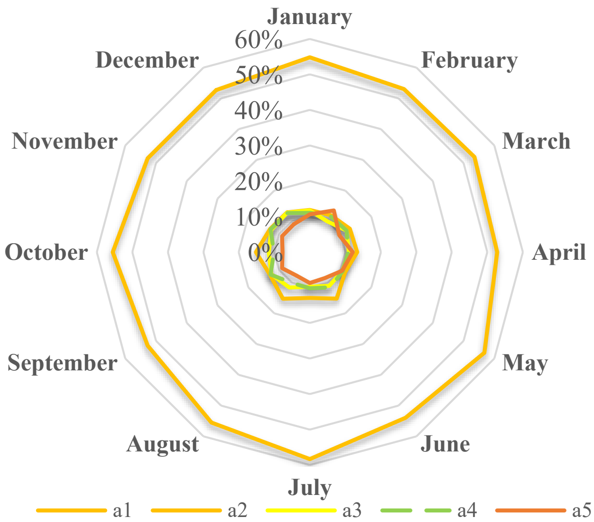

Figure 131. Quantification of the optimal demand-response policy according to the reinforcement learning algorithm used in the DREEM model.

In particular, simulation results showed that supporting smart self-consumption in Greece through dynamic price-based signals allows the electricity supplier to counterbalance revenue losses due to self-consumption by a margin of 13.15%, which given the charges assumed, equals to €33 per household annually. Scaling up at a national level, this is equivalent to a total offset in the range of €239M to €256M. On the other hand, though, simulation results showed that promoting the full electrification of heating/cooling in the Greek residential sector, could bring suppliers an additional annual revenue of €266.24 per household, which scaling up at a national level is equivalent to a total profit in the range of €1.92B to €2.06B. Of course, these estimations are rather conservative, considering that the building envelope under study is considered highly energy efficient. So, this exercise should be further explored for all the residential building typologies in Greece to have a clearer overview.

However, our modelling results provide strong evidence that by promoting smart self-consumption, along with the electrification of the heating sector in Greece, revenue losses could be offset and that considerable profits for energy suppliers could be achieved. As a result, further revenue opportunities for energy suppliers could also rise through the promotion of electrical smart building-scale technologies that allow energy savings, coupled with electricity generation from RES. This is also acknowledged by scientific literature suggesting a strong technoeconomic viability when integrating smart air-conditioning systems with solar PV generation (Novaes Pires Leite et al., 2019).

While modelling findings suggest that a shift to a decentralised vision of a low-carbon future electricity system in Greece, where consumers generate and store clean energy locally, and are motivated to comply with dynamic price-based DR signals, is a "win-win" situation for all the actors involved, an important implication should be highlighted: Part of this future electricity infrastructure will be only developed if consumers are willing to invest in the technological capabilities required. Before consumers choose to expose themselves to bilateral dynamic electricity price-based contracts with their suppliers, they should first pursue the technological capabilities that enable demand-flexibility. Considering that it is unlikely for consumers to invest in new technological capabilities having flexibility of the electricity system as their primary goal, it is reasonable to assume that consumers may only invest according to a value stemming from increased proportion of the self-produced electricity that they consume. While technological infrastructure is already available, business models and regulatory innovation are needed in order to find ways to maximise the value of the technological capabilities required as well as to monetize them in order to compensate consumers. This is also acknowledged by recent studies in the scientific literature (Li et al., 2019).

3.3.8. Environmental impacts

3.3.8.1. ***GR-C14:*** *Cross-sectoral emissions and the effect of emission targets on the electricity system*

Contributing models: QTDIAN, EMMA, BSAM, and WEGDYN

Research Questions' Overview

From 2005 to 2019 (pre Covid-19 period), Greece reduced its verified GHG emissions by 40.9% (from 160.3 to 94.8 million tonnes). With the additional effect of Covid-19, Greece further reduced its verified GHG emissions by 19.4 million tonnes between 2019 and 2020 achieving a total reduction equal to 52.9% between 2005 and 2020 (European Environment Agency, 2021). The reduction in total emissions in Greece was primarily achieved due to the decline in the emissions from the electricity and heat generation sector (-62%), the largest emitting sector in the country (Orfanos et al., 2019), mainly during the third phase of the EU-ETS (between 2013-2020) (Chatzieleftheriou and Mantzaris, 2021). More specifically, emission reduction in this sector is mainly attributed to the drastic reduction of lignite activity, especially since 2018, stemming from the large increase in carbon emission costs of lignite units due to the EU-ETS carbon price (Greek Ministry of Environment and Energy, 2019). However, a large part of the electricity production from lignite was replaced by fossil gas, causing a significant increase in emissions from fossil gas in Greece (+44% in 2020 compared to 2013). Considering the above, in this section we answer the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ60:** How are the average GHG emissions (by economic sector) expected to evolve in the Greek energy system under different transition pathways (under the "**RF_2030**", "**RF_2050**", "**RE_2050**", and "**P2X_2050**" scenarios)?
- **RQ61:** How are the average GHG emissions in the Greek electricity system expected to evolve under high RES penetration and reduced contributions from conventional GUs? What are the macroeconomic implications?

Results and Discussion

Emissions by sector and macroeconomic implications for a climate-neutral transformation (WEGDYN results)

Regarding the expected evolution of the GHG emissions by economic sector (**RQ60**), the change in sectoral shares of CO_2 emissions in Greece are reported in **Figure 132** for the **MDR**, **GDI**, and **PPO** storylines consistent with the EU27+ reduction target. While benchmark emissions in Greece are dominated by water transport, land transport, and electricity, only the emissions of the latter (almost) vanish already by 2030 due to the (almost complete) phase-out of fossil-fired generation across storylines (**Figure 79**) and there are still substantial emissions from road and water transportation, particularly for freight. Only further integration and upscaling of climate-neutral energy carriers, such as biofuels also brings connected emissions down. Electricity system's emission reduction in Greece are shown in **Figure 132** and unfolding macroeconomic implications in **Figure 87** under cluster **GR-C2 (Section 3.3.3.2)**.

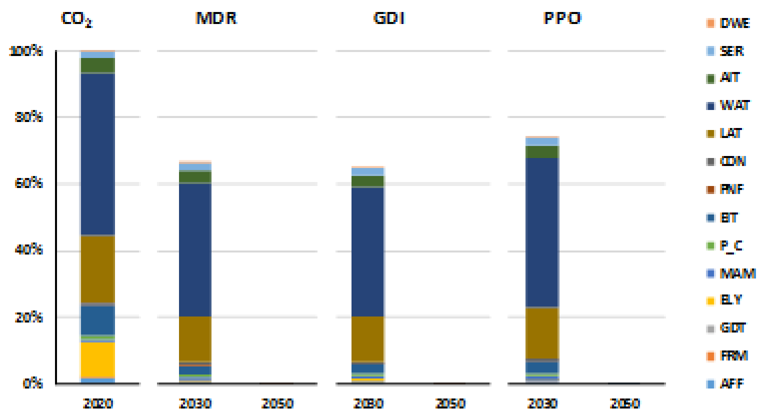

Figure 132. Share of sectoral Carbon Dioxide (CO_2) emissions in Greece across storylines; AFF: Agriculture, Forestry and Fishery; FRM: Fossil Resource and Mineral extraction; GDT: Gas distribution and hot water supply; ELY: Electricity; MAM: Manufacturing and Machinery; P_C: Refined oil products ; EIT: Emission intensive and trade exposed; PNF: Manufacture of precious and non-ferrous metals, and fabricated metal products; CON: Construction; LAT: Transport – Land; WAT: Transport –Water; AIT: Transport –Air; SER: Other services ; DWE: Dwellings and real estate. Further details in the Continental CS section.

Electricity system's emissions

RF scenario (BSAM results)

Regarding the expected evolution of GHG emissions in the Greek electricity system (first part of **RQ61**), **Table 83** is showing the total CO_2 emissions from electricity generation and their percentile reduction compared to 2019 (pre Covid-19 period) for each case. According to **Table 83**, a significant reduction in CO_2 emissions by 2030 is projected, with emissions in the "**IPTO-Baseline**" case being expected to drop by 61.7% compared to 2019, when about 24 million tonnes of CO_2 were emitted due to electricity generation (IEA, 2020c). Higher penetration of electricity production from solar and wind in the "**IPTO-Green Deal**" and "**EMMA-BSAM**" cases lead to larger emission mitigation in 2030 (4.6% and 5.8% difference with the "**IPTO-Baseline**" case respectively). Such emission drops are in line with existing studies (Koltsaklis et al., 2020) and are attributed to the increased displacement of thermal generation by VRES.

However, when considering the long-term decarbonisation in the power sector, in the "**IPTO-Baseline**" case, total emissions increase due to the rise in the electricity demand, which results in higher natural gas electricity generation in terms of energy output (**Table 58** in cluster **GR-C1 (Section 3.3.3.1)**) despite its reduced contribution to the generation mix. In fact, in 2050, we find much higher emissions compared to those included in the LTS50 (i.e., 3 million tonnes of CO_2) (Greek Ministry of Environment and Energy, 2020). This indicates that the contribution of thermal units to the electricity mix alone is not an indicator for the achievement of emission targets, since it is dependent on the increasing electricity demand trends. Instead, a reduction in the total energy output from these units (therefore more VRES capacity) should be considered as target towards set carbon emission reduction pledges, like in the "**IPTO-Green Deal**" and "**EMMA-BSAM**" cases.

Table 83. Carbon Dioxide (CO_2) emissions from electricity generation.

	"IPTO-Baseline" (2030)	**"IPTO-Green Deal" (2030)**	**"EMMA-BSAM" (2030)**	**"IPTO-Baseline" (2050)**	**"EMMA-BSAM" (2050)**
CO_2 emissions (million $tnCO_2$)	9.2	8.1	7.8	10.8	6.9
Emission reductions from 2019 (%)	61.7	66.3	67.5	55.0	71.3

Scenario comparisons (EMMA results)

As discussed in cluster **GR-C2 (Section 3.3.3.2)**, with tightening CO_2 budgets, EU ETS prices are not projected to be sufficient to reach emission targets. In this respect, the increasing emission restrictions cause the transition from an electricity system characterised by conventional baseload and mid-load power generation to one where conventional generation is reserved only for times when the residual load is exceptionally high. For example, as shown in cluster **GR-C2 (Section 3.3.3.2)**, the load factor of CCGT decreases in the "**RF**" scenario from 30% in 2030 to 9% in 2050, or even down to 2% in the "**RE_2050**" and "**P2X_2050**" scenarios.

The exogenous hydrogen demand in the "**P2X_2050**" scenario increases the share of intermittent renewable generation up to 87% (as discussed in cluster **GR-C6 (Section 3.3.4.2)**). The derived additional electricity demand is mainly supplied by further onshore wind capacities. Because of the high share of intermittent renewables, baseload electricity prices in the "**P2X_2050**" scenario remain moderate (**Figure 92** in **Section 3.3.3.4**), whereas H_2 prices increase (**Section 3.3.3.4**) when compared to the "**RE_2050**" scenario.

Finally, because the future development of carbon absorption technologies is uncertain, their representation in the EMMA model is stylised with just one technology capable of absorbing carbon at the cost of 1000 €/tCO_2. This does not occur in the proposed scenario framework. Nevertheless, if economical carbon absorption technologies emerge, results could substantially change.

*3.3.8.2. **GR-C15**: Pathways to high reduction of greenhouse gas emissions*

Contributing models: EnergyPLAN

Research Questions' Overview

The RQ dealt with in this cluster is a discussion of different transition pathways for reducing GHG emissions. The goal is to compare how different system layouts, from EnergyPLAN and Calliope can represent two different solutions for a renewable energy transition and reduction of GHG emissions. Both scenarios will illustrate a renewable energy transition, including system integration to decarbonise not only the electricity sector but also heating, transport and industry.

- **RQ62:** Which transition pathways (choice of technologies and deployment timing) for decarbonising the Greek electricity sector are capable of achieving high GHG emissions reduction? Which of these pathways are low-cost?

Results and Discussion

Based on energy system analyses in both EnergyPLAN and Calliope two transition pathways are investigated. Both provide a low-cost alternative but are built on fundamentally different perspectives.

As shown in **Figure 133**, the "**Smart Energy Greece**" scenario in EnergyPLAN utilises sector integration to achieve a system consisting of high amounts of VRES including offshore wind, onshore wind and PV, as well as some thermal plants using biomass and green gases. The Calliope scenario provides a slightly more expensive scenario, but this time relying only on VRES, mostly from onshore wind and PV. The Calliope scenario is dependent on massive build out of cost-efficient onshore wind and PV, which might provide planning challenges, whereas more offshore wind is included in the "**Smart Energy Greece**" scenario. The

"**Smart Energy Greece**" scenario could potentially provide lower costs, under the same onshore and PV assumptions.

Finally, the Calliope scenario relies on a heavy build out of transmission capacity throughout Europe, whereas the "**Smart Energy Greece**" scenario is only balanced with inland production; thus, it is potentially possible to transition Greece both with interconnection in mind or with a more domestic focus.

