Expanding Integrated Assessment Modelling: Comprehensive and Comprehensible Science for Sustainable, Co-Created Climate Action

D4.9 – European sub-national deep dives

WP4 – Modelling – Quantitative evidence in support of post-2030 Paris-compliant climate action

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EC Summary Requirements

1. Changes with respect to the DoA

No changes with respect to the work described in the DoA.

2. Dissemination and uptake

This deliverable reports results from (i) the Grant Agreement-prescribed work on the sub-national analysis of the European electricity sector transition, especially with the focus on air pollution and health co-benefits, and (ii) the first modelling cycle of the IAM COMPACT Policy Response Mechanism (PRM), where questions were raised around the topics of costs, energy security and resilience, as well as electrification. The PRM modelling cycle results will be fed back to policymakers as part of the PRM cycle. The Grant Agreement-prescribed work overall presents an internationally-novel spatial analysis on air pollution in Europe and its justice implications to be published in peer-reviewed literature.

3. Short summary of results

This IAM COMPACT Deliverable, D4.9, presents three studies related to the European sub-national and sectoral deep dives into questions of climate change mitigation, air pollution co-benefits and regional inequalities, energy security and resilience, and policy assessment. The first study quantifies air quality and health impacts of 250 mitigation scenarios in the European electricity sector in 2035 across 296 NUTS-2 sub-national regions. It shows that the direct $PM_{2.5}$ concentrations attributable to electricity generation could be reduced by 45% to 99%, if Europe follows a net zero emissions goal as compared to a reference system. The most vulnerable regions (Balkans, North-West Germany, Southeast France, and the West Midlands in England) would benefit from higher air quality co-benefits than the continental average. The second study, conducted as part of the first IAM COMPACT Policy Response Mechanism (PRM), uses a multi-model approach for Greece and the European Union and shows that the energy transition necessitates diversification from energy security and flexibility perspectives, combining dispatchable and variable generation, flexible demands, and energy storage. The third study, also part of the 1st PRM cycle of the project, uses a multi-model approach for the Greek power and residential sectors and shows the need to accelerate investments in variable renewable generation and energy storage and to phase out natural gas between 2037 and 2044. The required renovation rate in Greece should reach 2.5% to 3.5% of the housing stock per year with the focus on electrification rather than natural gas as a transition fuel.

4. Evidence of accomplishment

This report.

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Preface

IAM COMPACT supports the assessment of global climate goals, progress, and feasibility space, and the design of the next round of Nationally Determined Contributions (NDCs) and policy planning beyond 2030 for major emitters and non-high-income countries. It uses a diverse ensemble of models, tools, and insights from social and political sciences and operations research, integrating bodies of knowledge to co-create the research process and enhance transparency, robustness, and policy relevance. It explores the role of structural changes in major emitting sectors and of political, behaviour, and social aspects in mitigation, quantifies factors promoting or hindering climate neutrality, and accounts for extreme scenarios, to deliver a range of global and national pathways that are environmentally effective, viable, feasible, and desirable. In doing so, it fully accounts for COVID-19 impacts and recovery strategies and aligns climate action with broader sustainability goals, while developing technical capacity and promoting ownership in non-high-income countries.

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BC3 – Asociacion BC3 Basque Centre for Climate Change – Klima Aldaketa Ikergai	ES	
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Executive Summary

Using spatially-explicit as well as national- and continental-level modelling tools, this IAM COMPACT Deliverable, D4.9, presents three distinct studies related to the European sub-national and sectorial deep dives, covering a breadth of questions related to energy transition and climate mitigation: air pollution co-benefits and their regional inequalities, energy security and resilience implications, as well as requirements for effectively delivering on a National Energy and Climate Plan.

The first study, drawn from the DoA, quantifies air quality and health impacts of 250 mitigation scenarios in the European electricity sector in 2035, including a distribution of these impacts across 296 sub-national regions. The study links a spatially-explicit electricity sector model, EXPANSE, with a reduced complexity air quality model (Global InMAP) and a health impact model, and then applies a novel index to account for the susceptibility and vulnerability of populations to adverse health effects. Our research shows that the direct $PM_{2.5}$ concentrations attributable to European electricity generation in 2035 could be reduced by 45% to 99%, if Europe follows a net zero emissions goal for 2050 as compared to a reference system (2018 infrastructure capacities). Health co-benefits and their regional distribution can vary substantially across European regions depending on the scenario, but the most vulnerable regions (Balkans, North-West Germany, Southeast France, and the West Midlands in England) would benefit from comparatively higher air quality co-benefits than the continental average.

The second study, initiated as part of the first IAM COMPACT Policy Response Mechanism cycle, was driven by policymakers' questions (see also *D2.2 - Scoping policy relevant Research Questions*) and uses a multi-model approach (OSeMOSYS, EnergyPLAN, MARIO, and WILLIAM) and the case studies of the Greek power sector and complete energy system of the EU, for comparing energy scenarios in terms of flexibility and resilience, energy security, costs and prices, environmental effects, and trade. The study shows that the transition to renewable energy systems in Europe, as well as in Greece, necessitates the diversification of energy supply from energy security and flexibility perspectives, where renewable energy systems should be designed considering a balance between dispatchable and variable generation, flexible demands, and energy storage. Critically, we find that it is feasible to construct a fully renewable energy system without energy imports in Europe, if this is a political priority.

The third study, also initiated as part of the first IAM COMPACT Policy Response Mechanism cycle, uses a multi-model approach (OSeMOSYS, DREEM) and the case studies of Greek power and residential sectors with the focus on decarbonisation and electrification. This work shows that Greece should accelerate pending reforms to accomplish a transition in the power sector for achieving significant investments in variable renewable generation and energy storage, including hydrogen for remote systems. Dependency on natural gas is expected at least until 2037 and could potentially even extend well into another decade, because of the decision to phase out lignite by 2028: according to our results, natural gas could be phased out between 2037 and 2044, otherwise carbon capture and storage and carbon dioxide removal technologies would be required to offset the carbon emissions from natural gas. In the residential sector, the renovation rate required to achieve decarbonisation should reach 2.5-3.5% of the housing stock per year with the focus on electrification rather than using gas as a transition fuel. Ambitious policy planning could lead to lower costs in the case of decarbonisation by 2040, instead of 2050, and investing in electrification would eventually lead to lower total annual extra charges and fuel costs at the household level. Results also showcase the potential for increasing policy ambition in terms of small-scale PV capacity.

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1 Introduction

This IAM COMPACT Deliverable, D4.9 - European sub-national deep dives, presents the project's mid-term results related to the European sub-national and sectoral deep dives into the energy and climate mitigation questions, using spatially explicit, national- and continent-level modelling tools. To date, three studies have been conducted as part of Deliverable D4.9 based on the Grant Agreement and IAM COMPACT Policy Response Mechanism:

- Spatially-explicit analysis of the electricity sector transition in Europe by 2035 and the associated effects on air pollution, health benefits, and regional inequalities: This analysis is presented in Section 2 in the form of a peer-reviewed journal paper manuscript. The analysis stems from the work prescribed in the Grant Agreement.
- Multi-model analysis of energy security, resilience, flexibility, costs, and environmental indicators in renewable energy systems in Europe: This analysis is presented in Section 3 in the form of a report. It draws on the first PRM modelling cycle (see Deliverable D2.2 "Scoping Relevant Research Questions" for details), where policymakers raised questions on the different costs, energy security and resilience metrics, and how they compare for different scenarios in Europe.
- Multi-model deep dive into Greece's recently updated National Energy and Climate Plan (2023 draft), using different models: This analysis is presented in Section 4 in the form of a report. It also draws from a set of questions raised in the first PRM modelling cycle (see also Deliverable D2.2 "Scoping Relevant Research Questions"), specifically with regard to (a) the new round of NECPs and (b) electrification, with the specific case study application to Greece—a county with high renewables potential—and its residential and power sectors.

Overall, these studies already cover a breadth of deep-dive insights into energy transition questions of air pollution co-benefits and their regional inequalities, energy security and resilience, as well as policy assessment.

Despite the heterogeneity of its contents, this deliverable and the corresponding project task (Task 4.5) were explicitly designed to feature both Grant Agreement-prescribed work (Section 2) and research conducted in response to the Listening mechanism of the project (Sections 3 and 4)—much like several other tasks and deliverables in IAM COMPACT. We also acknowledge that the study presented in Section 3 ("Study 2" of the 1st PRM cycle—see D4.5 for an allocation of PRM Cycle 1 Studies across IAM COMPACT work and deliverables), does not lie well within the geographic scope of Deliverable D4.9, which is expected to offer sub-national deep dives into the EU; nonetheless, IAM COMPACT is designed to be primarily driven by—and plastic enough to adapt to—the PRM and, in turn, the needs highlighted and themes emerging from our interactions in our Policy Steering Groups and Core Working Groups, and this is why said study was deemed thematically closer to and therefore mapped onto Task 4.5 and this deliverable.

2 Subnational deep dive into air pollution and health co-benefits in Europe

Authors: Hannah Pehle, Jan-Philipp Sasse, Evelina Trutnevyte [University of Geneva]

2.1 Introduction

Decarbonisation of the energy sector is essential to reach climate goals. In the European Union (EU), energy sector emissions represent approximately 80% of total greenhouse gas (GHG) emissions, with electricity and heat generation being responsible for around a third of total emissions (Climate Watch 2022). With the European Green Deal, the European Commission has set the objective to reach carbon neutrality by 2050, reducing emissions by 50-55% compared to 1990 levels by 2030 (European Commission 2019). The electricity sector plays a pivotal role in reaching emission reduction targets and will need to decarbonise first to allow other sectors to follow (Williams et al. 2012; Davis et al. 2018). For Europe's electricity sector, the long-term carbon neutrality goal translates into emission cuts of at least 70% by 2035 compared to 2019 (European Commission 2020; Pietzcker et al. 2021). Questions remain with regard to how to reach these emission reduction targets, including the desired make-up of a low-carbon electricity supply system, which has to be informed by technical feasibility and cost-effectiveness. In addition to the technical and cost concerns, there is also an increasing recognition among policymakers of the justice implications of the low-carbon transition (European Commission 2019, 2021a; The White House 2021), the co-benefits (e.g., job creation (Ram et al. 2020, 2022), and improved air quality (Rafaj et al. 2018; Galimova et al. 2022)) as well as the potential unintended effects (e.g., job losses (Alves Dias et al. 2018; Kapetaki et al. 2020; Oei et al. 2020), divestment (Healy and Barry 2017), decreased tax revenue (Morris et al. 2019; Pollin and Callaci 2019), and land use conflicts (Meyerhoff et al. 2010; Mueller et al. 2017)). In particular, ambient, i.e., outdoor air pollution (hereafter referred to as air pollution), is a major public health concern and remains the single largest environmental health risk in Europe (European Environment Agency 2022a). Exposure to particulate matter with a diameter of 2.5 microns or less ($PM_{2.5}$) was responsible for an estimated 275,000 premature deaths in 2020 (European Environment Agency 2022b). With the Zero Pollution Action Plan, the European Commission has set a target for 2030 to reduce premature deaths caused by air pollution by more than 55 % compared to 2005 levels, while also aiming to reduce health inequalities (European Commission 2021b). Air pollution also causes a significant morbidity burden (European Environment Agency 2022b), but premature mortality is the most commonly used measure of the adverse health effects of air pollution.

As air quality and associated health co-benefits have been found to offset mitigation costs and to serve as an additional incentive to adopt mitigation measures (West et al. 2013; U.S. Environmental Protection Agency 2015; Bain et al. 2016), assessing these co-benefits has received a lot of attention in the scientific literature. Several retrospective studies quantified the air quality and health co-benefits of renewable energy deployment in the United States (US) (Barbose et al. 2016; Millstein et al. 2017; Qiu et al. 2022) or European Union (EU27 + UK) (Couvidat et al. 2021), or of instantaneous removal of fossil fuel emissions in the electricity sector (Kushta et al. 2021; Mailloux et al. 2022; Gallagher and Holloway 2022), though they considered individual technologies only without accounting for changes to the entire system. A number of prospective studies estimated co-benefits of specific policy interventions or long-term decarbonisation scenarios in China (Tang et al. 2022; He et al. 2010; Li et al. 2018), the US (Thompson et al. 2014; Polonik et al. 2023; Picciano et al. 2023), the Northeast US (Thompson et al. 2016), California (Zhao et al. 2019; Zhu et al. 2022), and the United Kingdom (Williams et al. 2018), but they did not focus on the electricity sector specifically and, with one exception (Williams et al. 2018) only, covered non-European countries. Others modelled future low-carbon electricity scenarios and investigated impacts on PM_{10} emissions (Sasse and Trutnevyte 2020, 2023a), air quality (Goforth and Nock 2022), or health (Phillips and Jung 2021; Mayfield 2022; Luo et al. 2022), but those conducted for the European context (Sasse and Trutnevyte 2020, 2023a) analysed only changes to particulate matter emissions and did not model the dispersion of pollutants in the atmosphere nor associated health impacts. In the US, numerous studies explored the air quality and health

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impacts of specific renewable energy deployment scenarios, mainly focusing on the impacts of wind and solar photovoltaic deployment at both the national (Siler-Evans et al. 2013; Wiser et al. 2016; Buonocore et al. 2019) and sub-national levels (McCubbin and Sovacool 2013; Buonocore et al. 2016b; Abel et al. 2018). One study explored how integrating air quality-related health co-benefits in the objective function impacts the design of a low-carbon electricity system in the US (Sergi et al. 2020). Others assessed the effect of carbon pricing (Dimanchev et al. 2019; Sengupta et al. 2023) or power plant emission standards (Driscoll et al. 2015; Buonocore et al. 2016a) or energy efficiency and/or renewable energy policy scenarios (Plachinski et al. 2014; Buonocore et al. 2015; Abel et al. 2019) on air quality and health impacts. Some of the mentioned studies considered inequalities in air pollution exposure in the US (Gallagher and Holloway 2022; Goforth and Nock 2022; Polonik et al. 2023) or the United Kingdom (UK) (Williams et al. 2018). Others investigated inequalities in health co-benefits between subpopulations in California (Zhu et al. 2022), Texas (Luo et al. 2022), and the US (Mayfield 2022; Qiu et al. 2022; Picciano et al. 2023), or in mortality burdens between Indian states (Sengupta et al. 2023). However, to the best of our knowledge, distributional justice implications of air pollution and related health impacts of future electricity supply scenarios in Europe have so far not been investigated.