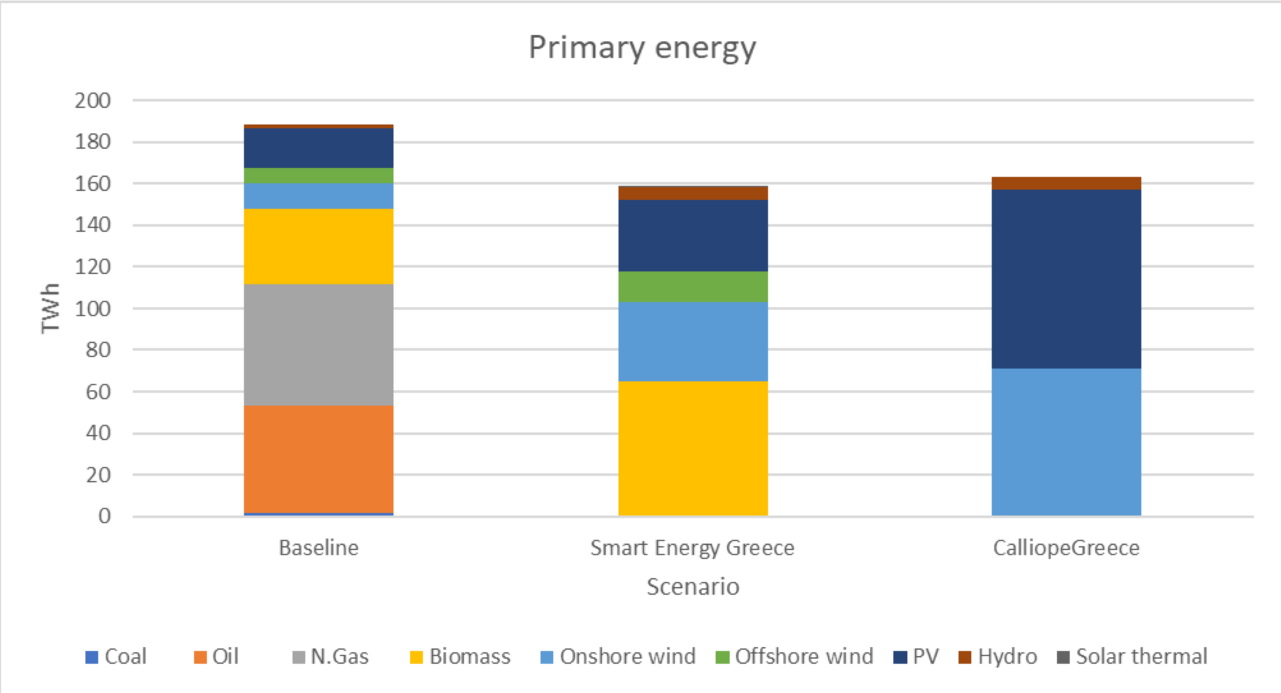

Figure 133. Primary energy comparison between three scenarios in Greece, the baseline showing a non-decarbonised scenario.

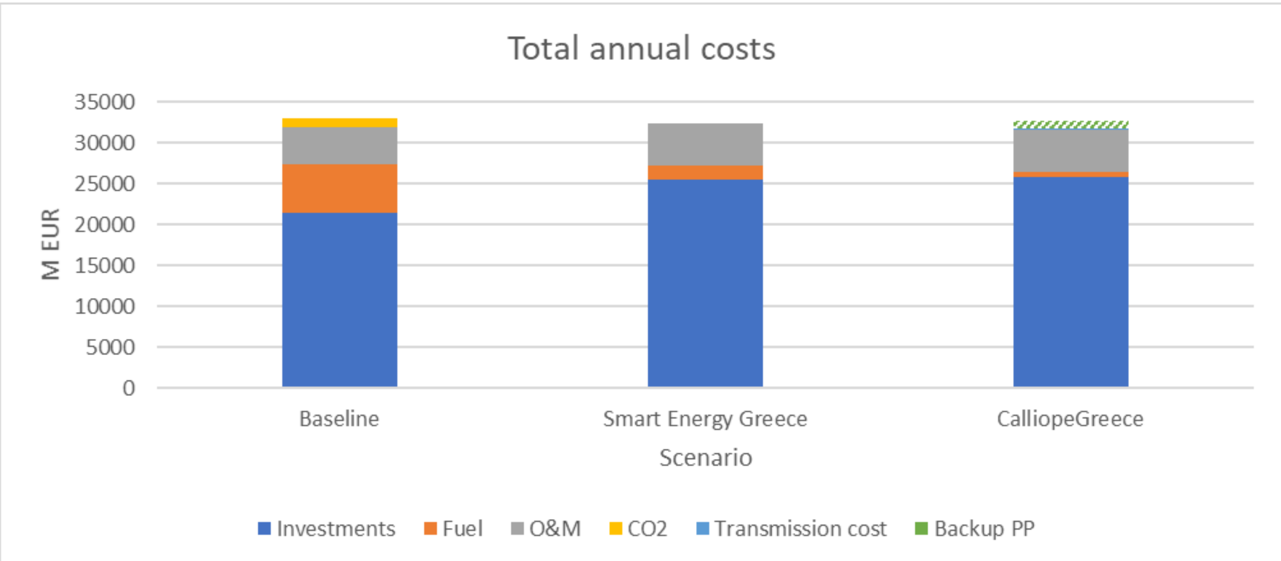

Figure 134. Total annual costs for the three energy system scenarios in Greece.

3.3.9. Socioeconomic implications

3.3.9.1. ***GR-C16:*** *Socio-economic implications of central or decentral governance for reaching climate-neutrality in Greece*

Contributing models: QTDIAN, Calliope, and WEGDYN

Research Questions' Overview

Using the QCW model ensemble (**Section 3.3.2.9**), we investigate a climate-neutral pathway for Greece in a European framework. This pathway is enriched by three different socio-political storylines ('governance' logics) to generate alternative future energy system configurations, which explore different degrees of demand electrification, expansion of renewables in the energy mix, and transmission to neighbouring regions as well as energy conversion and storage options to balance the intra-annual system. The three storylines are of different degree of decentralization rising in ascending order for the **MDR**, **GDI**, and **PPO** storylines. Equipped with this setting, we contribute to the following RQs, as identified in Deliverable 7.1 (Stavrakas et al., 2021):

- **RQ82**: In case of increased participation of citizens in the energy system, what are the costs and benefits for all the involved stakeholders in social (e.g., welfare distribution, etc.), environmental (total CO_2 emissions by economic sector), and economic terms (turnover by economic sectors)?
- **RQ83:** How are the total emissions (by economic sector) expected to evolve in Greece, when the centralised power system transforms into a system with increased participation of decentralised structures (e.g., energy communities, eco-villages, etc.)?

Results and Discussion

Increased participation of citizens is reflected in the **PPO** storyline. The welfare effects are shown in **Figure 98** under cluster **GR-C4 (Section 3.3.3.4)**, while total emissions are presented in **Figure 77** and emissions by economic sector in **Figure 132** under cluster **GR-C14 (Section 3.3.8.1)**. The sector turnover effects are presented below in **Figure 135**. The electricity and (bio-)refinery products sector are turnover gaining energy sectors, while also energy-intensive and services sectors expand their outputs.

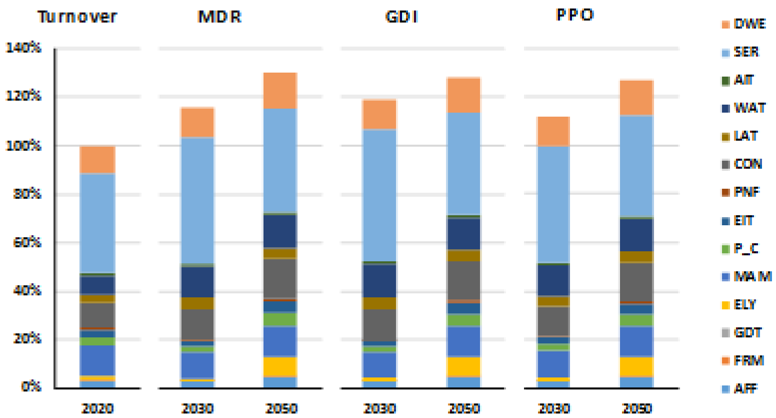

Figure 135. Share of sectoral turnover in Greece across storylines; AFF: Agriculture, Forestry and Fishery; FRM: Fossil Resource and Mineral extraction; GDT: Gas distribution and hot water supply; ELY: Electricity; MAM: Manufacturing and Machinery; P_C: Refined oil products ; EIT: Emission intensive and trade exposed; PNF: Manufacture of precious and non-ferrous metals, and fabricated metal products; CON: Construction; LAT: Transport – Land; WAT: Transport – Water; AIT: Transport –Air; SER: Other services ; DWE: Dwellings and real estate. Further details in the Continental CS section.

The macroeconomic assessment points to absolute decoupling of GDP and emissions in Greece, with rising GDP and emission cuts consistent with the EU's climate neutrality objective. Water and land transport represent the largest sectoral CO_2 emitters by 2030 but are also (in)directly electrified by 2050 using renewables and becoming climate-neutral.

The Greek electricity mix in 2030 is decarbonised due to strong build-out of renewables with a slower but still substantial pace in the **MDR** storyline (compared to the other two) due to the ability of increased net-imports. The additional transmission capacities in the **MDR** storyline turn Greece into an electricity net-exporter by 2050 because further domestic renewables capacities belong to the cheapest across Europe serving rising demand for electricity. Compared to the **MDR** storyline, LCOE is lower in the other two storylines in 2030 due to stronger cheap renewables penetration and less expensive imports, and higher in 2050 due to more expensive storage requirements and less profitable electricity net-exports. In combination with an assumed European-wide ETS covering all production-based CO_2 emissions (current ETS installations and effort sharing regulated sectors), the **MDR** storyline is connected to lowest unemployment figures and highest welfare, which is driven by productivity gains of transmitting low-cost renewable electricity from and to South-East and central Europe. A temporary additional welfare-gain is derived for the **GDI** storyline in 2030 (compared to the **MDR** storyline) due to additional revenues from EU-wide allowance trading, which, in the analysis, are channelled to increased provision of public goods and services.

The analysis reveals that Greece can act as an important renewable energy and power transmission hub for Europe. Although GDP figures are positive with the investigated Greek climate-neutrality transformation across all the three storylines, many non-market goods and services are not part of this performance metric (e.g. care work, biodiversity, air quality, etc.), nor are further relevant components of the changing energy system risk profile investigated, such as material supply risk. Further growth-agnostic indicators would add to a comprehensive picture, for instance, by extending the analysis with an environmental assessment. However, GDP might react negatively in the medium- to the long-term if the current situation leads to over-exploitation of new gas reserves to replace Russian imports, which ties financial resources that are required for the climate-neutral transformation in Greece. This might not only slowdown required structural changes but also lead to stranded assets because the remaining carbon budget is smaller than the accumulated emissions connected to the full life-time operation of new fossil fuel investments.

4. Discussion and conclusions

In this deliverable the applicability and usefulness of the updated SENTINEL modelling suite was tested in a set of CSs at three different geographical levels, namely: **Continental** (EU, Norway, Switzerland, the United Kingdom, and some Balkan countries), **Regional** (Nordic countries), and **National** (Greece), with diverse energy transition issues and challenges that policymakers and other stakeholders will face in the future. These cases were chosen to represent different spatial scales of the European energy transition as well as geographical contexts with varying demographic, economic, energy and climate characteristics, as well as different governance levels.

In this context, modelling teams in the SENTINEL Consortium further developed and parameterised their models, exchanged data, harmonised model assumptions, and soft-linked their models to answer a total of **80 RQs** across all the three CSs. The collection of RQs was extracted from Deliverable 7.1 (Stavrakas et al., 2021), which specified the CSs and the landscape for the model application process. In this deliverable, and following the analytical approach presented in **Section 2**, the initial, extensive collection of RQs was narrowed down to the set of questions for which the SENTINEL models could provide meaningful results, also considering disruptive developments of the last couple of years, time constraints, and available resources. Below, we summarise key modelling insights derived from the simulation results presented in **Section 3**, as well as an overview of the thematic areas for which the models have managed to provide results.

4.1. Thematic coverage

Overall, the SENTINEL modelling suite managed to address most of the thematic areas used in Deliverable 7.1 to categorise critical issues and challenges of the energy transition in the three CSs. This section provides and overview of the thematic areas to which the SENTINEL models have been applied, also highlighting potential areas of improvement in terms of further model development.

Figure 136 shows the number of RQs addressed by each SENTINEL model for each thematic area in the **Continental CS**. We see that all the thematic areas specified were addressed by the models, with an obvious focus on the "**Sector coupling**" thematic area, followed by the "**Decarbonisation of industry**" thematic area.

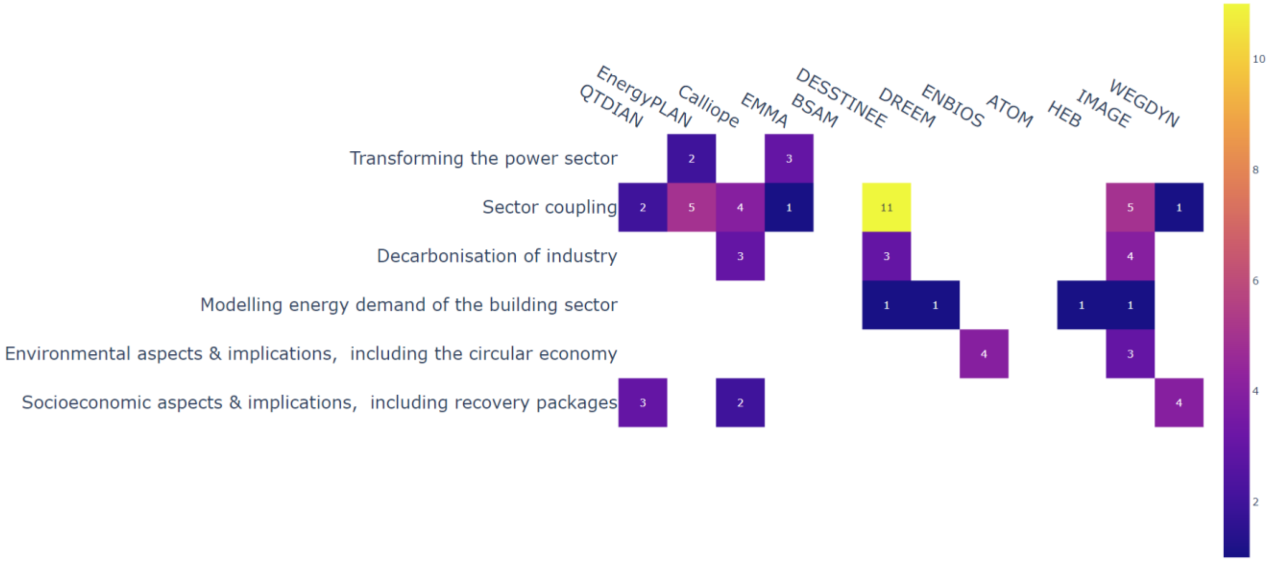

Figure 136. Total number of research questions addressed by each SENTINEL model for each thematic area under study in the Continental case study.