Adverse health effects of air pollution are the greatest for those people who are at the same time more exposed, more sensitive (susceptible), and otherwise more vulnerable (European Environment Agency 2022b). Including differential susceptibility and vulnerability in a holistic assessment of health risks associated with air pollution can provide a better understanding of the environmental justice implications of air pollution (Stilianakis 2015). A variety of vulnerability concepts were used in existing literature assessing inequalities in air pollution exposure or associated health impacts, including the Carstairs Index (Williams et al. 2018), the Index of Multiple Deprivation (Tonne et al. 2008), a social vulnerability concept (European Environment Agency 2018), and two frameworks developed for California (Huang and London 2012; August et al. 2021). Zhu et al. utilised the CalEnviroScreen score (August et al. 2021) to evaluate disparities in air pollution co-benefits resulting from decarbonisation strategies in California (Zhu et al. 2022). The score considers the pollution burden and characteristics of the sensitive population, accounting for the population's underlying health conditions and socioeconomic factors (August et al. 2021). Similarly, Huang and London developed indices for the spatial analysis of vulnerability to environmental hazards in California, considering cumulative environmental hazards, the sensitivity of the population to health challenges and the population's capacity to mitigate adverse effects (Huang and London 2012). The European Environmental Agency deployed a social vulnerability concept for the assessment of inequalities in exposure to and impacts of air pollution, distinguishing between individual sensitivity due to age and ability to cope with adverse health effects associated with socioeconomic factors (European Environment Agency 2018). This social vulnerability concept, however, compares pollution exposure by sensitivity and ability to cope separately. To the best of our knowledge, there is no framework for the spatial holistic analysis of both susceptibility and vulnerability to adverse health impacts of air pollution that has been applied to the European context.

The objective of this study is to investigate air pollution and associated health co-benefits of low-carbon electricity supply scenarios in Europe in 2035 and to quantify inequalities in their regional distribution as well as to assess to what extent air quality co-benefits accrue in regions most vulnerable to adverse health effects. To that end, the study aims to answer the following research questions:

1. How will low-carbon electricity supply scenarios in Europe in 2035, including scenarios minimizing total system costs and total air pollutant emissions, impact PM2.5 concentrations attributable to electricity generation and associated health impacts, especially mortality?
2. How will low-carbon electricity supply scenarios in Europe in 2035, including scenarios minimizing total system costs and total air pollutant emissions impact, affect:
    a. Regional inequalities in the distribution of these health impacts; and
    b. Relative disparities in air quality co-benefits by level of vulnerability when accounting for susceptibility and vulnerability of populations to these adverse health effects?

2.2 Methods

In this interdisciplinary study (Figure 1), using the electricity scenarios generated by the technology-rich spatially-explicit electricity sector model EXPANSE (Trutnevyte et al. 2012; Sasse and Trutnevyte 2019, 2020) (step 1), air pollutant emission inventories are created (step 2). These inventories are required as inputs into the reduced-complexity air quality model Global InMAP (Thakrar et al. 2022) to model PM2.5 concentrations (step 3). These concentrations are then used in a health impact model to estimate mortality associated with exposure to PM2.5 concentrations attributable to electricity generation (step 4). A novel composite vulnerability index is then developed to account for the differential susceptibility and vulnerability of populations to adverse health effects of PM2.5 exposure (step 5). Finally, inequalities in the spatial distribution of mortality as well as relative disparities in air quality co-benefits across regions with different levels of vulnerability are investigated (step 6). The following sections describe the methods and data used for each of the six steps in more detail.

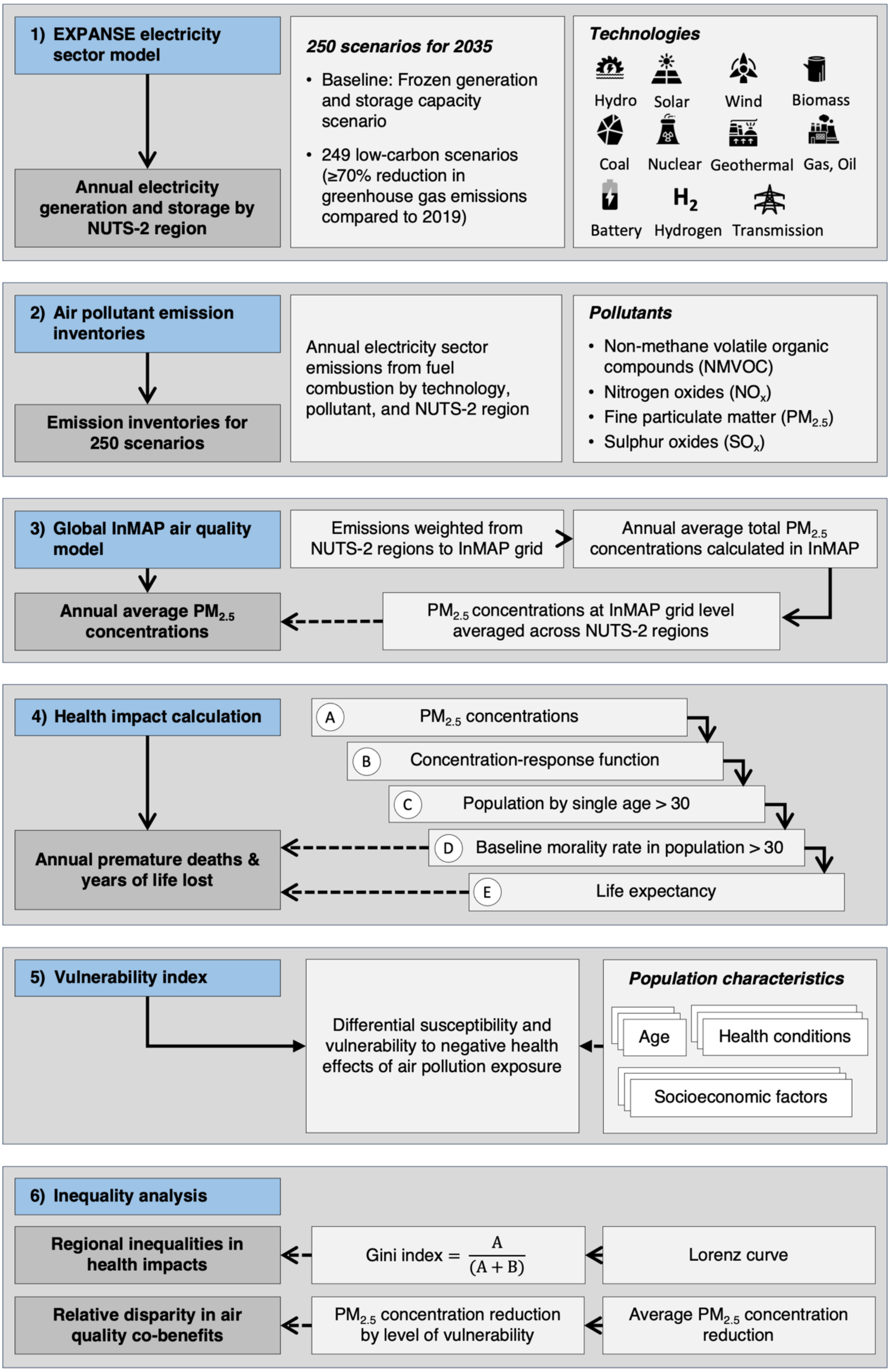

Figure 1. Methods flow chart

EXPANSE model

EXPANSE (Trutnevyte et al. 2012; Sasse and Trutnevyte 2019, 2020, 2023b) is a comprehensive spatially-explicit technology-rich cost optimisation model of the European electricity system in 2035. It includes 33 countries (EU without Cyprus and Malta, plus Albania, Bosnia and Herzegovina, Montenegro, North Macedonia, Norway, Serbia, Switzerland, and the UK) and considers electricity generation, storage, and transmission. The model operates at a spatially explicit level, with 296 NUTS-2 regions (European Parliament 2019) for electricity generation and 128 grid nodes for demand, storage, and transmission (Hörsch et al. 2018; Sasse and Trutnevyte 2023a). In the runs for this study, EXPANSE includes a maximum greenhouse gas emissions constraint of 245 $MtCO_{2\text{-}eq}$/year, consistent with a 70% emissions reduction by 2035 compared to 2019 to be consistent with the carbon neutrality goal in 2050 (Pietzcker et al. 2021; Sasse and Trutnevyte 2023a). EXPANSE uses the Modeling to Generate Alternatives (MGA) approach (Sasse and Trutnevyte 2019; Trutnevyte et al. 2012; DeCarolis 2011; Trutnevyte 2013), allowing for a cost-slack between 0% and 20% above the optimal total system costs in order to compute a diverse range of near-optimal scenarios. In total, EXPANSE computes 250 scenarios (Sasse and Trutnevyte 2023a):

- 248 MGA scenarios consistent with the 70% GHG emissions constraint, varying levels of cost slack, and additional impact constraints, i.e., minimizing total GHG emissions, particulate matter (PM10) emissions, and land use, as well as maximizing total employment,
- One minimum total system costs scenario consistent with the 70% GHG emissions constraint, and
- One baseline or 'Frozen generation and storage capacity' scenario, assuming at least the same generation and storage capacities as in 2018, while allowing transmission capacities to increase and new technologies to be built to meet higher electricity demand in 2035 but failing to meet the GHG emissions reduction target (Sasse and Trutnevyte 2023a).

With cost-effectiveness being a primary concern for policy makers and considering the European Commission's air pollution-related mortality reduction target, the minimum system costs scenario and the MGA scenario causing the lowest total air pollutant emissions will be highlighted in the analysis. Additionally, given the exploratory nature of the MGA scenarios, average impacts across all 248 MGA scenarios will be assessed. The baseline scenario serves as a reference to compare the impacts of the low-carbon scenarios to that of the current electricity system, projected to 2035. Details on the model's mathematical formulation, software implementation, and data sources are described by Sasse and Trutnevyte (2023a).

In order to estimate primary fuel use by technology and NUTS-2 region for the analysis of air pollution, regional electricity generation from combustible fuels (i.e., biogas, coal, lignite, gas, oil, waste, and woody biomass) taken from the EXPANSE model runs as described by Sasse and Trutnevyte (2023a) is used. The model output data are available at Zenodo (Sasse and Trutnevyte 2023c) and the most relevant assumptions are documented in Table 1.

Table 1. Assumptions used for emission inventories: electricity generation efficiencies in 2035, fuel types, and emission factors by technology and pollutant

EXPANSE technology	Efficiency		Fuel types	Emission factor [g/GJ]				
	%	Source		NMVOC	NO_x	$PM_{2.5}$	SO_x	Source
Biogas	41.0	Carlsson et al. (2014)	Biogas	10	202	5	25	Paolini et al. (2018), European Environment Agency (2019)
Coal	42.5	European Commission (2018)	Hard coal	0.9	82.5	5.2	820	European Environment Agency (2019)
Gas	58.5	European Commission (2018)	Natural gas	1.6	48	0.2	0.281	European Environment Agency (2019)
Lignite	37.5	European Commission (2018)	Brown coal/lignite	1.4	247	3.2	1680	European Environment Agency (2019)

Oil	35.0	European Commission (2018)	Heavy fuel oil	2.3	142	19.3	495	European Environment Agency (2019)
Waste	35.5	Carlsson et al. (2014)	Municipal solid waste	0.56	102	10	8.3	Nielsen et al. (2010), European Environment Agency (2019)
Woody biomass	37.0	Carlsson et al. (2014)	Wood and wood waste (clean wood waste)	7.31	81	133	10.8	European Environment Agency (2019)
Biogas	41.0	Carlsson et al. (2014)	Biogas	10	202	5	25	Paolini et al. (2018), European Environment Agency (2019)

Calculation of air pollutant emissions, $PM_{2.5}$ concentrations, and health impacts

Based on primary fuel use by generation technology and NUTS-2 region, air pollutant emission inventories are created for each of the 250 scenarios. To estimate total annual air pollutant emissions from fuel combustion, fuel-specific emission factors are used (Table 1). Data for non-methane volatile organic compounds (NMVOC), nitrogen oxides (NOx), (primary) fine particulate matter ($PM_{2.5}$), and sulphur oxides (SOx) are obtained from the European Monitoring and Evaluation Programme (EMEP) Emissions Inventory Guidebook (European Environment Agency 2019), Paolini et al. (2018), and Nielsen et al. (2010). Except for biogas, heavy fuel oil, and waste, combustion technology-specific emission factors (Tier 2) are available in the EMEP Emissions Inventory Guidebook. For biogas ($PM_{2.5}$) and heavy fuel oil (all pollutants), gas turbines and diesel engines are the respective assumed technologies of the Tier 1[1] emission factors (European Environment Agency 2019). Biogas emission factors for NMVOC, NOx, and SOx assume direct biogas combustion (Paolini et al. 2018; European Environment Agency 2019, p. 101). Emissions occurring at other stages of the fuel cycle, e.g., during fuel extraction, storage, or transport, are not considered.