Considering the total number of RQs in each thematic area in the **Continental CS**, as these were collected in Deliverable 7.1 (**Figure 137**), we see that the "**Sector coupling**" thematic area contains more RQs compared to the other thematic areas. This means that, for this particular thematic area, the SENTINEL models had the opportunity to be tested in a larger set of RQs. It also indicates that sector coupling is a very critical issue for the majority of the stakeholder groups interviewed under Deliverable 7.1 (since they expressed more inquiries for this particular thematic area), but also for modelling teams too (since they focused more on applying their models to this particular thematic area). On the other hand, an interesting observation is that the "**Decarbonisation of industry**" thematic area, despite being the thematic area with the less RQs, based on the work under Deliverable 7.1, is the second thematic area with the most RQs addressed; this speaks of the SENTINEL models' capabilities and sectoral coverage.

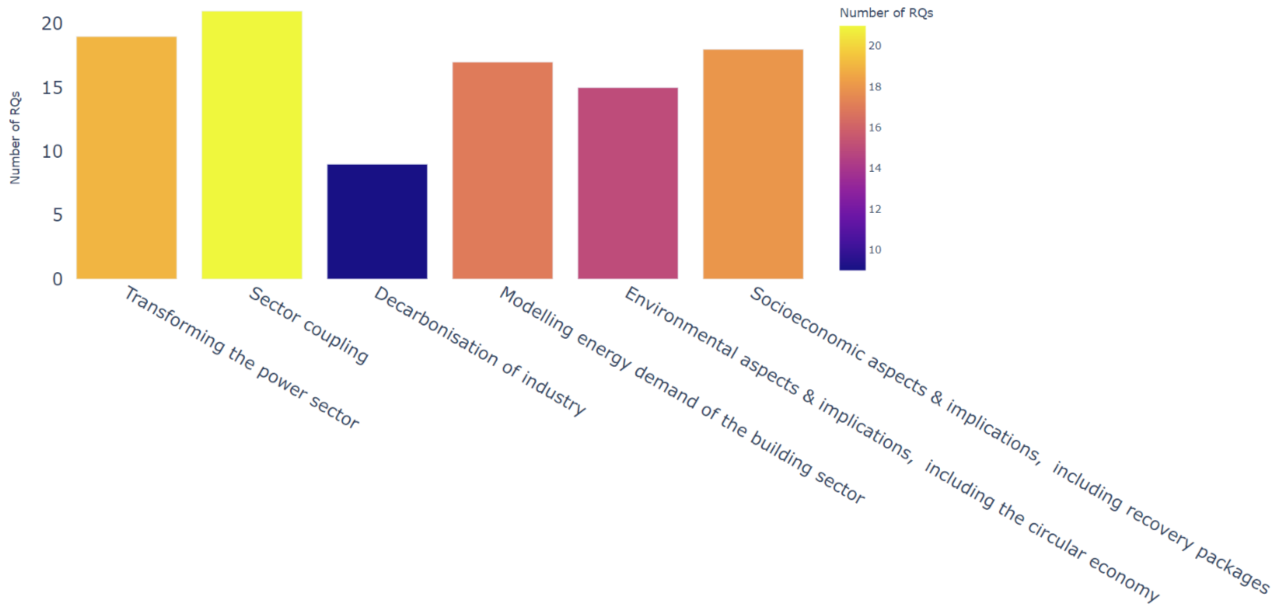

Figure 137. Distribution of research questions across the different thematic areas of interest in the Continental case study, as collected through the stakeholder engagement activities reported in the SENTINEL Deliverable 7.1.

For the **Regional CS**, we observe an underrepresentation of the SENTINEL models in terms of the number of RQs and the different thematic areas addressed, with only three out of the twelve models being able to provide results to half the thematic areas under study (**Figure 138)**. The latter gives us a first glance at some limitations of the SENTINEL modelling suite when it comes to spatial coverage and sheds light into areas of further model development to enhance spatial resolution on the regional scale. On the other hand, it is important to note that, given time constraints and resource availability, a lot of the SENTINEL models included the Nordic countries in their simulations under the **Continental CS**, exploring transition pathways in Europe as a whole. So, eventually, more results than the ones presented in this deliverable could be extracted for the **Regional CS**. This is something that we intend to address in Deliverable 7.3. However, enhancing spatial resolution is definitely a lesson that we intend to take from this modelling exercise moving forward.

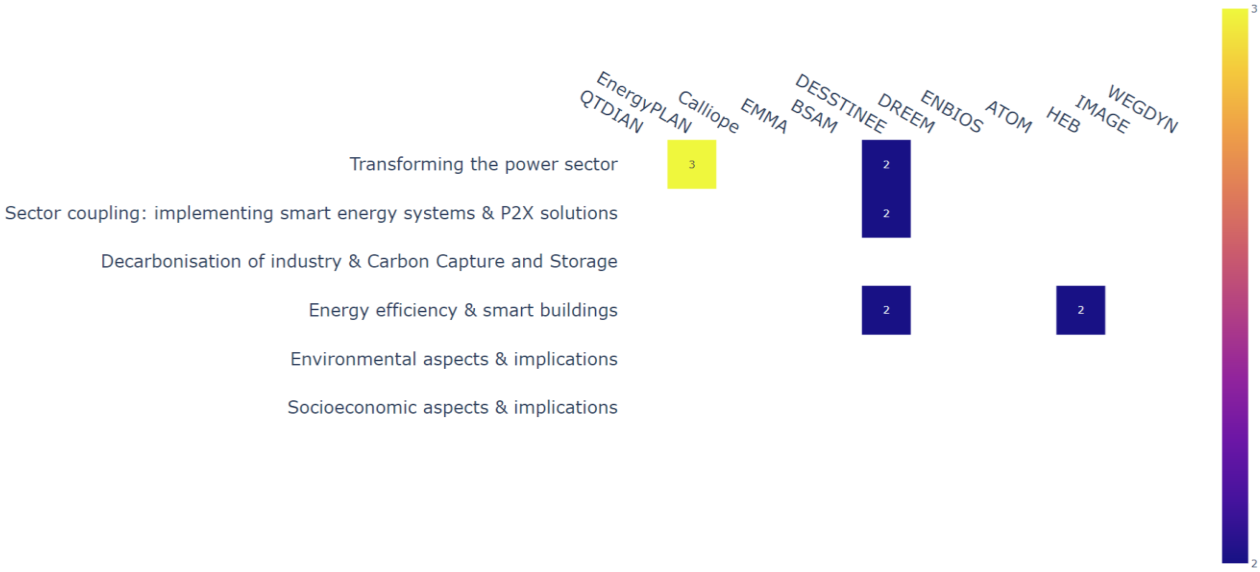

Figure 138. Total number of research questions addressed by each SENTINEL model for each thematic area under study in the Regional case study.

Finally, similarly to the **Continental CS**, and considering that the **National CS** is a CS of particular interest, with a relatively isolated energy system, many non-interconnected islands, an ageing building stock, high dependence to imported fuels for electricity generation, and an open policy agenda at the time with important issues and challenges to be resolved, e.g., phase-out of lignite, just transition in coal carbon-intensive regions, the development of new infrastructures to use natural gas as a transition fuel, etc., the SENTINEL models were able to enhance their resolution on the national scale to provide results to multiple RQs for all the thematic areas specified in Deliverable 7.1. As presented in **Figure 139**, the main focus was given to the *"***Energy resource planning with a focus on security of supply***"* thematic area, followed by the "**Direct and indirect electrification and energy efficiency**" and "**Distributed generation, storage, and curtailment**" thematic areas, which are directly related to the latter and are highly relevant to the priority areas set by the latest version of the Greek NECP.

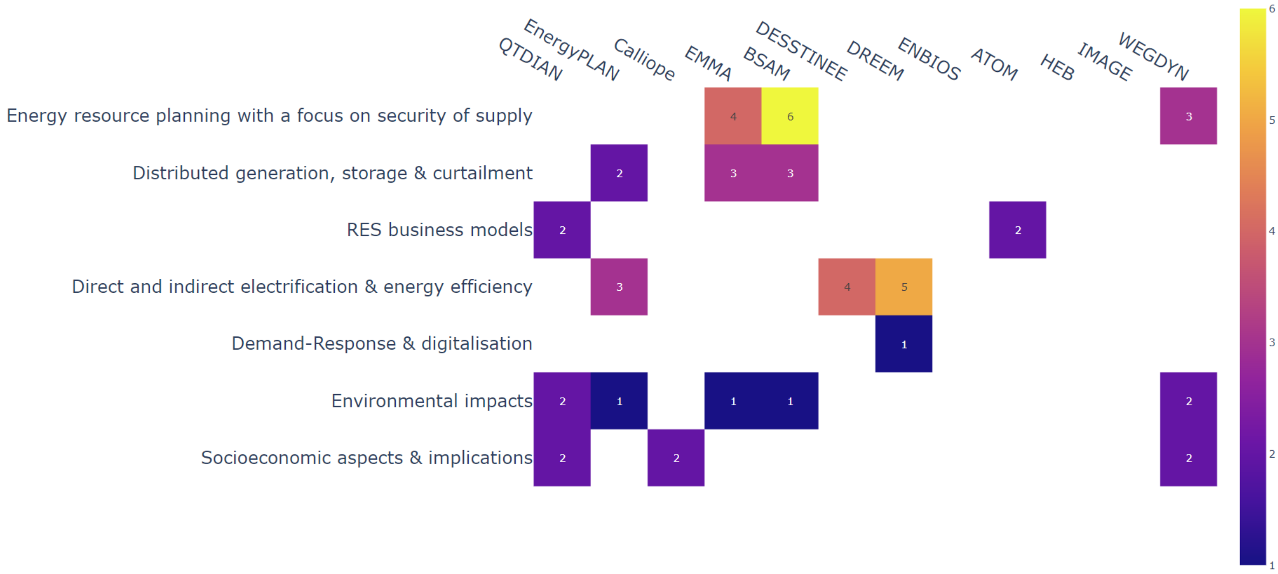

Figure 139. Total number of research questions addressed by each SENTINEL model for each thematic area under study in the National case study.

Considering the total number of RQs in each thematic area of the **National CS**, as these were collected in Deliverable 7.1 (**Figure 140**), we see that the number of RQs answered by the SENTINEL models follows the RQ distribution. However, even though the "**Direct and indirect electrification and energy efficiency**" thematic area is adequately addressed, the number of the initial RQs via the different stakeholder engagement activities carried out under Deliverable 7.1, shows that this sector is of major importance in Greece, and further focus should be given by energy system models to dealing with this particular thematic area. Indicatively, a potential area of improvement could be the expansion of models to account for isolated energy systems, with high potential in renewable energy penetration and significant value from energy-efficiency interventions due to an ageing building stock.

Closely related to the abovementioned is the "**Demand-response and digitalisation**" thematic area, which is another thematic area of importance in the context of the "Fourth Industrial Revolution (Industry 4.0)", especially in Greece. Considering that only one RQ was answered by the SENTINEL models under this thematic area, it becomes apparent that further model developments are necessary to enhance sectoral resolution and modelling content.

Finally, a cross-CS area, which is of outmost importance for different stakeholder groups, but it still needs more work in terms of further model developments, is the "**Socioeconomic aspects and implications**" thematic area. The QTDIAN toolbox, which has been developed from scratch in SENTINEL, offers a way to include political and social processes and preferences into energy system modelling tools. Yet, it is only a first step, and several aspects are not yet included, and other aspects, such as acceptability of demand changes and flexibility, or citizen preferences for certain renewable energy technologies, may need to be further refined in future efforts. Thus, further research is needed to improve the representation of socio-political aspects in energy modelling, to address important aspects of the energy transition, such as social implications for carbon-intensive areas in the context of fossil-fuel abatement, citizen opinions towards re-designing energy systems, or ownership structures of technologies. However, this also requires further empirical data, including different temporal and spatial scales. The existing version of the QTDIAN toolbox shows that it is possible to use socio-political preferences as a starting point for technical energy system modelling, and that it affects the results, arguably making them more realistic.