To model $PM_{2.5}$ concentrations (µg m–3) attributable to electricity generation, the emission inventories are used as inputs into the reduced-complexity air quality model, Global InMAP (Thakrar et al. 2022). Emissions are entered as elevated emissions assuming a uniform stack height of 200 m, stack diameter of 5 m, exit velocity of 23 m s-1, and temperature of 416.5 K (U.S. Environmental Protection Agency 2017; Sengupta et al. 2023). Applying area-weighting, Global InMAP weights emissions at the NUTS-2 level from the InMAP grid, for which it then calculates population-weighted annual average total $PM_{2.5}$ concentrations. The model requires baseline input data on meteorology and pollutants as well as variable grid resolution are based on population density, which are taken from Thakrar et al. (2022). Horizontal grid cell width ranges from 500 km in remote areas to 4 km in urban areas. Global InMAP considers emissions as perturbations to emissions from an underlying chemical transport model simulation used to parametrise physics, chemistry, and meteorology. It is therefore assumed that the modelled concentrations represent the absolute contribution of $PM_{2.5}$ from the electricity sector as has been done in existing literature (Sengupta et al. 2023). To estimate the annual average total $PM_{2.5}$ concentrations at the NUTS-2 level, concentrations at the InMAP grid level are averaged across NUTS-2 regions by applying area weighting. A more detailed description of the Global InMAP computational grid, the underlying chemical transport model simulation, and input data can be found elsewhere (Thakrar et al. 2022).

[1]Tier 1: A method using readily available statistical data on the intensity of processes (activity rates) and default emission factors. These emission factors assume a linear relation between the intensity of the process and the resulting emissions. To upgrade a Tier 1 to a Tier 2 method, the default emission factors should be replaced by country-specific or technology-specific emission factors.

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The assessment of mortality and morbidity impacts linked to air pollution relies on concentration–response functions, which define he correlations between een exposure ($PM_{2.5}$ concentrations) and health consequencese (Ru et al. 2023). Concentration-response functions are expressed as the percentage increase in the risk of mortality associated with an incremental increase in $PM_{2.5}$ concentrations of 10μgm^{-3}. Applying the methodology used by the European Topic Centre for Human Health and the Environment (Soares et al. 2022), all-cause natural mortality associated with long-term $PM_{2.5}$ exposure in ages above 30 years old is estimated for three alternative concentration-response functions (Table 2). . The primary concentration-response function used in this study is taken from the ELAPSE project (Brunekreef et al. 2021). To assess the sensitivity of mortality estimates to the concentration-response functions, alternative functions from the updated World Health Organisation (WHO) Global Air Quality Guidelines (World Health Organization 2021) and the WHO Health risks of air pollution in Europe (HRAPIE) project are considered (World Health Organization 2013). Mortality is quantified for two metrics, premature deaths, and years of life lost (YLL). While premature deaths refer to the number of deaths occurring earlier than the expected lifespan for a given population, YLL account for the age at which premature death occurs, thus assigning different weights to deaths at different ages (Kienzler et al. 2022; Soares et al. 2022; World Health Organization 2023a). The assumed population data, baseline mortality rates, cause of death, and life expectancy are derived from Eurostat datasets (Eurostat 2017, 2021a, b, c, 2022a).

Table 2. Concentration-response function: relative risk linking long-term exposure to $PM_{2.5}$ with all-cause natural mortality in ages above 30 years old

Source	Concentration-response functions as relative risk of mortality per 10μg m^{-3} exposure(95% confidence interval)
ELAPSE (Brunekreef et al. 2021)	1.118
World Health Organization (2021)	1.08
World Health Organization (2013)	1.062

Vulnerability index

For the purpose of this study, we create a new composite index to account for the differential susceptibility and vulnerability of populations to adverse health effects from air pollution. Susceptibility here refers to an increased health risk at any given level of exposure due to physiological factors, while vulnerability should be understood as a higher probability of being exposed, as well as a lack of capacity to avoid or cope with air pollution exposure and associated health effects (Samet 2014; Stilianakis 2015; European Environment Agency 2018). To account for both susceptibility and vulnerability across regions, the index consists of three components (Table 3):

(i) Age: Children are particularly susceptible to adverse impacts of air pollution due to factors such as higher breathing rates, increased oral breathing, developing organs, and weaker immune systems (World Health Organization 2018; Perera 2018; U.S. Environmental Protection Agency 2019). During pregnancy, exposure to air pollution increases the risk of adverse outcomes for babies and is linked to smaller size during pregnancy (Nyadanu et al. 2022), low birth weight (Johnson et al. 2021), and increased risk of pre-term birth (Ghosh et al. 2021). The elderly are also more susceptible to the negative health effects of air pollution due to a combination of age-related physiological changes (e.g., declining lung function), pre-existing health conditions (e.g., higher prevalence of cardiovascular and respiratory diseases), and decreased resilience as a result of accumulated damage from previous exposure (Simoni et al. 2015). Therefore, in this study, the indictors to account for increased susceptibility related to age are the share of children under the age of five, and the share of the population aged 65 or older in the total population, as well as the total fertility rate to account for unborn children.

(ii) Pre-existing health conditions: Those with pre-existing health conditions, such as low birth weight, asthma and heart disease, are also more susceptible to detrimental health impacts of air pollution (World Health Organization 2010; Belbasis et al. 2016; U.S. Environmental Protection Agency 2019; Manisalidis et al.

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2020). The proportion of new-borns with a low-birth weight is both an indicator of health problems during pregnancy as well as a predictor of new-born health and survival (World Health Organization 2020). Low birth weight is linked to an increased risk of future health problems (Belbasis et al. 2016), while air pollution has been identified as both a cause and an aggravating factor for asthma (Meng et al. 2011; Guarnieri and Balmes 2014). Even at low concentrations, $PM_{2.5}$ exposure has been associated with ischemic heart disease and stroke mortality (Hayes et al. 2020), with emerging evidence suggesting that long-term exposure to $PM_{2.5}$ reduces post-heart attack survival (Chen et al. 2016). Based on similar indicators used in existing literature (Huang and London 2012; August et al. 2021), the prevalence of low birth weight in newborns, as well as hospital discharges per 100,000 inhabitants by asthma and acute myocardial infarction (heart attack) diagnosis serve as proxies for susceptibility linked to the overall health status of a population across all ages in this study. Susceptibility due to health conditions is considered to be complementary to susceptibility related to age only. For example, all newborns are physiologically more susceptible to the adverse health effects of air pollution — accounted for by the fertility rate — but those born with a low birth weight are additionally more susceptible due to this condition —accounted for by the low birth weight prevalence.

(iii) Socioeconomic status: Socioeconomic status plays a role in determining the ability to cope with or avoid the impacts of air pollution (e.g., awareness of the health risks, access to health care, ability to relocate, or improve housing quality) and levels of exposure (e.g., location of dwelling, occupational exposure) (World Health Organization 2010; European Environment Agency 2018; U.S. Environmental Protection Agency 2020). Abundant research has investigated socioeconomic disparities in air pollution exposure, typically using income or poverty levels, education as well as employment metrics as proxies for socioeconomic status (Hajat et al. 2015). In line with existing literature (Huang and London 2012; European Environment Agency 2018; August et al. 2021), poverty and unemployment rates, as well as higher education deprivation are used as indicators for vulnerability related to socioeconomic factors in this study.

Table 3. Overview of the vulnerability concept, index components, and indicators

Component	Vulnerability concept	Indicator topic	Indicator definition	Unit	Source
Age	Increased susceptibility due to physiological factors related to age	Children	Share of children under age 5 in total population	%	Eurostat (2022b)
		Elderly	Share of population aged 65 or older in total population	%	Eurostat (2022b)
		Foetuses (pregnant women)	Total fertility rate	live birth $woman^{-1}$	Eurostat (2021d)
Health conditions	Underlying health conditions resulting in higher susceptibility	Low birth weight	Low birth weight prevalence	%	World Health Organization (2020)
		Asthma	Hospital discharges for asthma and status asthmaticus diagnosis	in-patients 100,000 $inhabitants^{-1}$	Eurostat (2020a)
		Cardiovascular diseases	Hospital discharges for acute myocardial infarction or subsequent myocardial infarction diagnosis	in-patients 100,000 $inhabitants^{-1}$	Eurostat (2020a)
Socioeconomic status	Vulnerability to health challenges due to socioeconomic factors and resources available to mitigate negative health impacts	Education	Higher education deprivation in age class 25-64 years (100% - share of population with tertiary education)	%	Eurostat (2021e)
		Poverty	Share of population at risk of poverty or social exclusion	%	Eurostat (2020b)
		Unemployment	Long-term unemployment (12 months or more) rate in economically active population	%	Eurostat (2022c)

For each of the three components in Table 3, the respective three indicators are normalised across all 296 NUTS-2 regions applying min-max normalization (Suarez-Alvarez et al. 2012):

$$x_{\mathrm{i,a_j},norm} = \frac{(\mathrm{x_{i,a_j}} - \min\left(\mathrm{x_{i,a_j}}\right))}{(\max\left(\mathrm{x_{i,a_j}}\right) - \min\left(\mathrm{x}_{i,a_j}\right))} \quad \text{(Eq. 1)}$$

Where a_j is one of the three components *age*, *health*, and *socioeconomic status* and x_i is one of the three indicators per component. For each indicator, regions with the highest (lowest) original value are thus assigned the normalised value 1 (0). In a second step, the three normalised indicators are summed up for each component applying equal weights of 1/3 to obtain average component indices (A_j):

$$A_j = \frac{1}{3}\sum_{i=1}^{3} x_{i,a_j,norm} \quad \text{(Eq. 2)}$$

Third, the resulting component indices A_j are again normalised across all regions using min-max normalisation:

$$A_{\mathrm{j,norm}} = \frac{(A_{\mathrm{j}} - \min(A_{\mathrm{j}}))}{\max(A_{\mathrm{j}}) - \min(A_{\mathrm{j}})} \quad \text{(Eq. 3)}$$

The final vulnerability index V is then calculated by summing up the three component indices with equal weights of 1/3 (Eq. 4), before again applying min-max normalisation to obtain index values for each region between 0 (lowest vulnerability) and 1 (highest vulnerability):

$$v = \frac{1}{3}\sum_{j=1}^{3} A_{j,norm} \quad \text{(Eq. 4)}$$

$$V = \frac{(v - \min(v))}{\max(v) - \min(v)} \quad \text{(Eq. 5)}$$

To assess the sensitivity of the index to the considered components, alternative vulnerability indices are calculated accounting only for health and socioeconomic status (V_{health_SES}), or the age and socioeconomic status components (V_{age_SES}). The calculation steps are the same as described above, with the exception of applying equal weights of 1/2 instead of 1/3 in and Eq. 4.

Regional inequality analysis

In this study, we focus on regional inequality in terms of air pollution and associated health effects in Europe, using the Lorenz curve, Gini coefficient, and comparison to the Europe-wide mean. Lorenz curves depicting the cumulative share of mortality burden as a function of the cumulative share of regions, as well as the Gini coefficient (Gini 1912) are used to graphically represent and quantify spatial inequalities in the distribution of mortality impacts. The Gini coefficient (η) ranges from 0 to 1, where the value of 0 indicates perfect equality, meaning that all regions have the same mortality burden, and a value of 1 indicates perfect inequality, meaning that one region bears the entire mortality burden. It is calculated by dividing the area between the Lorenz curve and the line of perfect equality, i.e., the diagonal line from the origin to (1,1), by the total area under the line of perfect equality. To quantify relative disparities in air quality co-benefits across regions with different levels of vulnerability, the percentage difference between population-weighted changes in $PM_{2.5}$ concentrations for five levels of vulnerability — using quantile classification with each level including an equal number of regions — is compared to Europe-wide mean reductions in concentrations. A similar approach has been used in a number of studies investigating historic (Liu et al. 2021; Qiu et al. 2022) and future racial or socioeconomic disparities in air pollution exposure (Wang et al. 2022, 2023; Goforth and Nock 2022; Polonik et al. 2023; Picciano et al. 2023), or the extent to which different subpopulations benefit from air quality improvements relative to the overall population average (Gallagher and Holloway 2022).

2.3 Results

Infrastructure capacities, air pollution and health co-benefits at the continent level

The range of infrastructure capacities to reach 70% GHG emissions reductions in 2035 from electricity generation are shown in Figure 2a with the use of fuel-combusting technologies exhibiting a significant variation across the 250 scenarios. While the total fossil fuel generation capacity (hard coal, lignite, natural gas, and oil) amounts to 292 gigawatts (GW) in the frozen generation and storage scenario, it needs to range from 0-158 GW to meet GHG emission targets. In the minimum system costs scenario, it stands at 133 GW, and it is almost eliminated in the minimum air pollutant emissions scenario (< 0.003 GW). On average, across 248 MGA scenarios, fossil fuel capacity amounts to 101 GW. In low-carbon scenarios, remaining fossil fuel capacities are dominated by natural gas (up to 140 GW), with maximum hard coal, lignite, and oil capacities reaching 33 GW, 34 GW, and 13 GW, respectively. Waste incineration capacities are consistent at around 7 GW for the frozen generation and storage scenario, minimum system costs, and minimum air pollutant emissions scenarios. In MGA scenarios, waste incineration capacities range from 7-11 GW. Biogas and woody biomass capacities are similar to the frozen generation and storage scenario (26 GW) in minimum system costs and minimum air pollutant emissions scenarios (23 GW) but vary more in low-carbon MGA scenarios (23-53 GW). In terms of other technologies that do not directly contribute to air pollution, nuclear capacities also show greater variation in MGA scenarios, ranging from 34-112 GW, while amounting to 115 GW in the frozen generation and storage scenario and 112 GW in the minimum system costs and minimum air pollutant emissions scenario. The total capacity of renewable technologies without operational air pollutant emissions (i.e., wind, solar, geothermal, hydro, battery, and hydrogen) shows the greatest variation between scenarios (frozen generation and storage scenario: 481 GW, minimum system costs: 833 GW, minimum air pollutant emissions: 1,245 GW, MGA scenario range: 690-1,566 GW).

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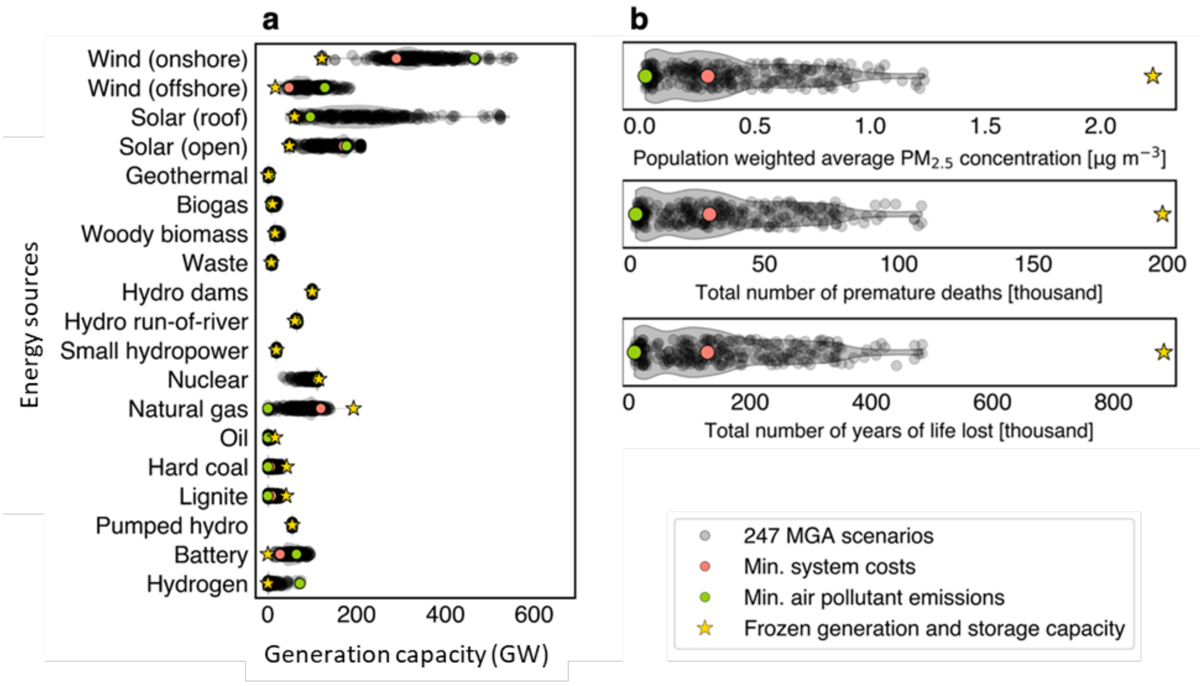

Figure 2. Analysed electricity sector scenarios in 2035, including the frozen generation and storage, minimum system costs, and minimum air pollutant emissions scenarios, as well as the remaining 247 MGA scenarios. (a) Ranges of electricity generation and storage capacities. (b) Ranges of impacts on $PM_{2.5}$ concentrations, premature deaths, and years of life lost in 2035.

Technologies emitting air pollutants represent a minority in the total installed capacity in all low-carbon scenarios. Comparing the frozen generation and storage scenario with the minimum system costs and minimum air pollutant emissions scenario, fossil fuel generation capacities contribute 31.7%, 12.0%, and 0% respectively, while capacities of waste represent 0.8%, 0.7%, and 0.6%. Biogas and woody biomass account for a maximum of 3.4% across all MGA scenarios, 2.8% in the frozen generation and storage scenario, 2.1% in the minimum system costs, and only 1.6% in the minimum air pollutant emissions scenario. While fossil fuel capacities and corresponding air pollutant emissions see a decrease in all low-carbon scenarios, emissions from waste, biogas, and woody biomass increase in the minimum system costs as well as several low-carbon MGA scenarios. The largest differences are observed for NOx emissions from waste, biogas, and woody biomass, as well as primary $PM_{2.5}$ emissions from woody biomass.

As a result, continent-wide population-weighted average $PM_{2.5}$ concentrations attributable to electricity generation and associated mortality impacts drop significantly as compared to the frozen generation and storage scenario, but then vary a lot across all scenarios (Figure 2b). Average concentrations in the frozen generation and storage scenario are estimated at 2.23μg m^{-3} and range from 0.02 to 1.23μg m^{-3} in the low-carbon scenarios, representing a decrease in concentrations by at least 45% and at most 99% compared to the frozen generation and storage scenario. In the minimum system costs scenario, average concentrations are 0.30μg m^{-3} (87% decrease), while the minimum air pollutant emissions scenario sees the second lowest concentration of all low-carbon scenarios at 0.02μg m^{-3} (99% decrease).

The substantial decrease in mortality impacts as compared to the frozen generation and storage scenario and the widespread outcomes depending on the low-carbon scenario resemble those of $PM_{2.5}$ concentrations. For the frozen generation and storage scenario, the total number of premature deaths and YLL is estimated at 198,000 and 883,000, respectively. In low-carbon scenarios, premature deaths and YLL range from 2,000 to 108,000 and 9,000 to 484,000 respectively (Figure 2b). Compared to the frozen generation and storage scenario, premature deaths and YLL drop by around 85% to 29,000 and 130,000 in the minimum system costs scenario and by 99%

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to 2,000 and 9,000 in the minimum air pollutant emissions scenario. Interestingly, the highest total mortality impacts in low-carbon scenarios are not observed in scenarios with the highest overall capacity from fuel-combusting technologies.

Regional impacts of air pollution and health co-benefits

The spatial distribution across NUTS-2 regions of $PM_{2.5}$ concentrations and associated mortality impacts varies significantly between scenarios too (Figure 3). Overall, not all regions with the highest $PM_{2.5}$ concentrations in each scenario also have the largest generation capacities from fuel-combusting technologies, reflecting the dispersion of pollutants beyond emitting regions. In the frozen generation and storage scenario, the highest $PM_{2.5}$ concentrations are found in selected regions in Germany, Czechia, Greece, Poland, and Bulgaria, mainly due to the ongoing presence of lignite, coal, and gas power plants. In the minimum system costs scenario, $PM_{2.5}$ concentrations are greatest in regions in Czechia, Poland, and the Balkans, due to lignite power plants located in Czech and Serbian regions, hard coal power plants in Poland, and gas power plants in the Balkans. With fossil fuel electricity generation eliminated, $PM_{2.5}$ concentrations approach zero for most European regions in the minimum air pollutant emissions scenario, except for parts of the UK, where large woody biomass generation capacities in the Yorkshire area result in concentrations of up to 0.26μg m^{-3}. On average, the distribution of $PM_{2.5}$ concentrations across all 248 MGA scenarios resembles that of the frozen generation and storage scenario, with the highest concentrations occurring in Germany, Czechia, and Poland, where regional generation capacities are dominated by natural gas, lignite, and hard coal.

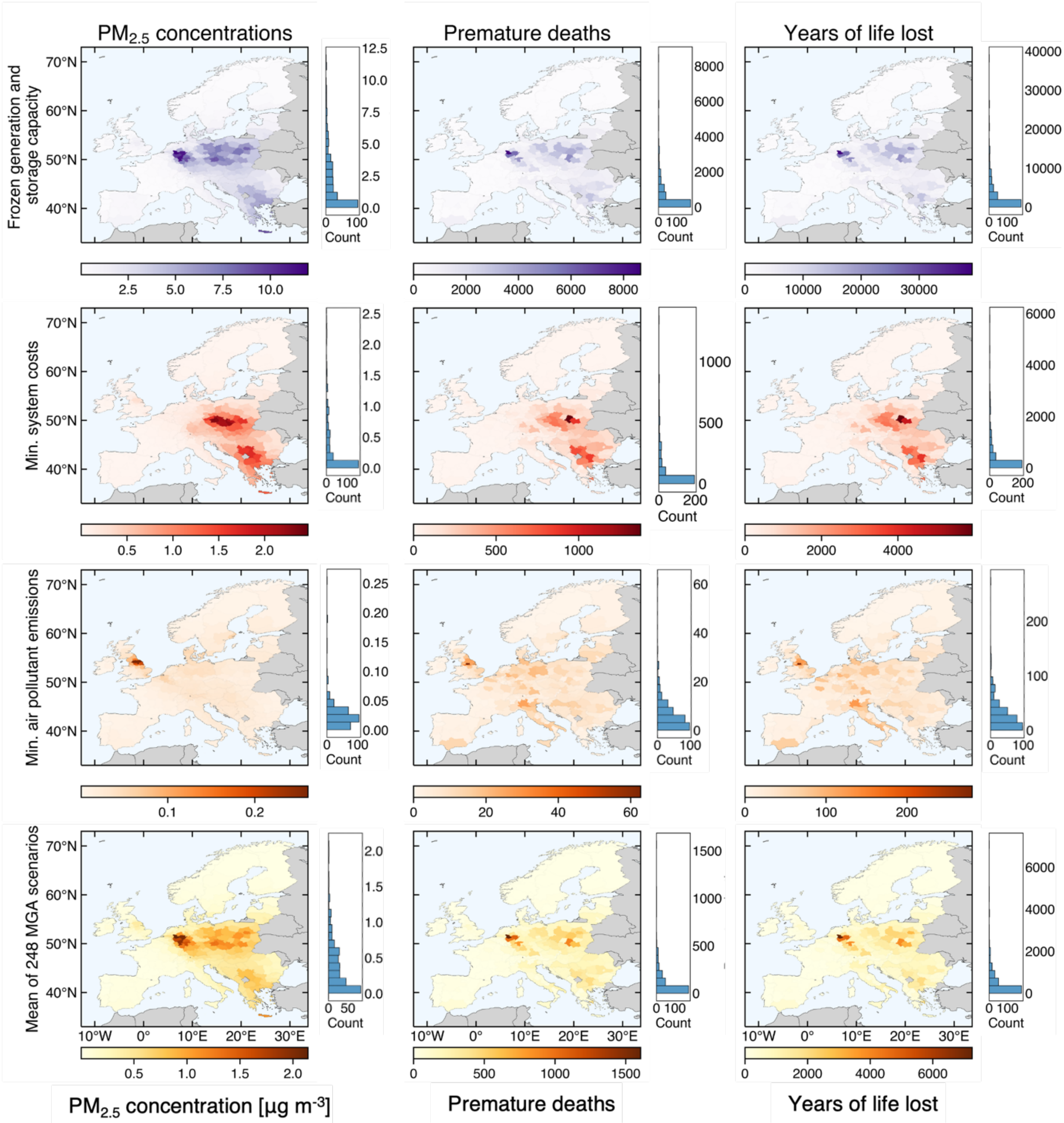

Figure 3. Maps of air pollution and mortality impacts in various electricity scenarios in 2035: the frozen generation and storage capacity scenario and scenarios reaching at least 70% GHG emission reductions – minimum system costs scenario, minimum air pollutant emissions scenario, and the mean of 248 MGA scenarios.

The spatial distribution of premature deaths and YLL reflects those of $PM_{2.5}$ concentrations, with differential population sizes by age and baseline mortality rates determining differences in mortality burden at equal levels of concentrations. In the frozen generation and storage scenario, mortality is highest in regions located in Germany, Poland, Greece, Bulgaria, Czechia, and Serbia, reaching up to 8,700 premature deaths and 39,100 YLL in 2035. In the minimum system costs scenario, the highest mortality burden is found in regions in Poland, Bulgaria, Serbia, Czechia, Greece, and North Macedonia, with a regional maximum of 1,400 premature deaths and 5,900 YLL. In the minimum air pollutant emissions scenario, the Yorkshire area and Greater Manchester in the UK see the highest mortality impacts, though at comparatively much lower absolute levels, with a regional maximum of only 62 premature deaths and 1,600 YLL. On average, mortality across the 248 MGA scenarios is distributed similarly to the frozen generation and storage scenario, but the maximum regional mortality (1,600

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premature deaths and 7,300 YLL) amounts to only around 18% of the maximum in the frozen generation and storage scenario.

The lowest reduction in mortality impacts in the minimum system costs scenario (≤ 75%) relative to the frozen generation and storage scenario are observed in North Macedonia, Serbia, Montenegro, Slovakia, Albania, Czechia, and Hungary (Figure 4). In the minimum air pollutant emissions scenario, all countries see a decrease in mortality of at least 95%, except for the UK (90%) and Belgium (94%). For most countries in Eastern Europe and the Balkans, the minimum system costs scenario leads to lower reductions in mortality relative to the frozen generation and storage scenario than the mean of MGA scenarios. Small differences in mortality reductions between the minimum system costs and minimum air pollutant emissions scenario are observed for Estonia, Spain, Finland, Luxembourg, and Portugal. On average, MGA scenarios reduce mortality by at least 75% in all countries, except for the UK (69%), Belgium (73%), and France (74%). Accounting for population size, relative mortality impacts per 100,000 inhabitants are distributed slightly differently across regions and countries than absolute impacts. At the national level, absolute mortality in the minimum system costs scenario is highest in Germany, Poland, and Czechia, however, in relative terms, mortality impacts are highest in Czechia, Serbia, and North Macedonia (premature deaths 100,000 inhabitants^{-1}), and Czechia, Serbia and Slovakia (YLL 100,000 inhabitants^{-1}). Similarly, the highest absolute mortality impacts for the MGA scenario average are observed for Germany, while in relative terms, the number of premature deaths (and YLL) per 100,000 inhabitants are highest in Bulgaria and Serbia (Czechia).