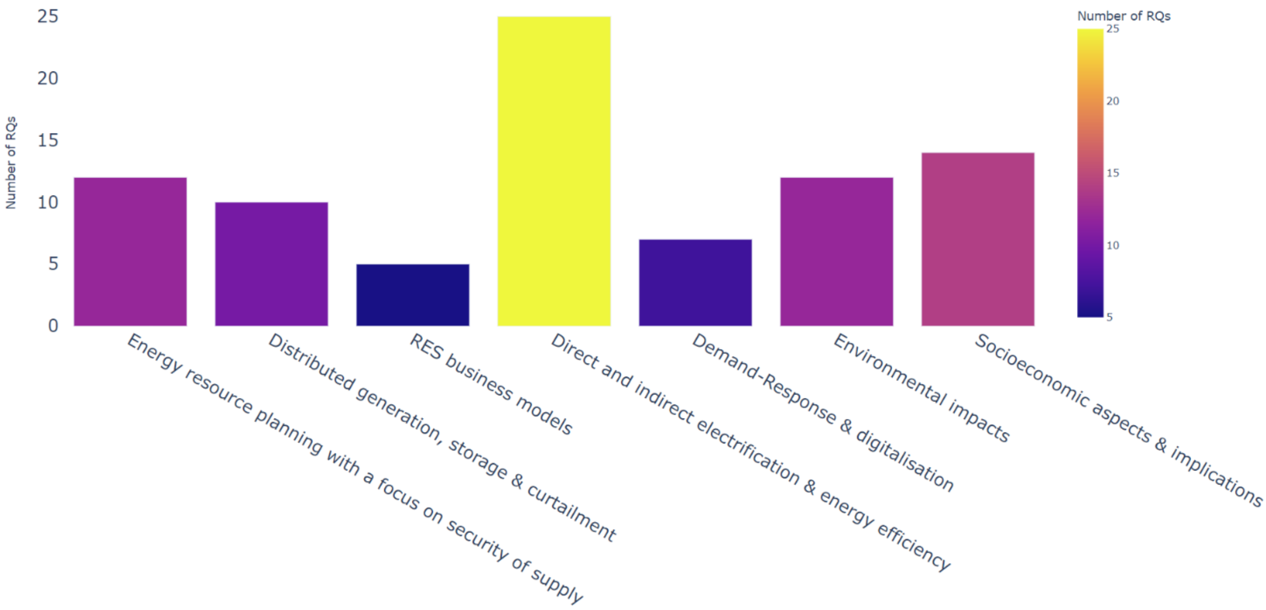

Figure 140. Distribution of research questions across the different thematic areas of interest in the National case study, as collected through the stakeholder engagement activities reported in the SENTINEL Deliverable 7.1.

4.2. Summary of modelling insights and further reflections

In this section, a summary of the key insights derived from the modelling exercises is presented in five thematic areas, namely: **(i).** Power sector transformation, **(ii).** Energy use and energy efficiency, **(iii).** Sector coupling, **(iv).** Land use, material use, emissions, and other environmental impacts, and **(v).** Socioeconomic implications. Each thematic area features modelling insights for those models, which mostly addressed RQs that best fit under each thematic area. However, several models contributed to more than one thematic area. In this respect, this section allows the reader to acquire a high-level understanding of the content under each thematic area, while for more detailed results under the specific thematic areas in each SENTINEL CS, the reader can see **Section 3**.

4.2.1. Power sector transformation

The **EMMA** model has been applied to the EU-wide power sector and has also been extended and calibrated to model the electricity system at the national scale in Greece. To also account for the effect of cross-border flows, outputs from the Calliope model, which is designed to model the entire Europe, have been incorporated into EMMA. In both case studies, EMMA results highlight that ambitious emission reduction targets require a substantial buildout of VRES capacity. This in turn, increases the value of flexibility on the supply side as well as on the demand side. As a result, short-term electricity storages (batteries) and long-term storage options (electrolysers paired with H_2-fuelled generation units) coexist and complement each other in the scenarios geared towards carbon neutrality. The benefit of a flexible demand becomes apparent when comparing the "**RE_2050**" and the **"P2X_2050**" scenarios in the **National CS**. The key difference between these two scenarios is that an additional flexible hydrogen demand is added to the "**P2X_2050**" scenario. This hydrogen demand results in an additional flexible electricity demand caused by electrolysers. Notably, adding this flexible demand does not result in a higher baseload price when the new market equilibrium (including investment decisions) is calculated. Although this result is partially caused by EMMA's linear representation (steepening cost potential curves would render a different result), it also shows that the effect of a higher electricity demand depends on its characteristics, and on the adaptability of the electricity system.

In terms of transmission capacity, results from the **Calliope** model highlight that different transition storylines would require different levels of expansion. For example, the **MDR** storyline defined by **QTDIAN** (Süsser et al., 2021c), which shapes the energy system in a cost-effective manner with a rather centralised system, would require a six-time expansion of the existing electricity grid in the EU28 and a three-time expansion considering also non-EU neighbouring countries. On the contrary, in the PPO storyline, which describes a much more decentralised energy system with strong regional expansion of renewable energy, hardly any expansion would be required as the dependence on grids is relatively low. Furthermore, modelling results suggest that, under different storylines, countries that are net electricity importers can turn into net electricity exporters and vice-versa.

For the **National CS**, the **BSAM** model has performed a deep-dive to the "**RF_2030**" and "**RF_2050**" scenarios, under three cases: the "**Baseline**" and the "**Green Deal**" cases following the projections of the IPTO (IPTO, 2021) and of the NECP (Greek Ministry of Environment and Energy, 2019), and the "**EMMA-BSAM**" case, which is a product of the soft-linkage between the two models. Modelling results show that the first step towards a RES-based electricity system, which is the planned phase-out of lignite in Greece, causes an increase in the consumption of natural gas for power generation compared to the pre-phase-out regime. In fact, with the exclusion of the only domestically extracted fossil fuel, Greece is forced to turn to imported commodities to cover its electrical needs, until high enough RES capacity expansion is accomplished. These imported commodities comprise of natural gas and direct electricity imports through interconnections. Even though Greece follows declining dependency rates on these imported commodities, it remains dependent for more than 43% even by 2050 under the assumptions of the "**Baseline**" and the **"Green Deal**" cases (**Section 3.3.2.2**). This slow decrease in dependency is justified by the parallel increase in electricity demand that is projected by 2030 and 2050. Characteristically, even though the contribution of natural gas to the electricity mix follows a declining trend with increasing RES capacity, the total energy output of natural gas power plants increases in order to cover the additional demand in 2030 and 2050.

The above observations change when more disruptive RES penetration levels are modelled. For example, in the "**EMMA-BSAM**" case, which features a higher simulated VRES capacity build out, we observe a faster declining trend in national dependency to gas-generated and imported electricity, reaching below 30% by 2050. Similarly, following steep reductions in the contribution of natural gas to the electricity mix, the total energy output of natural gas-fired GUs follows a declining trend as well. This indicates that gas-fired generation can be in fact displaced by a market-driven RES build-out. Of course, in order to achieve maximal gas displacement, the capacity ratio among the VRES generating technologies should also be taken into consideration, in order to match the country's load profile with the respective VRES generation profile. In Greece, the capacity ratio that appears to achieve good demand and supply matching consist of 67.5% WT and 32.5% PV.

On the unit level, as mentioned in the new "National Resource Adequacy Assessment" report, recently published by IPTO, three new natural gas units will be launched by 2027, which raised the question about becoming stranded assets during the power sector transformation course. As results from the BSAM model suggest, for the two simulated cases under the "**RF_2050**" scenario, gas-generated electricity will still be needed in 2050 at least by 20% in the electricity mix. Therefore, the operation of the new units is not expected to be disrupted by the projected RES capacity expansion, at least in the short term. In fact, an upward change could be observed in the contribution of fast and flexible GUs with increased VRES shares. This is caused by the additional uncertainty that is introduced to the residual demand, which makes the generation planning of dispatchable units a challenging task. Therefore, fast and flexible units might play a more important role in safely covering the country's electrical demand in a VRES-dominated electricity system.

Finally, in terms of the expected evolution of electricity prices, the increasing trend of natural gas and carbon emission prices drive wholesale prices to escalate, following the profit-maximising behaviour of generators, who pass their increased operational costs to the market. What is interesting is that with higher VRES penetration to the electricity mix, and consequently decreased residual demand to be met by thermal units, competition among generators is hardened, driving their profit margins downwards in order to remain competitive. Implications from this observation are twofold: **(i).** high VRES shares could be a driver for cost reductions additional to what is expected by their low operational costs, and **(ii).** even if natural gas and carbon pricing mechanisms may seem a burden for consumers, the market can be self-regulated to counterbalance part of it.

On the consumer side, the **ATOM** model has been applied to the **National CS** to explore the potential of small-scale PV diffusion towards the achievement of the 2030 targets, under the currently available schemes in Greece, NEM and FiT. Three different scenarios for each policy scheme were simulated. The scenarios came as a result of the soft linkage of the three **QTDIAN** storylines and the **ATOM** model. Modelling results show that the average expected PV capacity addition from the current NEM scheme during the period 2023-2030 is estimated at around 300 MW under the **PPO** storyline and at around 250 MW for the **GDI** and **MDR** storylines. The average expected PV capacity addition from the current FiT scheme is estimated at around 280 MW under the **PPO** storyline and at about 240 MW for the **GDI** and **MDR** storylines.

An interesting finding in the case of the NEM scheme is that the **PPO** storyline results in the least behavioural uncertainty related to consumers' decision-making process, indicating that consumers' initial high willingness to participate in the energy system plays a key role in the successful roll-out of a policy scheme that promotes prosumerism. Accordingly, our results imply that the **PPO** storyline is the most effective in terms of behavioural uncertainty for the FiT scheme, while the **MDR** storyline provides similar results with the **PPO** storyline. This is attributed to the fact that investing in small-scale PV systems under the current FiT scheme in Greece is considered an investment opportunity totally disconnected from the consumption patterns of consumers and the concept of prosumerism. Furthermore, even though the **MDR** and **GDI** storylines result to approximately the same PV capacity addition under both schemes, the **MDR** storyline provides more robust results in terms of its effectiveness by decreasing consumers' aleatoric uncertainty. This is mainly due to the fact that recent developments in the energy market have brought about increased profitability of investing in small-scale PV systems.

4.2.2. Energy use and energy efficiency

The **IMAGE** model has been applied to the **Continental CS**, providing answers to RQs as, how fossil-fuel use would be affected by the decarbonisation of industry and transport sectors, and how energy-efficiency improvements would contribute to emission reduction across sectors. Modelling results show that the energy use will decline by 61% in transport by 2050 compared to the 2015 levels in the "**Current Trends**" and the "**Neutrality**" scenarios, with a substantial reduction in the liquid fossil-fuel use. In 2050, the total energy use in industry only changes marginally in all three scenarios. In addition, higher electrification levels can be seen in 2050, especially the "**Neutrality**" scenarios, with fossil-fuel production decreasing by 2050 with respect to the 2015 levels. Improvements in energy efficiency contributes more to emission reductions in the passenger transport sector than in other sectors in the "**Neutrality**" scenarios (0.6 Gt CO_2 from 2015 to 2050). In the IMAGE model, energy efficiency is considered as aggregated technology efficiency in the different (sub)sectors, as for example energy efficiency of different vehicle types, or energy efficiency of each energy service in a building. Therefore, energy efficiency of the different (sub)sectors will increase as the technology matures over time in IMAGE, while fewer details on specific EEMs, or new technology, are included in the model compared to sectoral models. This is one limitation of IMAGE when it comes to energy-efficiency improvement opportunities.

In the context of the **Regional CS**, the **DESSTINEE** model was partially updated to better represent the challenges and opportunities derived from decarbonising energy uses in the Nordic countries. Such an update has enabled a more comprehensive technological representation across different demand-related sectors, whilst further disaggregating FEC results (including low-carbon solutions such as P2X carriers). A common pattern for all the five countries under study is that electrification will play a key role in reducing direct fossil CO_2 emissions from final energy uses, especially for road transport and industry. Energy-efficiency improvements, aimed at decreasing thermal energy needs in buildings, will be key to achieving the 2030 targets, both in the Nordic countries and at the European level. The expansion of electrification is projected to cause changes in hourly power demand, increasing peak demands aligned with assumptions on EV charging regimes, EV shares in the fleet, and power-based heating. These transformations will not be uniform across the different EU member states, the UK, Norway and Iceland, showing country-level patterns, which are consequent of economic and demographic development, resource availability, and weather conditions. The scenarios and results presented in this deliverable intend to provide clarity on feasible national decarbonisation pathways for demand, which respect national circumstances, whilst enabling the fulfilment of continentally-wide emission reduction objectives.

In addition, the **HEB** model demonstrated the potential of energy demand reduction in the building sector by implementing EU-wide state-of-the-art high-efficiency buildings. The findings of the study show that with a higher share of high-efficiency renovations and constructions (as assumed in the "**Deep Efficiency**" and the "**Net-zero**" scenarios presented in **Section 3.1.2.5**), it is possible to reduce final thermal energy use in the EU building sector by 85% by 2060. However, this pathway towards achieving a high-efficiency standard is ambitious in its assumptions and requires strong policy support. On the contrary, if policy support to implement more high-efficiency buildings is not in place ("**Frozen Efficiency**" scenario), or even the present policy scenarios are continued ("**Moderate Efficiency**" scenario), then the total thermal energy demand of the building sector can increase by 5% by 2060 compared to the 2022 level. Furthermore, if the present rate of EEMs is continued, thermal energy demand would only decrease by 58% by 2060, making the transition to a net-zero energy system difficult. Besides, by opting for the existing efficiency standards, almost 30% of the EU's final thermal energy savings can be locked in by 2060 in the building infrastructure. The lock-in effect in the EU building sector also indicates that if the present moderate energy-performance levels become the standard in new and/or retrofit buildings, it will be almost impossible to further reduce thermal energy consumption in such buildings for many decades to come.

Finally, the **DREEM** model has been used to address RQs relevant to the residential sector in both the **Continental** and the **National CSs**. For the **Continental CS**, the application aimed to identify retrofit measures, which are not only beneficial for the environment, but could also incentivise building owners and could ensure effective private and public budget spending. Modelling results show that the replacement of an old heating system with an energy-efficient HVAC system is one of the most cost-effective measures for all countries examined and for both old and newly built buildings. This happens mainly due to the measure's high potential of energy savings. On the contrary, the replacement of the traditional heating system with a more energy-efficient diesel boiler is shown to be the least cost-effective EEM due to its cost of replacement and the low values of expected annual savings in most cases (i.e., Italy, Spain, Croatia, Latvia, Romania, and Greece). Regarding the rest EEMs under study, it is observed that their energy-saving potential and cost-effectiveness differ among Member States and, thus, country-specific renovation packages need to be developed.