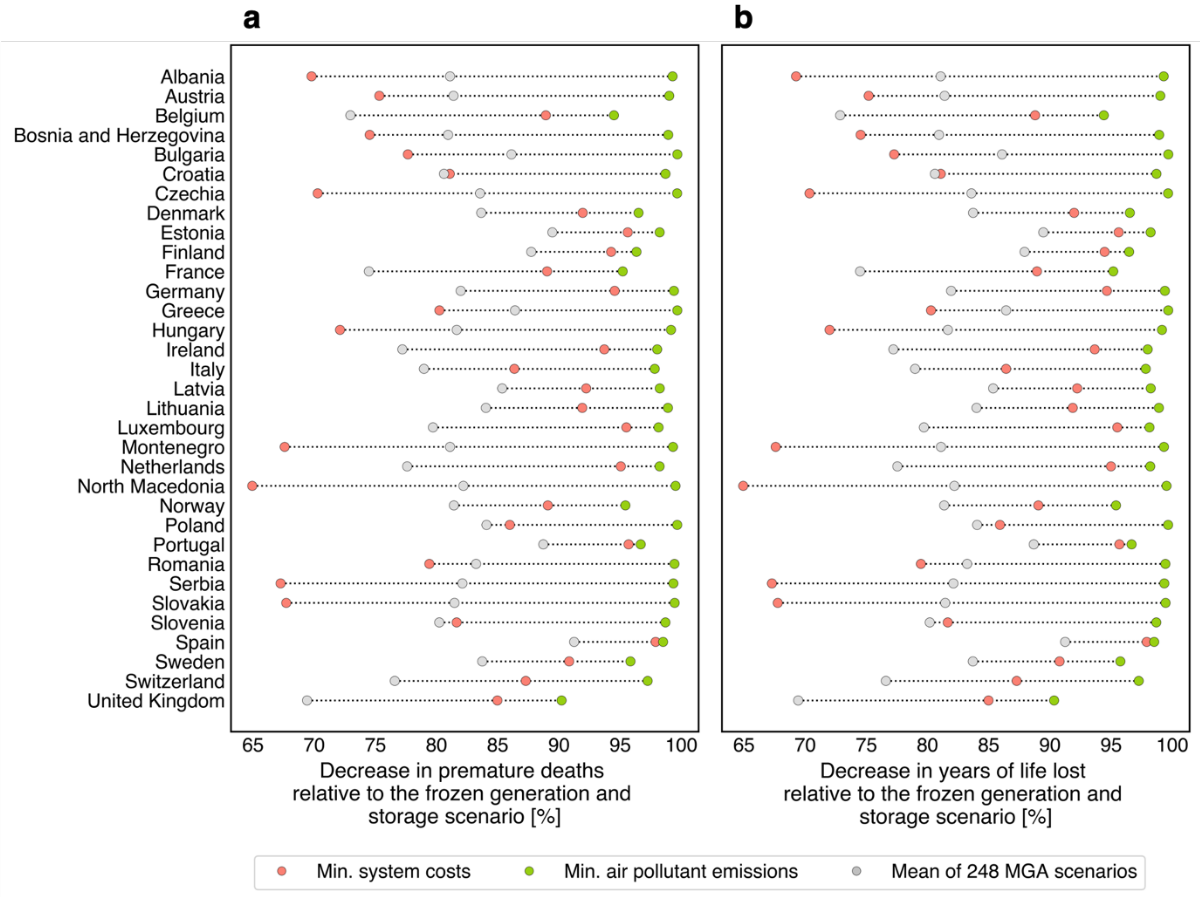

Figure 4. Percentage decrease in mortality in low-carbon scenarios relative to the frozen generation and storage capacity scenario by country for the minimum system costs scenario, minimum air pollutant emissions scenario, and the mean of 248 MGA scenarios.

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Inequalities in health impacts and relative disparities in air quality co-benefits

There are varying degrees of regional inequalities across NUTS-2 regions with respect to mortality impacts attributable to $PM_{2.5}$ concentrations associated with electricity generation in the different scenarios (Figure 5). The most equal (Gini index η=0.43) and unequal (η=0.77) spatial distributions of premature deaths are found among specific MGA scenarios. The minimum air pollutant emissions scenario shows almost the same level of inequality (η=0.46) as the most equal scenario, with around half of the highest mortality burden being shouldered by around 22% of the regions, compared to 11% and 9% in the frozen generation and storage and minimum system costs scenarios, respectively (Figure 5a). While the frozen generation and storage scenario leads to the overall highest mortality impact, the spatial distribution of mortality is more equitable (η=0.65) than in the minimum system costs scenario (η=0.71) and several MGA scenarios (Figure 5b). MGA scenarios with more equitable regional distributions than the frozen generation and storage scenario (η<0.65) show varying total mortality burdens ranging from more than 75,000 to less than 2,000 premature deaths (and more than 340,000 to less than 9,000 YLL). Inequalities in the spatial distribution of YLL are almost identical to those in the distribution of premature deaths (Figure 5c and Figure 5d).

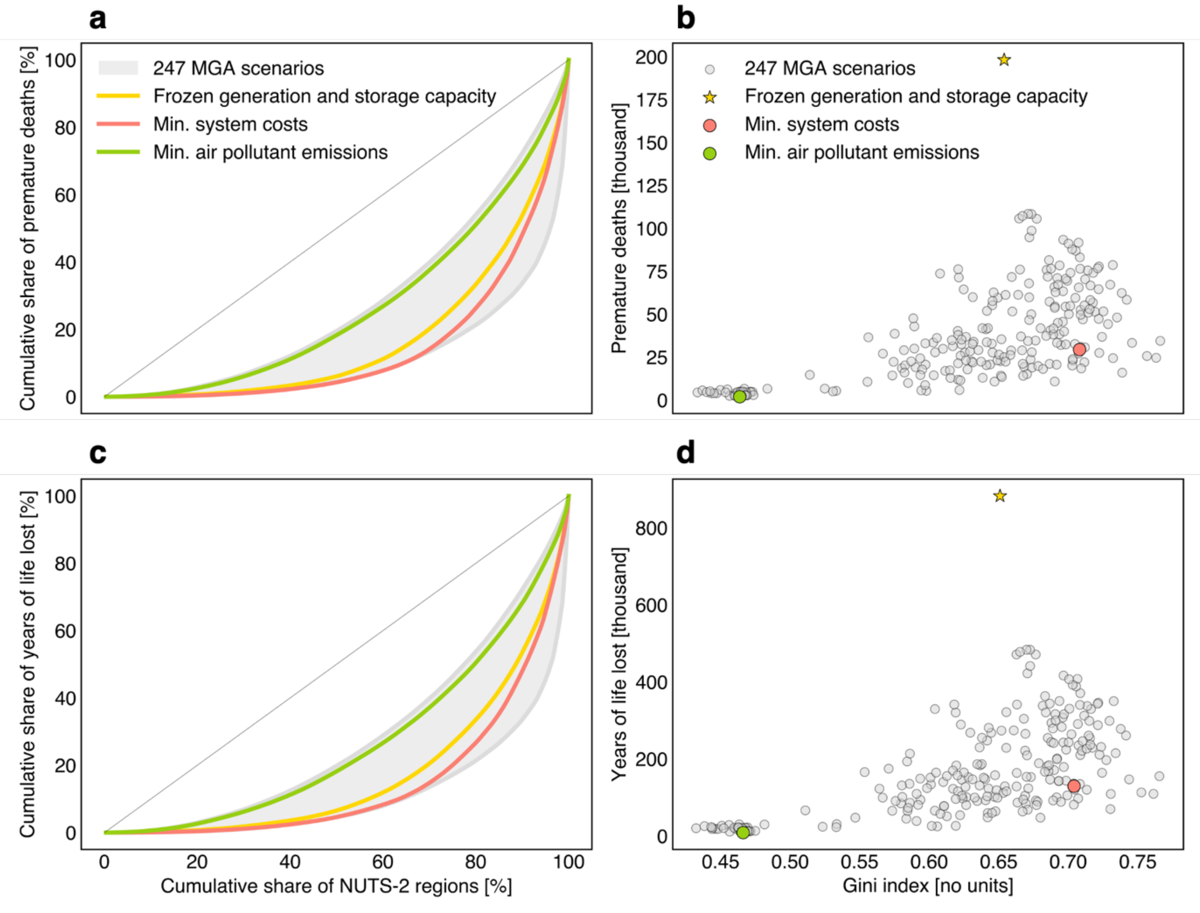

Figure 5. Inequality in the regional distribution of premature deaths and years of life lost. (a), (c) Lorenz curves of the regional distribution of premature deaths and years of life lost attributable to electricity generation across 296 NUTS-2 regions in 2035. (b), (d) Total number of premature deaths and years of life lost as a function of equality in their regional distribution across NUTS-2 regions quantified by the Gini index.

Accounting for age, health conditions, and socioeconomic status as contributing factors to the overall vulnerability of a region to adverse health effects of air pollution (Figure 6d), the highest vulnerability levels (Vulnerability Index V ≥ 0.45) are observed in the Balkan countries: Bosnia and Herzegovina (0.59), Montenegro (0.66), and North Macedonia (0.55), as well as selected regions in Bulgaria (0.47 –- 1), Romania (0.45 – -0.69), Greece (0.48 – -0.64), and Albania (0.61). Outside the Balkans, high levels of vulnerability are identified in several regions in France, Germany, Hungary, Italy, Slovakia, and the UK, with index values ranging from 0.45 to 0.7. Luxembourg (0.02), as well as selected regions in Finland (0.00 – -0.14), the UK (0.02 – -0.13), Poland (0.02 – -0.15), Austria (0.04 – -0.11), Spain (0.05 – -0.16), and Hungary (0.05), show the lowest levels of vulnerability (Figure 6d). Additionally, certain regions in Sweden, Switzerland, the Netherlands, Norway, Belgium, Lithuania, Slovenia, and Portugal are among the 20% least vulnerable regions (V ≤ 0.16). The different components, i.e., age, health, and socioeconomic status, contribute to varying extents to the overall vulnerability depicted in Figure 6d. For the most vulnerable regions in Romania, France, Germany, the UK, Hungary, and Slovakia, susceptibility due to age is the main factor contributing to vulnerability levels (Figure 6a). Susceptibility due to health conditions is primarily responsible for the high vulnerability levels in Bulgaria and north-eastern Germany (Figure 6b). In Bosnia and Herzegovina, Southern Italy, Albania, North Macedonia, and Montenegro, socioeconomic status is the main factor determining high vulnerability levels in selected regions (Figure 6c).

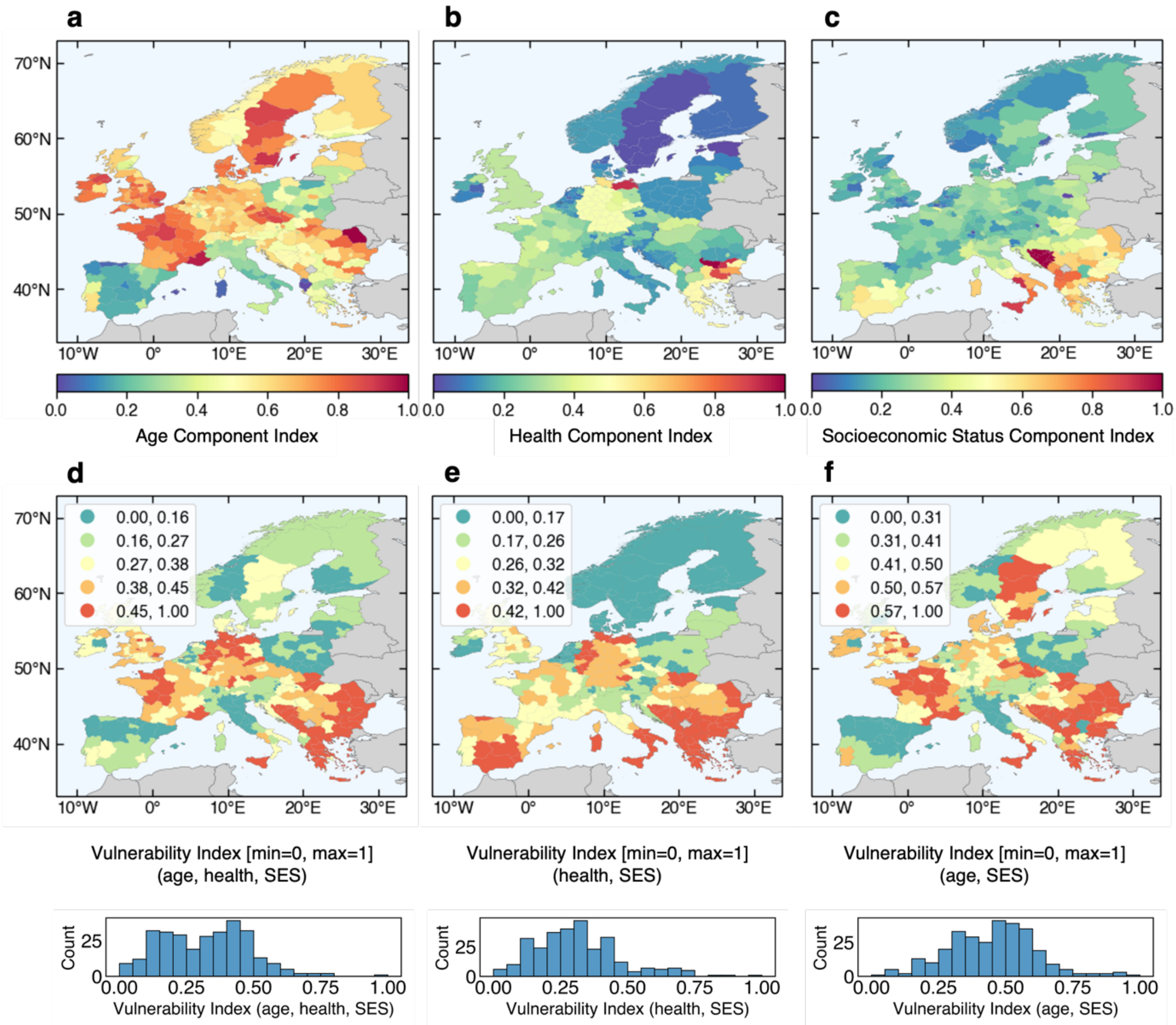

Figure 6. Maps of component indices and composite vulnerability indices: (a) age component index, (b) health component index, (c) socioeconomic status component index, and composite vulnerability indices accounting for (d) age, health, and socioeconomic status components, (e) health and socioeconomic status components, and (f) age and socioeconomic status components.

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Comparing relative disparities in air quality co-benefits between regions with differential levels of vulnerability and the overall continent-wide average allows to explore to what extent reductions in air pollution concentrations from different low-carbon system designs favour or accrue in regions most vulnerable to adverse health effects. For the analysed low-carbon scenarios, relative percentage reductions in population-weighted $PM_{2.5}$ concentrations are highest for the 20% most vulnerable regions (Figure 7a) when accounting for age, health, and socioeconomic status components (Figure 6d). Regions with high concentration levels in the frozen and generation and storage scenario, e.g., in Western and North-West Germany as well as the Balkans (Figure 7b) are among the most vulnerable, while also benefitting from comparatively higher reductions in $PM_{2.5}$ concentrations in low-carbon scenarios. Selected regions with high levels of vulnerability in France, Italy, and the UK (Figure 6d), see low concentration levels in the frozen generation and storage scenario, but only small reductions in pollution concentrations (Figure 7b). The minimum system costs scenario results in slightly larger co-benefits (49%) for the most vulnerable regions than the minimum air pollutant emissions scenario (45%) and the MGA scenario average (45%) (Figure 7a). Regions with lower levels of vulnerability (V < 0.38), e.g., in Finland, Sweden, Norway, Spain, Italy, and the Netherlands, see comparatively lower reductions in $PM_{2.5}$ concentrations than the continental average, as they are mostly characterised by low pollution concentrations in the frozen generation and storage scenario, and thus see only small reductions in $PM_{2.5}$ concentrations in low-carbon scenarios (Figure 7b).

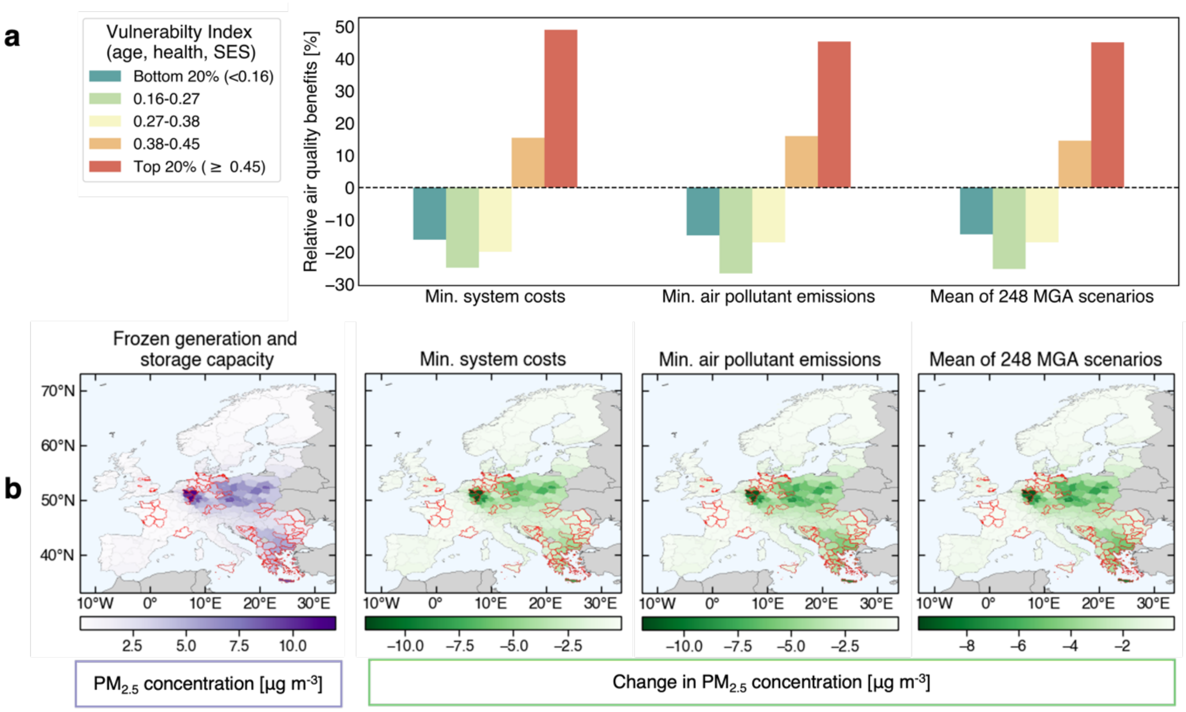

Figure 7. Relative air quality co-benefits by level of vulnerability accounting for age, health, and socioeconomic status: (a) Percentage difference between reductions in $PM_{2.5}$ concentrations for regions with different levels of vulnerability and European-wide average reductions for the minimum system costs and minimum air pollutant emissions scenario as well as the mean of 248 MGA scenarios. Positive (negative) values indicate that, on average, regions benefit from higher (lower) air quality improvements compared to the overall European average. (b) $PM_{2.5}$ concentrations in the frozen generation and storage scenario and changes in concentrations in the minimum system costs and minimum air pollutant emissions scenarios, as well as for the mean of 248 MGA scenarios. NUTS-2 regions delimited by a red border indicate the 20% most vulnerable regions.

2.4 Discussion

Previous studies have assessed excess mortality related to coal power plants in Europe (Kushta et al. 2021) and avoided mortality attributable to past renewable energy deployment in the EU (Couvidat et al. 2021). This study contributes to the assessment of air quality and related health co-benefits of low-carbon electricity generation in Europe by providing a first estimate of $PM_{2.5}$ associated mortality of a large number of spatially explicit electricity sector scenarios in 2035 considering a full mix of technologies. The results show that generation from fossil fuels and corresponding air pollutant emissions will be drastically reduced or can even be almost eliminated in low-carbon scenarios. Only emissions from waste incineration, biogas, and woody biomass see increases in several scenarios, including the minimum system costs scenario. $PM_{2.5}$ concentrations and related mortality burdens as well as their spatial distribution vary significantly throughout Europe between scenarios. The minimum system costs scenario leads to continent-wide excess deaths almost 15 times higher than in the minimum air pollutant emissions scenario, which would almost entirely eliminate $PM_{2.5}$-related mortality from fuel combustion in electricity generation. At the regional level, the minimum system costs scenario leads to the highest concentrations and mortality burdens in regions in Czechia, Poland, and the Balkans, mainly linked to the continued presence of fossil fuel power plants. In the minimum air pollutant emissions scenario, the highest impacts are found in regions in the UK with — or in proximity to — woody biomass generation capacities. For the MGA scenario average, impacts are associated with larger fossil fuel capacities concentrated in regions in Germany, Czechia, and Poland. Since no study investigating mortality impacts related to future European low-carbon electricity systems could be identified, evaluating the consistency of these new results is restricted to a relative comparison with roughly projected mortality levels attributable to air pollution from all sectors. If the number of $PM_{2.5}$-related premature deaths in the EU-27 followed a linear trend, it would amount to around 88,000 in 2035 (European Environment Agency 2022b). For the EU only (except Cyprus and Malta), this study estimates the number of premature deaths attributable to the electricity sector at 22,000 (rounded to the nearest thousand) on average across all low-carbon scenarios, equivalent to a quarter of the total mortality burden in 2035 if the number of premature deaths were to decrease at a similar rate as in the past. Given that energy supply in the EU, including electricity generation, overall accounts for a minority in total precursor emissions of $PM_{2.5}$ (European Environment Agency 2023), it is plausible that $PM_{2.5}$-associated mortality attributable to the electricity sector would only account for a minority in total mortality.

Several studies have assessed inequalities in the distribution of air quality and/or associated health co-benefits of future renewable energy deployment or decarbonisation scenarios in the US (Gallagher and Holloway 2022; Wang et al. 2022, 2023; Goforth and Nock 2022; Polonik et al. 2023), California (Zhao et al. 2019; Zhu et al. 2022), Texas (Luo et al. 2022), India (Sengupta et al. 2023), and the UK (Williams et al. 2018). Previous analyses for Europe quantified direct PM_{10} emissions from future electricity systems as well as regional inequalities but did not consider emissions of other air pollutants or their dispersion, resulting $PM_{2.5}$ concentrations, or associated health impacts (Sasse and Trutnevyte 2020, 2023a). By providing an evaluation of regional disparities in $PM_{2.5}$-associated mortality attributable to low-carbon electricity supply as well as of relative disparities in air quality co-benefits by level of vulnerability of exposed populations, this study contributes to the investigation of the justice implications of the low-carbon electricity supply transition in Europe. The results show that low-carbon electricity systems in Europe can reduce inequalities in the regional distribution of air pollution-related health impacts while also leading to comparatively higher air quality co-benefits in the most vulnerable regions. The degree of regional inequality in the distribution of mortality impacts varies between scenarios, with the minimum air pollutant emissions scenario ranking among the MGA scenarios with the lowest spatial inequality while at the same time resulting in the lowest total mortality burden across all scenarios. However, the minimum system cost scenario and several of the MGA scenarios lead to an increase in inequality compared to the frozen generation and storage scenario, though at much lower total mortality levels. Accounting for differential susceptibility and vulnerability to adverse health effects of air pollution, regions with the highest levels of vulnerability see larger relative air quality co-benefits from low-carbon electricity sector scenarios when compared to the overall European average, while less vulnerable regions benefit to a lesser extent.

To assess the robustness of the results, a sensitivity analysis has been conducted for the choice of the concentration-response functions as well as the vulnerability index composition. Mortality estimates vary significantly depending on the chosen concentration-response functions. For the two alternative functions considered (World Health Organization 2013, 2021) (Table 2), the respective total number of premature deaths (and YLL) is estimated at 138,000 and 108,000 (614,000 and 482,000) for the frozen generation and storage scenario, 20,000 and 16,000 (90,000 and 70,000) for the minimum system costs scenario, and 1,000 (6,000 and 5,000) for the minimum air pollutant emissions scenarios. When accounting for the 95% confidence interval of concentration-response functions, estimates range from a minimum of 12,000 premature deaths and 55,000 YLL on average across all MGA scenarios for the lower limit of the WHO HRAPIE project concentration-response function (1.040) (World Health Organization 2013) to a maximum of 51,000 and 229,000 for the upper limit of the ELAPSE concentration-response function (1.179) (Brunekreef et al. 2021). Vulnerability levels as well as relative air quality co-benefits are sensitive to the composition of the vulnerability index too. For example, selected regions in Spain rank among the most vulnerable for the index considering health and socioeconomic status (V_{health_SES}) (Figure 6e), while high vulnerability levels in Sweden and Finland are observed for the index accounting for age and socioeconomic status (V_{age_SES}) (Figure 6f). For the index V_{age_SES}, regions with the highest levels of vulnerability benefit from comparatively lower reductions in $PM_{2.5}$ concentrations than the continent-wide average. This can be explained by the comparatively high values for V_{age_SES} for certain regions in Sweden, Finland, and France, which have low concentrations in the frozen generation and storage scenario thus seeing limited reductions in low-carbon scenarios. For the index (V_{health_SES}) (Figure 6e), regions with the lowest levels of vulnerability benefit more than the overall average, although to a lesser extent than the most vulnerable regions, while regions with intermediate levels of vulnerability see even smaller co-benefits than for the other index compositions.

The study is subject to several caveats and limitations that could be addressed in future research. First, emission inventories are a major source of uncertainty. As air pollutants are co-emitted with GHG emissions, total air pollutant emissions in low-carbon scenarios in 2035 are expected to be lower than today's levels, despite an increase in electricity generation. This is the case for estimated NOx and NMVOC emissions when compared to EMEP gridded emissions data for the sector "Public electricity and heat generation" for 2020 (EMEP Centre on Emission Inventories and Projections 2020). However, primary $PM_{2.5}$ emission estimates in all low-carbon scenarios are higher than 2020 levels reported by EMEP, while SOx emissions estimates are higher in more than half of the low-carbon scenarios. This could be partly explained by the fact that EMEP data only includes emissions from combustion plants with a heat output greater than 50 megawatts thermal (European Environment Agency 2019), thus not considering smaller woody biomass (high $PM_{2.5}$ emission factor), lignite, hard coal, or oil generators (high SOx emission factors). Moreover, EMEP data is primarily based on reported emissions, making underreporting another possible explanation. For this study, emission inventories were created using universal emission factors and stack parameters running the air quality model with elevated areal emissions. Future research could develop inventories with country-specific emission factors, technology-specific stack parameters, and spatial proxies for plant locations to assess the robustness of modelled $PM_{2.5}$ concentrations and the resulting mortality impacts of these changes. Second, Global InMAP models annual-average $PM_{2.5}$ concentrations. Deploying a comprehensive chemical transport model would yield more precise concentration estimates at a higher temporal and spatial resolution, including for other critical air pollutants such as nitrogen dioxide (NO2) and ground-level ozone (O3). Third, this study focused on the mortality burden associated with long-term $PM_{2.5}$ exposure. Future analyses could assess the mortality and morbidity burden attributable to both long-term and short-term exposure to $PM_{2.5}$ as well as to NO2 and O3, to provide a more comprehensive estimate of health impacts. Fourth, only air pollutant emissions from fuel combustion were considered, excluding life-cycle emissions occurring at other stages of the fuel cycle (e.g., extraction, storage, or transport), which have been found to contribute considerably to the overall health impacts of energy sources such as coal, oil, and gas (Gasparotto and Da Boit Martinello 2021; Buonocore et al. 2023). Lastly, a main limitation of the study is the exclusive focus on the electricity sector, not accounting for expected emission changes in other sectors or the effects of climate change on air quality (Park et al. 2020; Hong et al. 2020). The study could thus be extended to account for emissions in all sectors to investigate how decarbonisation across the entire energy economy would impact air pollution and related health outcomes, as well as inequalities in their distribution.