For the **National CS**, the DREEM model has also been used to explore energy-transition pathways by 2050 in the Greek residential sector. To do so, six scenarios have been simulated, four based on the current NECP renovation rate of 60000 household renovations/year, and two where a reverse engineering process was applied to explore the necessary renovation rate to decarbonise the sector by 2050 and 2040, respectively. Modelling results highlight that the current NECP target of 60000 household renovations per year (1.5% annual renovation rate) cannot lead to decarbonisation by 2050. Another interesting finding is that when investing in natural gas as a transition fuel, more energy derived from fossil fuels (oil products and natural gas) is consumed by 2050. On the other hand, modelling outcomes from the two 'reverse engineered' scenarios suggest that to decarbonise the Greek residential sector by 2050, 100000 households should be renovated each year (2.5% annual renovation rate), while, in order to decarbonise it by 2040, 145000 households should be renovated each year (3.5% annual renovation rate). Finally, when comparing these two scenarios, striving to be ambitious and decarbonising the residential sector by 2040 leads to a less harmful environmental footprint and lower total costs than decarbonising it by 2050. The latter highlights the need for more aggressive and ambitious policies towards the achievement of the national decarbonisation targets as well as the need for greater focus on investing in electrification rather than in natural gas.

Similar results are also derived on the regional (Peloponnese region) and local (Megalopolis municipality) scale in Greece. Both cases have been selected to test the DREEM model capability to produce results not only at a national scale, but also at both the regional and the local scale. In addition, the Peloponnese region is an interesting application because of the planned interconnection to the natural gas distribution network for the first time, which raises questions regarding the viability of the decision, and because it is the only Greek region that consists of regional units in three out of the four climate zones in Greece, combining different climatic and weather conditions. Results from the DREEM model show that investing in electrification could lead to lower total costs at both the household and the regional level, in comparison to investing in natural gas as a transition fuel. Moreover, modelling results highlight that the current NECP renovation rate is not able to lead to the complete decarbonisation in the residential sector. If decarbonisation is the goal, then regional palling should focus on investing in electrification as early as possible, since modelling results show that this is the most attractive choice, with more electrification meaning less renovation intensity.

At the local level, the residential sector in the Megalopolis municipality is another interesting application, as Megalopolis is a coal and carbon intensive region, where the decision to phase-out lignite directly affects the residential sector's energy system. This is due to the fact that 30% of the residential buildings' heating and hot water needs are covered by the local DH system, which is fuelled by the lignite units. Modelling outcomes from the DREEM model indicate that investing in electrification leads to lower ETS and fuel costs in the long run, while renovation costs are higher when electrification is intensified. Nevertheless, total savings for households by 2050 are notably higher in the electrification scenario. Note that, in this analysis, the DREEM model did not consider infrastructure and other costs, which are not accounted to households and could, however, increase total investment costs of using natural gas as a transition fuel. Therefore, investing in electrification as early as possible is the most efficient scenario in terms of energy consumption reduction, environmental footprint, and potential extra charges on households. These results also bear a social dimension, considering that in the long run, extra charges from the replacement of existing oil boilers with gas boilers at the household level will amplify the energy poverty phenomenon in the Megalopolis municipality, as it could result to increased energy costs.

4.2.3. Sector coupling

The **EnergyPLAN** model illustrated the potential of sector coupling and the integration of high levels of VRES in the design of a climate neutral EU-wide energy system, as well as in the Nordic countries and Greece. The "**Climate Neutrality**" scenarios apply a Smart Energy Systems approach (Lund et al., 2017), in which both existing and new infrastructure, energy grids, and energy-efficient technologies play a great role in enabling synergies across the different energy end-uses and sectors, and providing flexibility to a 100% renewable energy system.

The analysis conducted shows that expanding renewable energy capacities, namely onshore and offshore WT, PV, and solar thermal will be paramount to supply the additional electricity consumption stemming from increased electrification in all sectors, and future demand developments projected by the DESSTINEE and HEB models in their "**Neutrality**" and "**Moderate Efficiency**" scenarios, respectively. In this context, sector integration is critical to provide flexibility to the energy system and ensuring an adequate balance between energy supply and demand.

In the transport sector, BEV gain precedence both as more energy efficient alternatives to combustion engine vehicles and as a DR solution via smart charging. The remaining of the transport sector is also coupled to the electricity sector, as e-fuels produced via different P2X pathways can be used as fuel replacements in combustion engine vehicles and can make use of excess electricity in hours in which it would otherwise be curtailed.

In the heating sector, individual boilers based on fossil fuels can be replaced by electrifying the heating supply with individual heat pumps in those areas where DH is not in place. Meanwhile, the introduction and expansion of DH infrastructure can be expected to provide further levels of system integration, flexibility and security of supply when connected to diverse heat supply sources and thermal energy storages. For instance, with the expansion of DH networks in the "**Climate Neutrality**" scenarios, it would be possible to utilise the excess waste heat from power, industry, and e-fuel production as heat supply sources, while at the same time electrifying shares of the supply with large-scale heat pumps and integrating large-scale renewable heat sources like solar- and geothermal plants. Furthermore, the implementation of thermal energy storages can provide additional system flexibility and a more cost-efficient alternative than relying on batteries and electricity storage, which could increase system costs. The changes in heat supply considered depend on the introduction of energy savings through e.g., building renovations, etc., and considering the developments from the "**Moderate Efficiency**" scenario from the HEB model (**Section 3.1.2.5**).

Finally, fuel replacements in the industry sector and in the remaining fuel supply for power production are also considered in the scenarios modelled by the EnergyPLAN model. E-fuels from carbon capture and utilisation and electrolysis, supplemented with sustainable bioenergy products, aid in decarbonising industrial processes that may be difficult to electrify, while for power production, these fuels help stabilise the energy system in times of low wind or solar production. These direct fuel replacements also allow the use of existing energy infrastructure (e.g., gas grids, conversion units, etc.), thereby, potentially decreasing new investment costs. In the "**Climate Neutrality**" scenarios, H_2 serves as an intermediate fuel used in combination with carbon sources for the production of e-fuels, yet direct H_2 utilisation is not considered. However, H_2 may be suited for industrial purposes, especially if it can replace biomass or biomass-based fuels.

4.2.4. Land use, material use, emissions, and other environmental impacts

The **IMAGE** model has also been used in the **Continental CS** to provide answers to RQs relevant to: biomass demand and possible environmental effects by 2030 and 2050, focusing on land-use changes and CO_2 emissions from biofuel use, GHG emissions from non-ETS sectors and land use, and pollutants produced by different energy use and sectors in 2050.

Biomass use, in all scenarios, increases in 2050 relative to 2015 levels, especially for the electricity sector in the "**Neutrality**" scenarios. Specifically, for the latter, the biofuel use increases more than 200% leading to an increase in land use for energy crops in Europe, while biofuel imports also grow. This analysis also shows the strengths of land-use simulation component in the IMAGE model, which would be useful in further environmental impact analysis.

GHG emissions in non-ETS sectors (including land use) decrease by 2050 in all scenarios compared to 2015 levels, from 2.4 $GtCO_2$ to 0.6-0.9 $GtCO_2$. More than two-third of GHG emissions in 2050 are from land use in the "**Neutrality**" scenarios. Comparing to the "Clean Planet" modelling results ("**Clean Planet 1.5TECH**" scenario), IMAGE has a smaller carbon sink from LULUCF due to different applied LULUCF calculation methods in the models. Pollutant emissions also decrease by 2050 relative to 2015 levels (even in the "**Current**

Trends" scenario). In the residential sector, in both "**Neutrality**" scenarios, pollutant emissions are sometimes higher than in the "**Current Trends**" scenario by 2050, due to the stricter building transition policies applied in the "**Current Trends**" scenario.

Two additional significant aspects of the energy transition investigated by the **ENBIOS** model in the **Continental CS** are the raw material requirements for additional infrastructure- particularly the so-called CRMs- and GHG emissions and other environmental impacts assuming that a life-cycle approach is followed.

For material requirements, a key finding is that all the three socio-political storylines under **QTDIAN** are likely to face significant issues with respect to supplies of CRMs by 2050. Elevated supply risk scores are largely related to wind and solar PV technologies. From the three storylines investigated, the **PPO** storyline provided the highest risks in both 2030 and 2050. Future requirements of gallium and magnesium contribute the highest overall risk, although risks relating to samarium, neodymium, praseodymium, gadolinium, and lanthanum are all expected to significantly rise.

For life-cycle environmental impacts, ENBIOS confirmed that fossil fuels and waste generate the highest levels of GHG emissions, although the use of biodiesel and biomass as fuels are also found to generate high levels of emissions. Similarly, although a range of results are observed for other environmental indicators (e.g., human toxicity, human health, water depletion, particulate matter formation, terrestrial acidification, etc.), electricity and heat from fossil fuels and biodiesel production tend to generate the worst outcomes in most categories. Perhaps the most telling finding was that, aside from GHG emissions, all indicators rose for all the three storylines under study between 2030 and 2050, suggesting that GHG reductions tend to be offset by poorer performance in other areas.

It is important to note that ENBIOS simulations were primarily driven by inputs from the Calliope model. As such, as a newly developed tool, the definition of the energy system employed within ENBIOS was largely defined by the architecture and level of resolution within Calliope. However, the development of the module was also constrained by the level of data available within the LCA database used to provide inputs to the raw material supply and environmental impact calculations undertaken within ENBIOS. While this was generally not an issue, it is noted that a lack of available LCA data means that material requirements and impacts relevant to energy storage technologies could not be included in ENBIOS.

Finally, it is acknowledged that the clearest shortcoming of ENBIOS relates to future changes in energy background systems- particularly for electricity- and the fact that current LCA data assumes that the energy inputs occurring in the backgrounds of these processes are to remain "as-is" (i.e., containing significant levels of fossil fuels). In reality, many of these processes will become "greener" over time, but this is difficult to incorporate into current LCA data. Much research is being undertaken to develop methodologies for integrating future energy system changes into LCA data. However, this research remains in its infancy.

4.2.5. Socioeconomic implications

The resemblance of the existing EU27+ energy system is largely a result of a long-lasting period of low fossil energy prices. Currently, there is substantial turmoil in energy markets, which has already started prior but escalates due to the Russian invasion of Ukraine with energy prices spiking to unprecedented heights. In the debate on how to address the consequences of high energy prices cascading through the energy and socio-economic system, one crucial aspect is often overlooked. High prices themselves are not the problem but shortages, scarcity and deficiency are. This is the case because high prices are the signal of the underlying problem and, hence, policy instruments addressing shortages directly are better suited than "manipulating" essential price signals. The build-up of sufficient supply capacities to counter excess demand takes time but is likely stronger and faster, holding price-based incentives up and functional. In the short term, arising social and economic pressure due to high prices requires instruments that keep an eye on vulnerabilities and response capabilities across societal and economic actors to address undesired distributional and economic effects by adequate and goal-oriented fiscal responses.

In the context of climate change mitigation, one crucial shortage is the remaining carbon budget that would allow humankind to limit global warming to well below 2°C compared to pre-industrial times (Masson-Delmotte et al., In Press). Another crucial shortage is the lack of security for European people after the revelation of Russian geopolitical interests, which are in direct conflict to European security concerns. Both shortages (economists call them "externalities") are addressed in the **Continental CS** by the future energy system configurations analysed using the **QCW** model ensemble. The issue of a scarce carbon budget is captured in **WEGDYN** by a gradually declining number of emission certificates in Europe to ensure that eventual productivity-led rebound effects of analysed energy system configurations do not undermine climate mitigation objectives. The current deficiency in energy security of supply is addressed in **Calliope** by minimising imports from non-European regions. Both objectives have different socio-economic implications if diverse governance logics are accounted for, here with a broad spectrum generated by the **QTDIAN** toolbox along the dimensions of social preferences and political priorities.

We provide three key learnings. First, and in terms of results, the three storylines developed by QTDIAN provide different boundary conditions for the evolution of climate-neutral configurations of the energy system quantified by Calliope. Based on the knowledge of what this new climate-neutral future looks like in terms of cost-quantity pairs of energy, the analysis of WEGDYN shows absolute decoupling of CO_2 emissions (declining) and economic activity (rising), which is a double dividend. The full analysis shows that restricting power transmission across Europe is a key cost driver at the aggregate and regional level in Europe requiring additional integration cost components for energy conversion and storage to balance the climate-neutral system. However, the system with highest cost turns out to be the one with largest economy-wide welfare benefits due to positive employment effects not included from a bottom-up system design perspective. We also show that governments may have other intertemporal incentives than private households, which is driven by recycling rule assumptions of carbon pricing revenues (here, remaining in public budgets to finance provision of public goods and services).

Most crucially, Europe's energy dependency from non-European regions is strongly reduced, which points to a potential further substantial third dividend. However, the several order of magnitudes high cost reduction potential of transmission between Europe and other world regions is neglected here (Grossmann et al., 2015). Furthermore, the three different socio-political storylines imply rising regional welfare disparity across European regions with energy systems that comprise less interconnected power supply. Using GDP and welfare as key economic performance indicators can be challenged in favour of more growth-agnostic metrics because other criteria may be more relevant "real-world" barriers or enablers, such as the health co-benefits of increased air quality, or social and political divide or cohesion. Distributional effects within the EU member states are only considered here in terms of functional income sources (un-/skilled workers and capital owners), pointing to lower unemployment and a rising wage share with the most decentral but least interconnected system. Other dimensions such as income class or residence location might play a more important role than the one investigated here.