2.5 Conclusions

While decarbonising electricity supply in Europe in line with the European Green Deal's target of carbon neutrality by 2050 will overall improve air quality and public health in 2035, our results suggest that depending on the make-up of the electricity system, total air quality and mortality co-benefits can vary significantly, as does their spatial distribution across European regions. System designs almost or entirely eliminating fossil fuels result in the lowest total air pollutant emissions, associated $PM_{2.5}$ concentrations, and mortality impacts, as well as the lowest regional inequalities in the distribution of health impacts. If cost-effectiveness is the primary policy goal, health impacts would be up to 15 times higher than in several near-cost optimal scenarios. Compared to the current system, inequality in the spatial distribution of morality would be exacerbated too, with the lowest reductions in mortality being observed for countries in Eastern Europe and the Balkans. In all low-carbon scenarios, though to a varying extent, the distribution of air quality co-benefits favours regions with the highest levels of vulnerability to adverse health effects of air pollution.

The decarbonisation of electricity supply is essential to reaching the EU's carbon neutrality target, and it also contributes to the reduction of $PM_{2.5}$-related mortality as envisaged in the EU's Zero Pollution Action Plan. Low-carbon electricity system designs with GHG emission reductions exceeding 70% by 2035 compared to 2019 levels — becoming necessary by 2050 at the latest to reach carbon neutrality — have the potential to drastically reduce and even almost eliminate the $PM_{2.5}$-related mortality burden attributable to air pollution from electricity generation. They could also allow for a more spatially equitable distribution of health impacts than in a system determined by cost-effectiveness alone. Differences in the socio-demographic situation as well as susceptibility and vulnerability to adverse health effects of air pollution across societies will likely continue to exist for a long time. Hence, understanding how the air quality and health impacts of future low-carbon energy systems are distributed across regions and societies is fundamental to ensuring a just transition as it can help establish where targeted policy interventions might become necessary to avoid the transition exacerbating existing inequalities and to pre-empt public resistance.

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3 Energy security, resilience, flexibility, costs, and environmental indicators in renewable energy systems

3.1 Introduction

Energy systems are changing as a result of the transition to renewable energy (RE) and the increased deployment and integration of fluctuating renewable energy sources. However, global supply chain challenges and the energy crisis in recent years have underlined the need for not only carbon emission reductions and cost optimisation in energy systems but also the need for flexibility, resilience, and security. This adds new dimensions to energy system modelling and in particular to the evaluation of energy system scenarios as an integral part of energy strategies and energy policy development.

This study explored methods and tools for modelling energy systems and comparing multiple energy system futures in the form of energy scenarios. General indicators and parameters are established for evaluating flexibility and resilience, energy security, costs and prices, and environmental effects in renewable energy system scenarios. Four concrete energy system scenarios for Greece and one for the EU are employed as case studies to exemplify the application of the established indicators and compare tangible energy system futures in both a national and European context.

For Greece, energy system modelling is conducted with the OSeMOSYS-GR tool, a case-specific implementation of the open-source energy system model generator OSeMOSYS, employing linear optimisation to determine least cost pathways. The power system of Greece is modelled, and four scenarios explore the impact of pursuing early carbon neutrality in 2042 with and without carbon capture and storage, and carbon neutrality in 2050 with forced shut down of natural gas power plants in 2040 and 2045 respectively. These scenarios are further explored in Section 4 with a deep dive into Greece's national energy and climate plan.

For the EU, an aggregated energy system is modelled with the EnergyPLAN tool, a deterministic hourly simulation model for modelling of complete energy systems i.e., heating and cooling (including district energy solutions), electricity and gas grids, transportation, and infrastructure. Three scenarios for the EU are analysed and compared; a Baseline scenario for 2050 and a 1.5 TECH scenario based on PRIMES modelling for the European Commission, in addition to a Smart Energy Europe Scenario.

For energy security and resilience, diversity of energy demands and electricity generation are explored alongside upstream supply chain commodity linkages. Flexibility is explored through an evaluation of peak electricity demands and residual electricity demands relative to the dispatchable and variable generation capacity, and the availability of energy storage technologies. With the MARIO modelling framework, an input-output analysis of backward linkages of electricity produced by different energy sources. This serves as a proxy of how the power sector in the EU is dependent on foreign industrial activities. The integrated assessment model WILLIAM is applied to estimate costs and price projections for raw materials depending on energy system scenarios, in addition to material demand projections in different energy systems.The transition to renewable energy systems necessitates a diversification of the energy system, both from an energy security and flexibility perspective. Renewable energy systems should be designed considering a balance between dispatchable and variable electricity generation and the available potential for flexible demands and energy storage. It is pertinent that future discussions of energy system scenarios for the EU include discussions of acceptable levels of import reliance and the EU's energy system development accordingly to fulfil both energy resource demands and technology manufacturing demands domestically. As evident from the Smart Energy Europe scenario evaluated as part of the study it is feasible to construct 100% renewable energy system scenarios without energy imports if this is a political priority.

3.2 Methods and tools

This section introduces the tools applied for the modelling of energy system scenarios and for the modelling of economic and environmental effects, including data exchange and model linkages.

EnergyPLAN

EnergyPLAN is a tool for simulation of the entire energy system including all sectors, i.e., heating, cooling, industry, transportation, as well as electricity and gas grids (H. Lund et al., 2021). Hourly temporal resolution allows for detailed modelling of variable renewable energy generation in addition to weekly and seasonal differences in electricity and heat demands. EnergyPLAN is a deterministic model based on analytical programming, making calculations very fast even for complex energy systems. EnergyPLAN optimises the operation of the energy system for a single year rather than the investments, which is instead done exogenously by the user.

In Figure 8 an overview of technologies, energy demands, and flows as represented in EnergyPLAN can be seen.

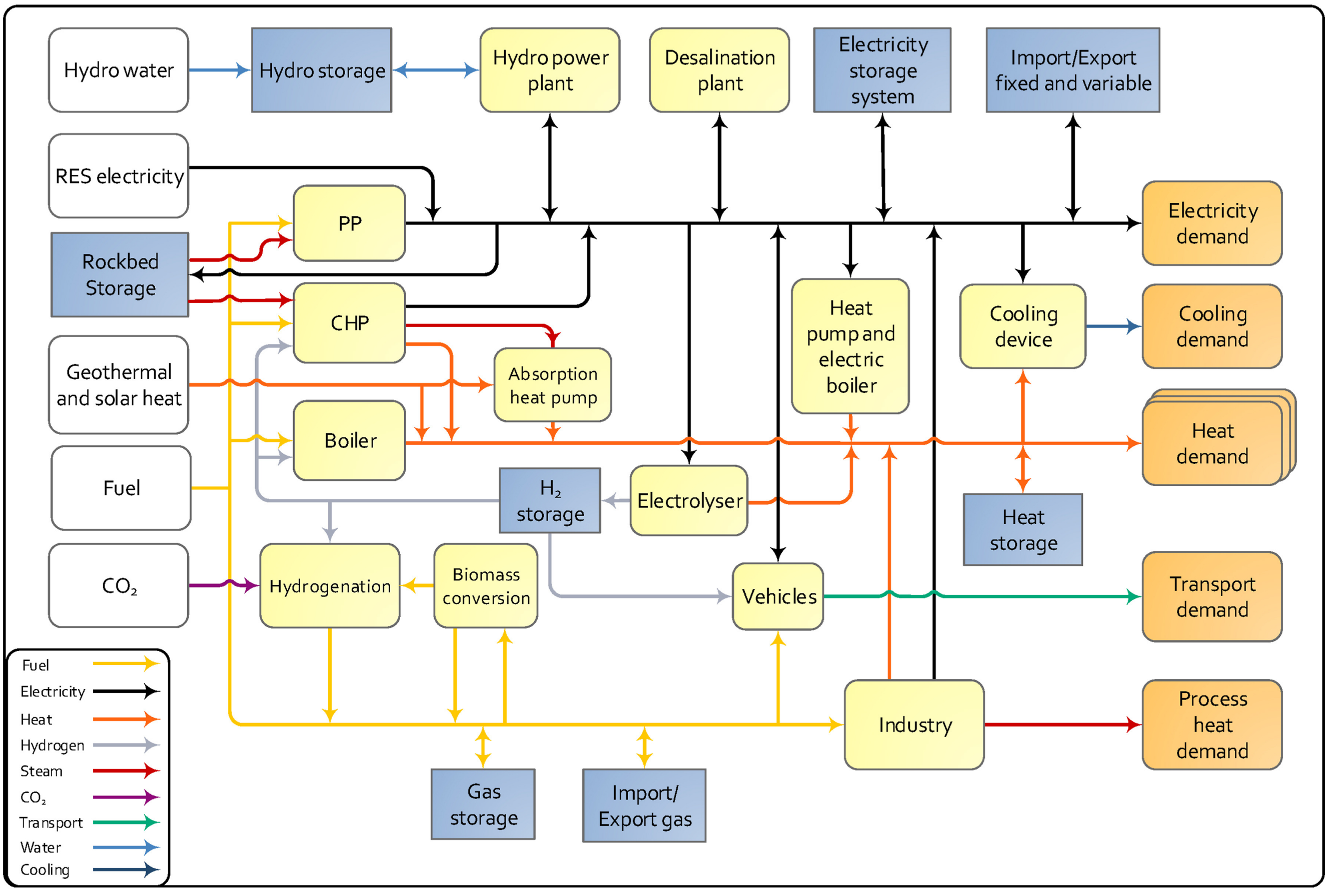

Figure 8. Overall technology and flow model for EnergyPLAN.

A number of data inputs are needed to simulate an energy system in EnergyPLAN:

- Energy demands (heat, electricity, transport, industry, etc.).
- Energy generation technologies and resources (wind turbines, power plants, gas boilers etc.) and energy conversion technologies (electrolysers, gasification plants etc.).
- System characteristics (simulation and operation strategies, technical limitations such as transmission capacity).
- Cost (fuel costs, fixed and variable operation and maintenance costs).

The resulting outputs are annual and hourly energy balances with annual productions, and total costs including fuel consumptions, import and export of electricity (Lund et al., 2021).

EnergyPLAN has been widely applied for energy systems modelling, with most studies focusing on the development of scenarios with shares of renewable energy integration (Østergaard, 2015). Studies typically employ several indicators for system evaluation, such as primary energy supply, CO_2 emissions, system costs, and excess electricity generation (Østergaard, 2015).

OSeMOSYS-GR

The Open Source energy MOdelling SYStem (OSeMOSYS) is an open-source energy system linear optimisation model generator that follows a dynamic, deterministic, technology-rich, bottom-up, linear-programming approach for medium-to-long-term energy planning (Howells et al., 2011). OSeMOSYS is utilised to determine the most economically efficient pathway by minimising the discounted cost of the system. This is achieved by optimising the capacity and electricity generation of each technology to meet the predefined final energy demand. The optimisation considers various technological factors such as costs and lifetimes, as well as system constraints like emission limits and renewable energy targets.

In this study, we use OSEMOSYS-GR, a specific implementation of OSeMOSYS that has been developed and adjusted in the context of the IAM COMPACT project to accurately model the unique characteristics of the Greek power system from 2021 to 2050. In OSEMOSYS-GR, the electricity supply system is represented by importing and extraction technologies, fossil-fired power plants using lignite, natural gas, oil, renewable energy power plants (i.e., hydro, wind onshore and offshore, solar photovoltaics (PV), biomass, geothermal), electricity storage (i.e., battery and pumped hydro), hydrogen production and consumption (namely electrolysers and fuel cells), transmission, and distribution systems, as well as interconnections with neighbouring countries.

MARIO

MARIO is a versatile modelling framework for easy input-output analyses and model handling. It is programmed in Python and comes with a set of useful features which are of paramount relevance to performing scenario and economic-environmental impact assessment and footprinting analyses adopting input-output tables (Tahavori, Golinucci, Rinaldi, Rocco, & Colombo, 2023). Based on the classical Leontief model approach, MARIO can be used for macroeconomic and environmental policy analyses both as a stand-alone tool and to complement other modelling tools' results as in the case of this study.

In fact, MARIO, based on the Exiobase v3.8.2 input-output database (Stadler et al., 2021), was used in synergy with EnergyPLAN. Results from EnergyPLAN scenarios, in terms of new addition of PV and wind (both off-shore and on-shore) capacities and new electricity demands have been implemented as "shock" analyses into the input-output table. The economic shock simulated in the table triggers new production levels by all the supply chains underlying the production of electricity and technology capacities, resulting in new economic and environmental impacts which are then refined and fine-tuned into the WILIAM model. Moreover, MARIO is used to calculate the so-called backward linkages of the technologies, thanks to the application of the Ghosh model (Ghosh, 1958), a traditional approach in input-output economics allowing to analyze the inter-linkages among global supply chains. Such linkages provide an indication of how each commodity (i.e., electricity produced by different energy sources) relies on upstream supply chains and whether these latter are based within or outside the EU borders.how each commodity (i.e., electricity produced by different energy sources) relies on upstream supply chains and whether these latter are based within or outside the EU borders. each commodity (i.e., electricity produced by different energy sources) relies on upstream supply chains and whether these latter are based within or outside the EU borders. each commodity (i.e., electricity produced by different energy sources) relies on upstream supply chains and whether these latter are based within or outside the EU borders. each commodity (i.e., electricity produced by different energy sources) relies on upstream supply chains and whether these latter are based within or outside the EU borders.