The second learning concerns methodological findings. A stand-alone application of a state-of-the art macroeconomic model is helpful but has its limits. Substantial structural breaks from a top-down perspective are enabled by sourcing information from more fine-grained models, tailor-made for the issue under consideration. This allows taking advantage of the merits of both bottom-up and top-down approaches. In this study, socio-political aspects are core drivers to generate future alternatives of energy systems (QTDIAN). Fed into an energy model, the presented approach also warrants that physics is not violated considering temporally, spatially, and technologically highly resolved service demands to optimise the energy supply to cover them. Hence, the resulting allocation is physically possible and shown to be climate-neutral and low-cost (Calliope). On top, we use a comprehensive approach that accounts for economy-wide income and expenditure effects showing that the allocation is also beneficial in the aggregate (WEGDYN). A further relevant methodological insight concerns the choice of the scenario framework. Instead of comparing a climate-neutral path with a baseline (or business-as-usual), we are only interested in different designs of the climate-neutral pathway. Using a still emission-intensive baseline development and comparing a climate-neutral path to it would neglect the cost of inaction that are connected to climate change impacts. These social costs are hardly includable in the underlying framework due to uncertain tipping points in the Earth's climate system rendering a safe minimum standard approach (i.e., "well below 2°C") a safe bet.

The third learning is a reflection on the current situation and the way forward to escape the prevalent lock-in ("bad equilibrium") also in the context of the current energy crises in the aftermath of the Russian war with Ukraine. It is important to identify forces that yet keep society in this situation and forces that bring about a new climate-neutral structure of the European energy system that is also very soon much less dependent on fossil imports from Russia. The current energy price hikes are substantial incentives that attract the European energy system towards the climate-neutral configurations analysed here. While keeping these incentives up is consistent with medium- to long-run societal objectives, energy price shocks come with tremendous and undesired distributional effects now particularly at the bottom end of the European income distribution. Now, providing sufficient public relief, for instance, by lump-sum payments to most vulnerable private households is essential. For energy-intensive firms, good experiences have been made with temporary short-time work programmes during past recessionary phases such as the financial crisis after 2008 and also the recent COVID-19 pandemic. Such transfer-like policy instruments are not only incentive-compatible but also much more effective than price-signalled manipulations through, for instance, cuts in excise taxes on fossil energy. Europe is in a situation with highly inelastic fossil energy demand, which is why undesired distributional outcomes eventually exacerbate further with such instruments. There are indications that domestic and foreign energy producers already earn substantial windfall profits (for domestic due to the merit order effect and for import partner Russia due to sky-rocketing fossil energy prices). These would further rise with broad energy excise tax cuts not (sufficiently) relieving the burden of final consumers because of high pass-through rates in these markets.

Short-term fiscal responses must be complementary with clear medium- to long-term targets that are generally required for guidance and orientation ("mission-orientation"). One of the drivers of the great financial crises and ensuing disruptions has been the phenomenon of "collective moral hazard" (Farhi and Tirole, 2012), which describes the out-sourcing of individual business risk to current, or future consumers, which provide the bailouts in case of an event. In financial crises, a clear societal objective about the role and functioning of financial markets has been lacking. Consequently, and as a second-round effect, the design of bailout-instruments favoured the status quo and made them the source of subsequent turmoil. "Adopting a risky balance sheet turned out profitable" (ibid), although these financial activities were actually unprofitable without regular bailouts. This is one of the positive feedback loops preserving prevailing structures, in this case of the financial system. Modelling results show that escaping this feedback loop requires a clear target first in order to guide the respective design of concrete measures and instruments. Analogous, there are indications that the current energy system is affected by moral hazard behaviour because the absence of a clear and credible societal objective since the Russian war against Ukraine led to counterproductive claims such as cuts in fossil energy taxes from various economic actors. Decision-makers are thus well-advised to keep the objective of the here-analysed climate-neutral and much less import-dependent configurations of the European energy system on their core agenda. Otherwise, temporary relief measures that are inconsistent with these objectives may similarly end up as the source of even more serious socio-economic consequences in the not-so-distant future.

Finally, the analysis here does not address all components of the risk profile in the old and the new system, such as geopolitical or market power asymmetries in energy value chains. This risk profile changes with a new socio-techno-economic structure. The energy systems analysed here are connected to minimised energy dependence from non-European regions (including Russia) but perhaps higher material supply risks due to the large role-out of renewables. Hence, the next step would be to apply material flow and life cycle analysis to explore reciprocal dependences due to international division of labour and resource abundance. Modelling results are also not a reason to claim that climate-neutral transitions will necessarily run smoothly. The "real-world" situation is a dunning example because the resource curse also seems to apply to the Russian Federation. A lot of "real-world" frictions and tensions are unknown or not accountable with the chosen modelling ensemble. For instance, monetary policy challenges are assumed away because WEGDYN is restricted in relaxing optimal central bank reactions, one of the limitations that should be kept in mind.

4.3. Model application in the case studies: processual challenges and lessons learnt

Throughout the first round of the SENTINEL stakeholder engagement activities, as these have been reported in Deliverable 7.1 (Stavrakas et al., 2021), we have identified a large number of various RQs for each CS. These RQs mean to serve as a comprehensive reference list for stakeholders interested in an updated overview on the latest policy developments, the critical issues, and the challenges of the energy transition in diverse spatial scales and socioeconomic contexts. They also meant to serve as the testing ground in which the applicability and the usefulness of the SENTINEL models, would be tested, either individually, or by soft-linking the models.

Depending on the problem formulation for each RQ and each CS, thus, diverse model types were suitable to be deployed in providing responses, i.e., while some models were a better fit to understand long-term developments and answer a wide range of energy-policy questions, others were a better fit to answer precise policy questions, relevant to specific sectors, or localities. Overall, in this deliverable, we reported modelling results to **37 RQs** in the **Continental CS** (EU, Norway, Switzerland, the United Kingdom, and some Balkan countries), **10 RQs** in the **Regional CS** (Nordic countries), and **29 RQs** in the **National CS** (Greece).

The SENTINEL modelling suite was able to successfully represent and analyse different scenarios and transition pathways, also considering a plethora of critical issues of the European energy transition to climate neutrality by 2050, as, e.g., decentralisation, large-scale expansion of fluctuating RES-based power leading to increased need for system-side flexibility, sector coupling, including the electrification of mobility and heating, the impacts of different market designs on the behaviour of energy-sector actors, etc. To do so, we had to go beyond just improving the models' resolution and sectorial coverage, as our vision was to create a system where smaller, more specialised models are combined in a modular fashion to answer complex RQs, which, otherwise, it would be impossible to be answered individually by a single "*one-size-fits-all*" model. This allowed for a more resilient and robust approach to providing the level of detail that the energy transition requires and the level of transparency that stakeholders demand. An important challenge, though, was that the application of such a novel approach required additional time in order to coordinate the activities between the different research teams and develop conceptual ties between the models.

In addition, some of the identified RQs were not possible to be answered due to technical and modelling constraints, and to the nature of the questions themselves. This mainly concerned qualitative questions that referred to social implications, or regulatory specifications and constraints, since such aspects are always difficult to quantify using numerical modelling approaches. Beyond the technical feasibility of the models, though, there were also complications about the way how some of the RQs were formulated by stakeholders; they were formulated in a normative manner that did not align with the core scope of the modelling tools and their capabilities. To meet stakeholders' expectations regarding their involvement and the questions they are interested in, it is important to clearly communicate and explain the aspects of such misalignment. The latter will be further addressed during next steps of the work under Work Package 7 (Deliverable 7.3), also highlighting new modelling paradigms and trends as well as priority areas, which energy system models should consider under their scope in the future.

Finally, considering Russia's invasion of Ukraine and the potential consequences for the European energy transition (e.g., the shortages of the Russian gas supplies, integration of the Ukrainian electricity network into the European grid, socioeconomic impacts, etc.), further research and modelling studies should definitely shed light to the strategic EU decisions regarding the faster reduction of the dependence on fossil fuels, and especially Russian oil and gas. Further model application is needed to better understand the diversity of the different issues and challenges of energy transition pathways to climate neutrality by 2050, by specifically accounting for emerging geopolitical developments that can affect strategic decisions. Future research should also dive deeper into the specific reasons for the observed differences (why) and the interactions between different scales (governance perspectives). Such an approach should also build around stakeholder visions on how the European energy systems' elements should be integrated and managed in the future, either from a participatory/multi-level governance perspective, or a cost-benefit point of view.

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Appendix A – Data Gathering Protocol

1. Introduction

A vital step to ensure that the models in the SENTINEL suite work not only in theory, but also in practice is their application to a range of case studies, also considering stakeholders' and model users' insights and needs. To this end, under WP7, SENTINEL includes a set of case studies at three different geographical levels: National (Greece), Regional (Nordic countries), and Continental (European Union, Iceland, Norway, Switzerland, the United Kingdom, and some Balkan countries), to identify the main issues and challenges of the European energy transition, which modellers and policymakers will be faced with in the future.

Every modelling exercise requires an extensive amount of input data. Since different and diverse models will be applied in SENTINEL, they will require input data from diverse sources. Therefore, a Data Gathering Protocol is an important step to organise the work of data collection in the implementation of the case studies, ensuring that data providers have a single point of communication within the project. Furthermore, as the SENTINEL project aims at improving quality and transparency of energy system modelling, it is essential to document the sources and the path of data from the providers to each model.

In this document, we are dealing only with model input data, which will be used to initialise all models for the three case studies. Data collected from public sources will be made available on the project website. Depending on the models applied in each case study, publicly available data will include, among others, transmission capacities between or within countries (including both statistics for the current situation and planned projects which can be used in the scenarios formulation), installed generation capacity by country or region, historical and projected energy demand profiles, weather data, agents on the electricity wholesale markets, and fuel costs. Regarding collecting and storing data, we will closely follow the principles described in the SENTINEL data management plan (DMP, Deliverable 9.3). The approach in the DMP is to store model input data in either ".csv" files to allow for an easy and low-threshold access or in a more complex data management platform. All three case studies focus on European countries, therefore most of the models' input data would be available from sources encompassing European databases, such as ENTSO-e, EEX, Eurostat, ICE, IEA, IRENA, Renewables Ninja, EEA, Eurostat, EU statistical pocketbook, Odysee-Mure database and WRI. It is important to note that most of these sources are listed on Open Power System Data.

Building on the SENTINEL DMP, in the context of the SENTINEL Data Gathering Protocol we are **analysing** the **process** for providing **answers** to the following questions:

- *What kind of data is needed for each case study?*
- *Where can we find this data?*
- *How should we coordinate with data providers?*
- *How should we facilitate the process of data exchange and possible clarifications?*
- *How can we ensure coordination with WP8 and WP9 on data management and data exchange?*
- *How can we ensure that data are FAIR (Findable, Accessible, Inter-operable and Re-usable)?*

2. Data gathering

Energy system models require typically a lot of data to calibrate historical data, estimate parameters and perform projections. Although a large amount of data already exists in the public domain, some of it might need to be collected from specific public and/ or private organisations operating in the energy sector.

2.1. Allocation of responsibilities

Different models will be applied in the different case studies of SENTINEL, to address specific research questions, therefore, a clear allocation of responsibilities between the SENTINEL WP7 partners is necessary. The overall coordination of the data collection process within WP7 will be performed by UPRC. For each case study a coordinator is assigned according to the table below. Furthermore, in order to have a single point of communication between SENTINEL and the various data providers, one or two project partner(s) is/are assigned as data-responsible for each case study:

Case Study	Coordinator	Data-responsible partners
National (Greece)	UPRC	PPC
Regional (Nordic)	UPRC/RGI	RGI/PPC
Continental (Europe)	UPRC/RGI	RGI/PPC

2.2. Data gathering process

For the data gathering process we envision the following steps (**Figure A1**):

i. **Identification of data needs:** Under the guidance of the Coordinator, modelling teams will identify the case study data needed. In some cases, modelling teams might also need to confirm the validity of data which they already have from other sources with the key stakeholders. We will formulate a data request template, which will have a standard layout and will include: **i)** a detailed description of the case study data needed, **ii)** the desirable format of the data, and **iii)** any other information, for which it is important to communicate with data providers.

ii. **Identification of data sources:** A certain amount of the necessary data is already publicly available in sources already listed on the Open Power System Data. The modelling teams will acquire this data directly from the online sources and will provide to the Coordinator the information described under point 5 below, to keep track of all data-related information. The Coordinator, in close contact with TU Delft (WP6 Leader) and ETHZ (WP9 Leader), will be in charge of making sure that this information is consistent and will feed in the meta-data collected under both WP6 and WP9. However, in some case studies or for some models, data might not be available in the already identified online sources. In this case, modellers in collaboration with the data-responsible partners will identify the organisations, which could provide this data to proceed with data requests.

iii. **Contact with organisations identified as data providers**: For each case study, the data-responsible partner will contact data providers identified in the previous step, using the standard data request template described in point 1. The data-responsible partner will coordinate the process to ensure that each data provider is only contacted once for all the necessary data, so that we avoid potential un-coordinated communication between modelling teams and data providers. Possible *bilateral meetings* between modelling teams and data providers will be also facilitated by the data-responsible partners. In case the data provider is either not willing to provide the necessary data or is restricted by confidentiality issues to disclose the data to the project, the data-responsible partner will support the modelling team to find alternative sources. If this approach is not successful either, the modelling team in collaboration with the data-responsible and the case study coordinator will use reasonable assumption based on inputs which are already available to the project team.

iv. **Data gathering**. The data-responsible partner will be in charge of data gathering from the relevant sources and will make sure to forward it then to the SENTINEL modelling teams.

v. **Documentation**. For each set of data as collected from data providers, each case study's Coordinator will compile an information sheet, which will include the following:

a. *Description of data according to the data request template.*
b. *Model(s) which will utilise the data.*
c. *Code of the variable in the intercomparison database (if it exists).*
d. *Source of data (data providing institution).*
e. *Contact points within the data providing institution.*
f. *Date of access.*

This information will be consistent with the meta-data definitions in the SENTINEL DMP.

vi. **Data storage.** For each case study, raw data, as collected from data providers, will be stored initially by the Coordinator, and then, in collaboration with ETHZ/TU Delft, the options of storing it in the SENTINEL main data repository will be explored.

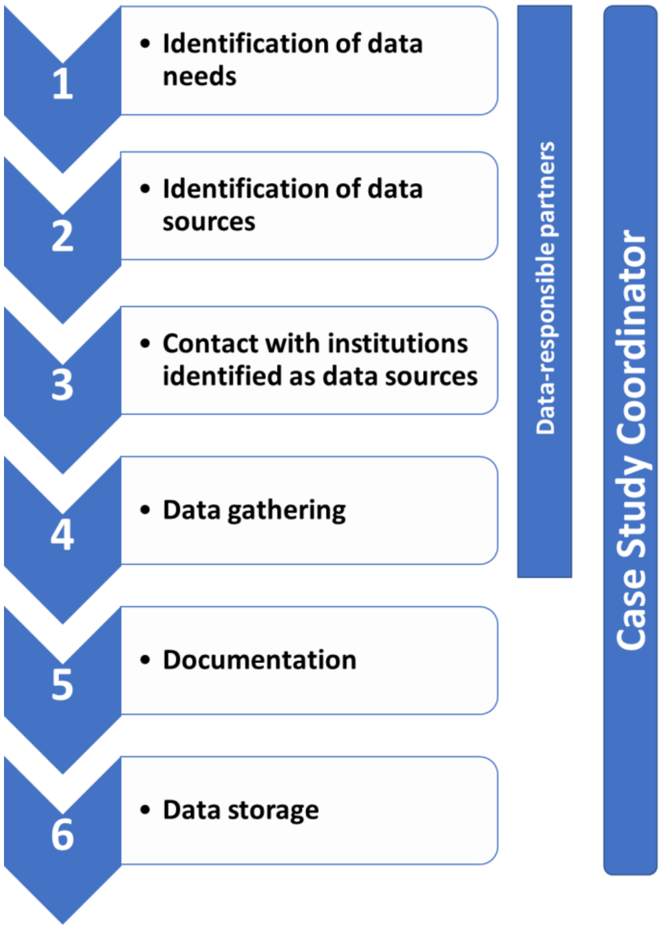

Figure A1. Data gathering process during the case study application phase.

2.3. Harmonisation of Data gathering

Within SENTINEL, WP6, WP8, and WP9 deal with the overall data management, harmonization, and storage, for all types of data (i.e., model inputs, model outputs, and workshop and stakeholder data). For each SENTINEL case study, the Coordinator will work together with the leading partners of each one of these WPs to ensure that:

- *All data collection procedures will abide to the guidelines of the SENTIEL DMP.*
- *All data collected will be available for the needs of WP8, will be consistent with the procedures of WP6, and will become available in the central SENTINEL repository under WP9.*

The following general guidelines are proposed in order to have a harmonised dataset:

- *Modelling teams should share CSV files as part of a ZIP/TAR archive which will make it easier to manage and link data. As an option, the package which has already been developed in the framework of WP6 can be used for managing CSV files.*
- *All datasets should include the publishing date as a version tag.*
- *A "README" file should be included in all datasets. This should include at least a brief description of the context of the data inputs, and any further processing steps, which might be necessary before the data can be used further.*
- *Modelling teams should host data in repositories that can be updated directly by them, for example a public repository like GitHub or Zenodo.*

2.4. Data security

Data gathered within WP7 will be distributed to the SENTINEL modelling teams and will be initially stored by the Coordinator of each case study. All data stored will be backed-up regularly to ensure the possibility of data recovery. Data in use for modelling at the different SENTINEL partners' institutes will be subject to each institute's policies for data security and backup. For any data included in the central SENTINEL repository we will follow the procedures described in the SENTINEL DMP.

2.5. Sensitive Stakeholder Data

Along with model input data contact information of identified key persons within data providers will be gathered, as described in **Appendix A-Section 2.2**. This stakeholder data will be under restricted access, available only to few members of UPRC, RGI, and PPC, ensuring that all the binding legislative agreements between partners (as dictated by the Consortium Agreement and the SENTINEL Ethics Requirements) are respected. No identifiable data will be stored longer than required. After the completion of the project the data will be destroyed. Stakeholder data protection will be also enhanced through the PPC partner's data protection protocol, which as the PPC in Greece, has years of experience in confidential treatment of information and contact details of stakeholders.

3. Making the case study data FAIR (Findable, Accessible, Inter-operable and Re-usable)

Making data available, findable, inter-operable and open are core aspects of the SENTINEL project. These principles will be applied to the data which will be used for the case studies following the approaches described below.

Making data findable

The raw data, as collected from data providers, will be described through meta-data as described in **Appendix A-Section 2.2**. The overall approach used for the data management in SENTINEL will be considered for the case study data as well, in coordination with WP9.

Making data accessible

The raw data, as collected from data providers, will be stored in a repository so that they can be accessible by all the SENTINEL modelling teams, following the guidelines of the data management in SENTINEL.

Making data interoperable

The data collected for the case studies will be interoperable; that means data exchange and re-use between researchers, institutions, organizations, and countries will be possible. We will adhere to format standards compliant with available (open) software applications as much as possible.

Increase data re-use

SENTINEL partners have already signed a memorandum of understanding that all new data developed during the project will be made openly available (see the SENTINEL DMP, Deliverable 9.3). However, we envision the use of open licenses for input data, insofar as this is possible based on what licensing restrictions applied to data from third parties. These principles will be applied to all data collected within WP7.

Appendix B – Supplementary Tables and Figures

Table B.1. Summary of linkages between ENBIOS structural processors and Euro-Calliope outputs.

ENBIOS structural processor		Euro-Calliope output(s)		
		File	**"techs"**	**"carriers"**
Electricity	Wind - Onshore	flow_out_sum	wind_onshore	electricity
	Wind - Offshore	flow_out_sum	wind_offshore	electricity
	Hydro - Reservoir	flow_out_sum	hydro_reservoir	electricity
	Hydro - River	flow_out_sum	hydro_run_of_river	electricity
	Solar PV - Field	flow_out_sum	open_field_pv	electricity
	Solar PV - Roof	flow_out_sum	roof_mounted_pv	electricity
	Biomass	flow_out_sum	chp_biofuel_extraction	electricity
	Waste	flow_out_sum	chp_wte_back_pressure	electricity
	Coal	flow_out_sum	coal_power_plant	electricity
	Natural gas	flow_out_sum	ccgt	electricity
		flow_out_sum	chp_methane_extraction	electricity
	Nuclear	flow_out_sum	nuclear	electricity
Heat	Biomass	flow_out_sum	biofuel_boiler	heat
		flow_out_sum	chp_biofuel_extraction	heat
	Waste	flow_out_sum	chp_wte_back_pressure	heat
	Natural gas	flow_out_sum	chp_methane_extraction	heat
		flow_out_sum	methane_boiler	heat
Fuel	Biodiesel	flow_out_sum	biofuel_to_diesel	diesel
		flow_out_sum	biofuel_to_liquids	diesel
		flow_out_sum	biofuel_to_liquids	kerosene
		flow_out_sum	biofuel_to_methane	methane
		flow_out_sum	biofuel_to_methanol	methanol
		flow_out_sum	biofuel_to_liquids	electricity
	Natural gas	flow_in_sum	demand_industry_methane	methane
		flow_in_sum	gas_hob	methane
	Diesel	flow_out_sum	diesel_supply	diesel
	Kerosene	flow_out_sum	kerosene_supply	kerosene
	Methanol	flow_out_sum	methanol_supply	methanol

Table B.2. Summary of additional factors for CRMs.

Material	**Supply risk** (European Commission, 2020b)	**Local impacts** (European Commission, 2020b)	**EoLRIR** (European Commission, 2020b)	**EU consumption** *[tonnes]*
Palladium	1.27	0.51	28%	59 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Platinum	1.84	0.62	25%	64 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)

Rhodium	2.14	0.65	28%	7 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Dysprosium	6.20	0.54	0%	14 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Europium	3.66	0.54	38%	24 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Gadolinium	6.06	0.54	1%	11 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Terbium	5.51	0.54	6%	24 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Yttrium	4.20	0.54	31%	509 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Cerium	6.17	0.54	1%	4,027 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Lanthanum	6.04	0.54	1%	645 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Neodymium	6.07	0.54	1%	100 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Praseodymium	5.49	0.54	10%	41 32,493 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Antimony	2.01	0.48	28%	649 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Baryte	1.26	0.58	1%	506,410 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Beryllium	2.29	0.30	0%	38 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Borates	3.19	0.27	1%	62,850 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Cobalt	2.54	0.43	22%	31,441 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Fluorspar	1.15	0.40	1%	755,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Gallium	1.26	0.52	0%	27 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Lithium	1.64	0.45	0%	3,225 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Magnesium	3.91	0.55	13%	113,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)

Natural graphite	2.27	0.59	3%	86,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Phosphorus	3.55	0.55	0%	48,300 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Silicon metal	6.12	0.54	1%	6 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Samarium	1.18	0.47	0%	433,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Strontium	2.57	0.41	0%	49,298 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Tantalum	1.36	0.71	0%	395 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Titanium	1.26	0.45	19%	1,509,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Tungsten	1.61	0.53	42%	431 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Vanadium	1.69	0.51	2%	12,717 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Aluminium	0.59	0.49	12%	5,252,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs European Commission et al., 2020b)
Arsenic	1.19	0.59	0%	354 (Eurostat, 2018)
Cadmium	0.34	0.40	30%	700 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Chromium	0.86	0.61	21%	1,200,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Copper	0.32	0.44	17%	4,000,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Diatomite	0.46	0.33	4%	132,493 (Eurostat, 2018)
Gold	0.19	0.52	29%	1,425 (Eurostat, 2018)
Gypsum	0.50	0.51	1%	4,596,092 (Eurostat, 2018)
Iron ore	0.46	0.46	31%	292,000,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Kaolin clay	0.40	0.42	1%	3,100,479 (Eurostat, 2018)
Lead	0.09	0.42	75%	1,385,399 (Eurostat, 2018)
Magnesite	0.65	0.52	2%	49,459 (Eurostat, 2018)
Manganese	0.93	0.55	8%	800,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)

Molybdenum	0.94	0.46	30%	60,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Nickel	0.49	0.38	17%	460,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Perlite	0.42	0.38	42%	3,677,958 (Eurostat, 2018)
Rhenium	0.45	0.33	50%	2,842 (Eurostat, 2018)
Selenium	0.41	0.29	1%	1,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Silver	0.68	0.41	19%	3,800 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Sulphur	0.27	0.40	5%	1,223,738 (Eurostat, 2018)
Talc	0.40	0.43	16%	1,114,963 (Eurostat, 2018)
Tellurium	0.51	0.41	1%	30 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Tin	0.90	0.57	31%	63,932 (Eurostat, 2018)
Zinc	0.34	0.45	31%	4,000,000 (Directorate-General for Internal Market Industry Entrepreneurship and SMEs, European Commission et al., 2020)
Zirconium	0.83	0.40	12%	273,789 (Eurostat, 2018)

Table B.3. Summary of combustion factors for selected fuels.

Fuel	Combustion factor *[kg CO_2-eq/TJ]*	Reference
Biodiesel	71,229	(IPCC, 2021) (biodiesel)
Natural gas	64,629	(IPCC, 2021) (natural gas)
Diesel	74,529	(IPCC, 2021) (diesel and other oil)
Kerosene	73,223	(IPCC, 2021) (jet fuel and kerosene)
Methanol	68,128	(Yao et al., 2018)

Table B.4. Summary of human labour data for selected electricity, heat, and fuel technologies (Rutovitz et al., 2015).

		Manufacturing	Construction & installation	Time	Operation and maintenance	Decommissioning	Time	ELEC & HEAT TOTAL	FUEL TOTAL
		[job.yr.MW⁻¹]	*[job.yr.MW⁻¹]*	*[yr]*	*[job.yr.MW⁻¹]*	*[job.yr.MW⁻¹]*	*yr*	*[job.MW⁻¹]*	*[job.MJ⁻¹]*
Electricity	Wind - Onshore	4.7	3.2	2	0.3			4.3	
	Wind - Offshore	15.6	8.0	4	0.2			6.1	
	Hydro - Reservoir	3.5	7.4	2	0.2			5.7	
	Hydro - River	10.9	15.8	2	4.9			18.3	
	Solar PV - Field	6.7	13.0	1	0.7			20.4	
	Solar PV - Roof	6.7	13.0	1	0.7			20.4	
	Biomass	2.9	14.0	2	1.5			10.0	
	Waste	2.9	14.0	2	2.25			10.7	
	Coal	5.4	11.2	5	0.14			3.5	
	Natural gas	0.9	1.3	2	0.14			1.3	
	Nuclear	1.3	11.8	10	0.6	0.95	35	35.2	
Heat	Biomass	2.9	14.0	2	1.5			10.0	
	Waste	2.9	14.0	2	2.25			10.7	
	Natural gas	0.93	1.3	2	0.14			1.3	
Fuel	Biodiesel								8.6
	Natural gas								8.6
	Diesel								8.6
	Kerosene								8.6

Table B.5. Correspondence table - Calliope technology to WEGDYN sector in/output.

Calliope technology	WEGDYN sector input	WEGDYN sector output[22]	System cost component
coal_power_plant	CoalBL	ELY	Generation
ccgt	GasBL	ELY	
chp_biofuel_extraction	GasBL	ELY	
chp_methane_extraction	GasBL	ELY	
chp_wte_back_pressure	GasBL	ELY	
hydro_run_of_river	HydroBL	ELY	
hydro_reservoir	HydroP	ELY	
nuclear	NuclearBL	ELY	
open_field_pv	SolarP	ELY	
roof_mounted_pv	SolarP	ELY	

[22] See **Table B.7** for acronym definition.

biofuel_to_methanol	CRP	CRP	Integration (conversion & storage)
hydrogen_to_methanol	CRP	CRP	
syn_methanol_converter	CRP	CRP	
electric_hob	ELY	DWE	
gas_hob	GDT	DWE	
battery	TnD	ELY	
dac	TnD	ELY	
electrolysis	TnD	ELY	
hydrogen_storage	TnD	ELY	
pumped_hydro	TnD	ELY	
wind_offshore	WindBL	ELY	
wind_onshore	WindBL	ELY	
chp_hydrogen	GasBL	ELY	
hydrogen_to_methane	GAS	GAS	
methane_supply	GAS	GAS	
biofuel_to_methane	GAS	GAS	
methane_storage	GAS	GAS	
biofuel_boiler	GDT	GDT	
electric_heater	GDT	GDT	
heat_storage_big	GDT	GDT	
heat_storage_small	GDT	GDT	
hp	GDT	GDT	
methane_boiler	GDT	GDT	
waste_supply	GDT	GDT	
biofuel_supply	P_C	P_C	
biofuel_to_diesel	P_C	P_C	
diesel_supply	P_C	P_C	
hydrogen_to_liquids	P_C	P_C	
kerosene_supply	P_C	P_C	
biofuel_to_liquids	P_C	P_C	
syn_diesel_converter	P_C	P_C	
syn_kerosene_converter	P_C	P_C	
syn_methane_converter	P_C	P_C	

Table B.6. Correspondence table for EU27+; Calliope countries to WEGDYN regions; *SEE includes Malta.

Calliope country		WEGDYN region	
Austria	AUT	AUT	Austria
Netherlands	NLD	BNL	Benelux and Switzerland
Belgium	BEL	BNL	
Switzerland	CHE	BNL	
Luxembourg	LUX	BNL	
Slovenia	SVN	CEU	Central Eastern Europe
Hungary	HUN	CEU	
Poland	POL	CEU	
Czech Republic	CZE	CEU	
Slovakia	SVK	CEU	
Germany	DEU	DEU	Germany
France	FRA	FRA	France
Greece	GRC	GRC	Greece
Portugal	PRT	IBE	Iberian Peninsula
Spain	ESP	IBE	
Italy	ITA	ITA	Italy
Sweden	SWE	NEU	North-eastern Europe
Ireland	IRL	NEU	
Norway	NOR	NEU	
Denmark	DNK	NEU	
Iceland	ISL	NEU	
Finland	FIN	NEU	
Estonia	EST	NEU	
Lithuania	LTU	NEU	
Latvia	LVA	NEU	
Romania	ROU	SEE	South-eastern Europe*
Serbia	SRB	SEE	
Bulgaria	BGR	SEE	
Croatia	HRV	SEE	

Bosnia Hercegovina	BIH	SEE	
Albania	ALB	SEE	
Cyprus	CYP	SEE	
Macedonia	MKD	SEE	
Montenegro	MNE	SEE	
Great Britain	GBR	UKD	United Kingdom

Table B.7. WEGDYN sectoral resolution.

Acronym	Sector aggregates in the WEGDYN model	Comprising GTAP sectors
AFF	Agriculture, Forestry and Fishery	Agricultural sectors (1-8), Agricultural sectors (9-12), forestry (13) and fishing (14)
COA	Coal	Coal Mining (15)
OIL	Crude Oil	Oil extraction (16)
GAS	Natural Gas	Natural Gas extraction (17)
GDT	Gas distribution and hot water supply	Manufacture of gas, distribution, steam and hot water supply (44)
OMN	Other mining	Other mining (18)
ELY	Electricity	Production, collection and distribution of electricity (share of 43)
MAN	Manufacturing	All food processing sectors (19-25), beverages and tobacco products (26), Textiles (27), Wearing apparel (28), Leather products (29), Wood products (30), Manufacture of paper products and publishing (31), Other Manufacturing: includes recycling (42)
MEM	Machinery, data processing equipment, electronic and optical products, Electronic Equipment, Motor, Motor vehicles and parts and other Transport Equipment	Motor, Motor vehicles and parts: cars, lorries, trailers and semi-trailers (38), Other Transport Equipment: Manufacture of other transport equipment (39), Electronic Equipment: office, accounting and computing machinery, radio, television and communication equipment and apparatus (40), Other Machinery & Equipment: electrical machinery and apparatus n.e.c., medical, precision and optical instruments, watches and clocks (41),

P_C	Refined oil products	Petroleum, coal products (32)
CRP	Chemical industry	Chemical, rubber, plastic products (33)
NMM	Manufacture of other non-metallic mineral products	Manufacture of other non-metallic mineral products (34)
I_S	Manufacture of basic iron and steel and casting	Manufacture of basic iron and steel and casting (35)
PNF	Manufacture of precious and non-ferrous metals, and fabricated metal products	Precious and non-ferrous metals (36), fabricated metal products (37)
CON	Construction	Construction (46)
LAT	Transport – Land	Other Transport (including road and rail transport) (48)
WAT	Transport –Water	Water transport (49)
AIT	Transport –Air	Air transport (50)
SER	Other services	Water (45), Trade: all retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel (47), post and telecom (51), financial services (52), insurance (53), Recreational & service activities (55), public administration (56)
DWE	Dwellings and real estate	Dwellings (57), real estate & other business (54)

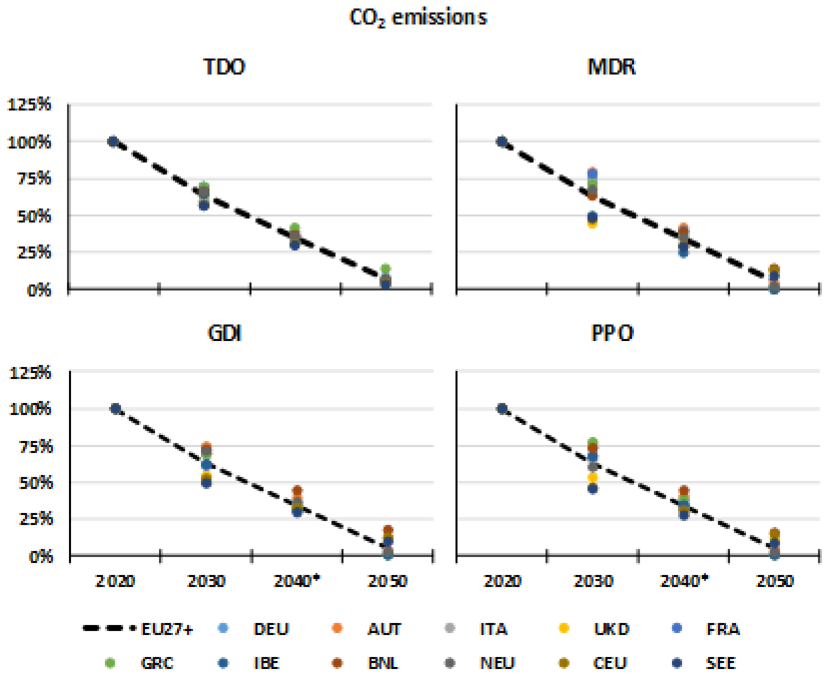

Figure B.1. EU27+ regional Carbon Dioxide (CO_2) emission reductions; *2040 interpolated; AUT: Austria; BNL: Benelux and Switzerland; CEU: Central-Eastern Europe; DEU: Germany; FRA: France; GRC: Greece; IBE: Iberian Peninsula; ITA: Italy; NEU: North-Eastern Europe; SEE: South-Eastern Europe; UKD: United Kingdom. Further details in **Table B.6.**

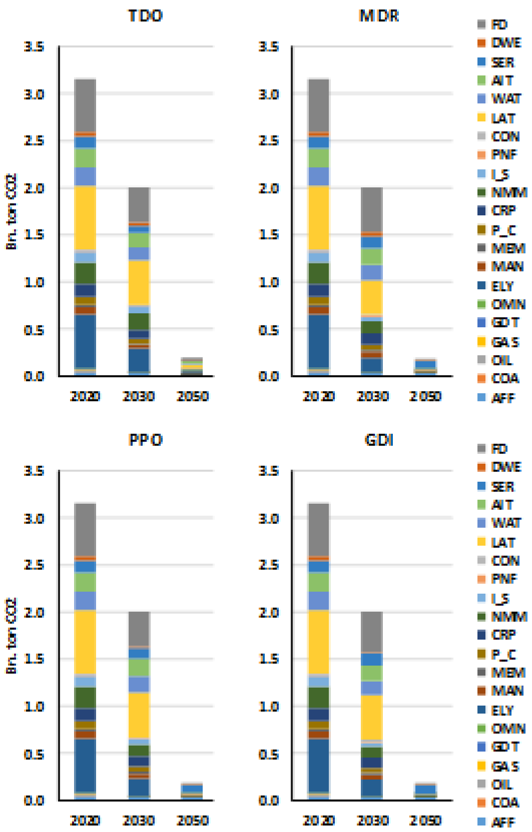

Figure B.2. EU27+ sectoral Carbon Dioxide (CO_2) emission reductions; *2040 interpolated; FD: final demand; AFF: Agriculture, Forestry and Fishery; COA: Coal; OIL: Crude Oil ; GAS: Natural Gas; GDT: Gas distribution and hot water supply; OMN: Other mining; ELY: Electricity; MAN: Manufacturing; MEM: Machinery, equipment, other; P_C: Refined oil products ; CRP: Chemical, rubber, plastic products; NMM: Manufacture of other non-metallic mineral products; I_S: Manufacture of basic iron and steel and casting; PNF: Manufacture of precious and non-ferrous metals, and fabricated metal products; CON: Construction; LAT: Transport – Land; WAT: Transport –Water; AIT: Transport –Air; SER: Other services; DWE: Dwellings and real estate. Further details in **Table B.7**.

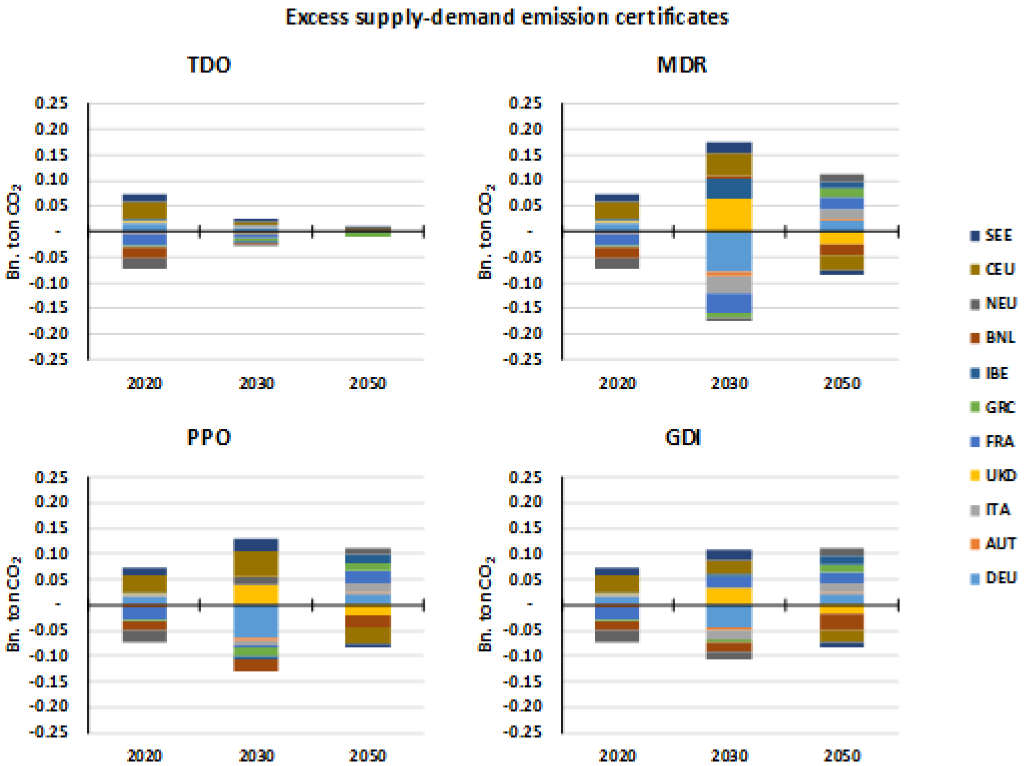

Figure B.3. Excess supply of (>0) and excess demand for Carbon Dioxide (CO_2) emission allowances (<0) across regions; AUT: Austria; BNL: Benelux and Switzerland; CEU: Central-Eastern Europe; DEU: Germany; FRA: France; GRC: Greece; IBE: Iberian Peninsula; ITA: Italy; NEU: North-Eastern Europe; SEE: South-Eastern Europe; UKD: United Kingdom. Further details in **Table B.6**.

Table B.8. Decomposition formula for power generation.

Population		Activity		Renewables		Efficiency		Carbon Intensity		CCS
$\mathbf{Pop}$	×	$\frac{elec\ prod}{pop}$	×	$\frac{elec\ prod}{(1-\%ren)}$	×	$\frac{PE\ (1-\%ren)}{elec\ prod\ (1-\%ren)}$	×	$\frac{CO_2\ +CCS}{PE(1-\%ren)}$	−	CCS

Pop: Population change; $elec\ prod$: Electricity production, $\%ren$: share of renewables and nuclear in primary energy; PE: Primary energy

Table B.9. Decomposition formula for industry.

Population		Activity		Structure (Electrification)		Efficiency		Carbon Intensity		CCS
$\mathbf{Pop}$	×	$\frac{product\ production}{Pop}$	×	$(1-\%Elc)$	×	$\frac{FE}{Act}$	×	$\frac{CO_2+CCS}{FE(1-\%Elc)}$	−	CCS

Pop: Population change; Elc: Electricity share in energy use; FE: Final energy use

Table B.10. Decomposition formula for transport.

Population		Activity		Mode shift		Efficiency		Carbon Intensity
$\mathbf{Pop}$	×	$\frac{Pkm\ or\ Tkm}{Pop}$	×	M	×	$\frac{FE}{Pkm}$	×	$\frac{CO_2}{FE}$

Pop: Population change; Pkm: Passenger-kilometer, Tkm: Tonne-kilometer, FE: Final energy use