WILIAM

The WILIAM model (Within Limits Integrated Assessment Model) is a novel Integrated Assessment Model (IAM) rooted in system dynamics, specifically designed based on MEDEAS model to overcome limitations in the IAM field. System dynamics enables the capture of intricate feedback loops and non-linear relationships among social, economic, and environmental variables. Comprising 8 modules—demographics, society, economics, finance, energy, materials, land and water, and climate—WILIAM takes a granular approach, with disaggregation into 62 sectors. Covering 9 regions and 35 countries, including the EU27, the model incorporates Input-Output Analysis (IOA) for its sectoral breakdown and production sub-module. Its production and international trade sub-modules are based on IOA, which guarantees that all the upstream and downstream supply chain effects are fully captured. Armington-elasticities are also applied to the international trade sub-module, resulting in different import shares from one region to others. This allows assessing these spill-over effects across countries and regions.

3.3 Indicators for evaluating renewable energy systems

This section introduces a review of indicators for evaluating renewable energy systems and outlines indicators assessed for this study. Indicators are established based on a combination of existing scientific literature and feedback from stakeholders and policy makers as part of a workshop on optimal energy transition modelling (see deliverable D2.4 – Proceedings of Stakeholder Interactions).

Energy security and resilience

Energy security is defined as the ability of the system to manage long-term disruptions, e.g., due to geopolitical, climatic, supply chain constraints, or other system disruptions. Energy security relates to the long-term stability of the energy system, as opposed to the short-term balancing and stability of the system which instead is referred to as resilience. In Table 4 an overview of existing literature on energy security and resilience indicators can be seen.

Table 4. Energy security and resilience indicators and characterisation identified in existing literature.

Reference	System boundaries	Indicators/characterisation	Notes
Hughes (2012)	Energy system	Security - Availability - Affordability - Acceptability	Develops generic energy security indicators applicable to any energy system.
Ranjan and Hughes (2014)	Energy system	Security - Availability - Affordability - Acceptability - Diversity	Presents a relationship between energy security and diversity, arguing that a diverse energy flow is not necessarily secure, and vice-versa, a secure energy flow is not necessarily diverse. Suggests energy systems are evaluated based on a set of energy security indicators and the Shannon diversity index.
Gracceva and Zeniewski (2014)	Energy system	Security - Stability - Flexibility - Adequacy - Resilience - Robustness	Argues that energy security has not been addressed in the context of climate change based on simplified indicators. A suggested framework is presented for evaluating energy security in low-carbon scenarios and impacts from a low-carbon transition are presented.
Månsson et al. (2014)	Energy systems	Security - Supply of primary energy - Upstream markets and imports - Domestic markets and	Classifies a broad range of methods for assessing energy security in energy systems

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		infrastructure - Economic vulnerability - Integrated methods	
Azzuni and Breyer (2018)	Energy system	Security - Availability - Diversity - Cost - Technology and efficiency - Location - Timeframe - Resilience (adaptive capacity) - Environment - Health, Culture, Literacy - Employment - Policy - Military, Cyber security	Determine 15 dimensions of energy security in energy systems as a basis for developing a generic definition. Define energy security as the *"feature (measure, situation, or a status) in which a related system functions optimally and sustainably in all its dimensions, freely from any threats."*
Martišauskas et al. (2018)	Energy system (electricity, heating)	Security - Unserved energy - Energy cost increase from disruption	Introduces a step-by-step methodology for energy security assessments in energy systems and proposes a quantitative energy security metric.
Galinis et al. (2020)	Energy systems	Security - Fuel/generation diversity - Transmission capacity - Dispatchable generation capacity - Generation costs	Finds that it is difficult to select specific energy security measures due to the broad range of threat the energy system is facing. Higher CO_2 prices resulting in earlier decommissioning of fossil fuel-based power plants and rapid deploy of variable renewable energy (VRE) capacity could cause disruption in the short- to medium-term.
Khan et al. (2023)	Power systems	Security - Diversity - Import reliance - Generation costs - Supply uncertainties	Evaluates the relationship between energy security and RE in the context of geopolitical risk. Finds that RE positively impacts energy security and vice-versa, supporting a faster transition to RE also from an energy security perspective.
Molyneaux et al. (2016)	Energy systems	Resilience - Diversity in fuel types - Spare capacity in energy production - Efficiency in energy supply	Argues resilience in energy systems to be system's capacity to *"cope with the unexpected"* which should be measured as the systems adaptive capacity.
Lin and Bie (2016)	Energy systems (electricity, heating, cooling, gas)	Resilience - Demand side management - Accurate weather forecasting - Microgrid operation - Black start capabilities	Defines resilience as *"the ability of a system to anticipate, resist, absorb, respond to, adapt to, and recover from a disturbance."*
Jasiūnas et al. (2021)	Power systems	Resilience - Redundancy - Functional diversity - Adequate adaptability	Argues that assessing system resilience and establishing indicators is difficult due to conflicting definitions. Further

		- Firebreaks	complicated by being a system characteristic, and hence a result of system structure, relationships, and interactions more than individual components.
Ahmadi et al. (2021)	Power systems	Resilience - Energy performance - Time of repair - Cost of recovery and cost incurred due to disruption - Damaged performance	Established four main characters of energy system resilience: *anticipation*, *absorption*, *adaptation*, and *recovery.*
Gasser et al. (2021)	Energy systems (emphasis on power grids and gas grids)	Resilience - Reliability - Vulnerability - Robustness	Finds that the resist/restabilize functions in a resilience curve are more developed in energy systems than rebuild and reconfigure functions. Further argues that there is a need to operationalise resilience assessment in energy systems.

The literature review uncovers several tendencies in research on energy security and resilience. Studies on energy security generally consider energy systems in a broader sense (i.e., multiple energy sectors) whereas studies on resilience predominantly revolve around the power system. This is likely a natural effect caused by the power system being the most vulnerable to short-term disturbances, but some principles such as redundance, reliability, and robustness could be applied and considered in other sectors as well. For energy security, diversity is a consistent theme in existing research and could be considered both from an energy consumption perspective (i.e., diversity of "fuel") and from an energy generation perspective (i.e., diversity of available generation technologies). Other important security aspects relate to the affordability of energy and resources, and the reliance on upstream supply chains and foreign supply relative to domestic production.

The question of energy system security and resilience indicators was discussed at the Optimal Energy Transition Modelling workshop of IAM COMPACT (D2.4 – Proceedings of Stakeholder Interactions). Stakeholders and workshop participants considered it timely and relevant to discuss these aspects of renewable energy systems given the recent geopolitical events of COVID-19 and Russia's invasion of Ukraine, causing supply chain disruptions and the energy crisis. Discussions at the workshop revolved around various forms of supply diversification considerations including gas supply diversity, raw material supply, oil depletion and biophysical limits. A second key issue was import dependency, considering supply chain diversity, geopolitical conflict constraints, and non-energy (material) resources. Manufacturing of clean technologies within the EU is another aspect to consider (e.g., for battery technologies) and domestic manufacturing in general. For resilience, discussions revolved around energy system design and how to design systems capable of managing short-term fluctuations and recovering from outages. This could be done through testing of system shock responses. Other aspects such as the resilience of energy infrastructures to climate-related weather hazards, electricity demand projections, and potential price cannibalisation from variable renewable energy generation were discussed as potential future challenges to the resilience of energy systems.

Based on the outcomes from the literature review and workshop, this study specifically will investigate the diversity of energy systems both from a consumption and generation perspective, and the backward linkage reliance of commodities and upstream supply chains, split between domestic and foreign supply chains.

Flexibility

Flexibility is assessed to evaluate the short-term operation of the energy system, i.e., the balance of supply and demand at all points in time. Flexibility has traditionally referred to the ability of an electricity system and grid's ability to cope with fluctuations, traditionally realised through power plants with short response times. However, with the increasing prevalence of sector coupling and variable renewable electricity generation, we extend this analysis to evaluate the flexibility of the energy system in a broader scope, considering e.g., effects of sector coupling or distributed generation. While the flexibility of energy systems can be evaluated at various temporal scales, this study will focus on flexibility at the hourly level, as opposed to short-term assessments of electricity grid frequency and voltage control. In Table 5 an overview of existing literature on energy security and resilience indicators can be seen.

Table 5. Energy system flexibility indicators and characterisation identified in existing research.

Reference	System boundaries	Indicators/characterisation	Notes
Huber et al. (2014)	Power systems	Flexibility - Share and mix of VRE - Balancing area size - Power plant flexibility - Storage capacity - Demand side response	Identifies share of PV and wind power as a determining factor for system flexibility requirements.
Lund et al. (2015)	Power systems	Flexibility - Demand side management - Energy storage capacity - Transmission capacity - Power plant capacity and response - Curtailment	Argues that flexibility metrics may be unambiguous to different flexibility definitions as different aspects of energy systems need to be addressed.
Lund et al. (2017)	Energy systems, all energy sub-sectors	Flexibility - Dispatchable generation - Storage capacity (heating, cooling, synthetic fuels, electricity) - Flexible demands	Introduces the Smart Energy Systems concept as an approach for integrating smart thermal, electricity, and gas grids to derive system flexibility and integration of VRE.
Deason (2018)	Energy systems	Flexibility - Variable generation capacity - Dispatchable generation - Storage capacity - Flexible demand	Concludes that a wide range of strategies and measures can be used to provide flexibility in 100% renewable energy systems.
Impram et al. (2020)	Power systems	Flexibility - Power capacity - Up/down ramping - Loss of wind estimation - Curtailment - RE imbalance	Divides flexibility into four categories. Flexibility for *power*, *energy*, *transfer capacity*, and *voltage*.
Degefa et al. (2021)	Power systems	Flexibility - Power capacity - Ramping capacity - Storage capacity - Service recovery duration - Location, costs - Predictability, credibility - Controllability	Argues for three necessary criteria for flexibility definitions. *Type* of flexibility resource, *duration* of flexibility resource, and *incentive* for activation.
Pfeifer et al. (2021)	Energy systems, all energy sub-sectors	Flexibility - Dammed hydro capacity - VRE capacity - Transport electrification - Smart and vehicle to grid charging in transport - Power to heat and thermal storage	Derives a flexibility index for energy systems based on a range of system characteristics.

		capacity - District heating share - Power plant flexibility	

The literature review of flexibility indicators in energy systems shows a clear emphasis on power systems in existing research. Consistent aspects include the share of dispatchable generation capacity relative to variable generation capacity, storage capacities, and flexible demands. Other common indicators relate to technical performance metrics for power plants such as up/down ramping abilities and response times. Curtailment of electricity is sometimes considered an indication of a system's ability to integrate renewable electricity and imbalances. Flexibility is rarely considered much from an integrated system perspective, but relevant flexibility potentials are found in other sectors such as transport and utilisation of electric vehicles for battery storage, or heating through powe-to-heat technologies and thermal storage.

The external stakeholders and workshop participants agreed on a need for further assessing both the demand for flexibility (how much flexibility is actually needed), and secondly, what is the potential for flexibility (how much can be provided within the energy system). Both these questions are naturally impacted by technologies and market structures, and hence the discussion also circulated on what technologies and flexibility measures are most relevant to include in analyses. In general, evaluating the availability of dispatchable energy generation capacity relative to variable generation capacity was considered a key aspect. Other relevant energy system aspects discussed included various forms of energy storage (electricity, pumped hydro, methane, hydrogen, thermal) and their role in energy systems, interconnection capacities and grid infrastructure, and the role and relevance of smart grids. Economic incentives and market structures for realising flexibility potentials were also discussed, including price signals (locational/zonal pricing) or price signals for vehicle-to-grid charging.

Based on the outcome of the review and workshop, this study will focus on dispatchable and variable generation capacity relative to demand flexibility and the availability of storage solutions in energy systems as indicators of system flexibility.

Costs and prices

Costs are a common and almost standardised evaluation parameter or indicator in energy system analysis, in stark contrast to energy security, resilience, and flexibility. However, evaluating impacts on prices (e.g., consumer electricity prices, fuel prices, or raw materials) is less established. In Table 6 an overview of existing literature on energy security and resilience indicators can be seen.

Table 6. Costs and price indicators and characterisation identified in existing literature.

Reference	System boundaries	Indicators/characterisation	Notes
Murphy and Hall (2010)	Energy systems	- Energy return on investment	Conducts a review of methods for energy return on investment calculations, i.e., an indication of the amount of energy required to extract or produce energy.
Pfenninger et al. (2014)	Energy systems	- Cost-benefit analysis - Cost-effectiveness	Observes that energy system models are typically used to design systems minimizing total energy system costs. Further dimensions such as human behaviour, indirect costs, socio-political and non-financial barriers are typically lacking.
Santoyo-Castelazo and Azapagic (2014)	Energy systems	- Capital costs - Total annualised costs - Levelised costs	Develops a framework for analysing sustainability in energy systems based on environmental, economic, and social indicators.

Deason (2018)	Energy systems	- Total energy system cost - Electricity price	Compares flexibility strategies and technologies across 100% renewable energy scenarios for multiple regions. Large variance in included technologies and measures, and variations in cost calculation methods.
Hansen (2019)	Energy systems	- Levelised-cost-of-energy (per unit generation cost) - Energy system analysis cost (total system cost) - Primary energy - CO_2 emissions	Evaluates and compares levelized-cost-of-energy and energy system analysis methods cost calculation. Finds that future energy priorities change according to cost methods. Temporal correlation, system synergies, energy losses, and flexibility are only recognised in the energy system analysis method.
Ram et al. (2020; 2022)	Energy systems	- Job creation (employment factors)	Assesses employment effects from a global energy transition, finding an overall positive impact on future stability and growth of economies around the world.
Simón-Martín et al (2022).	Energy systems	- Levelised cost of energy, heating, cooling, and storage	Introduces and defines levelised cost of energy indicators and argue for their relevance in feasibility studies for renewable energy projects.

From the review of the literature, it is seen that most research is conducted in an energy systems context with main indicators being total energy system costs. Levelised cost of energy or electricity approaches are commonly applied for feasibility studies or techno-economic assessments of specific projects, but less commonly in a system perspective. Other indicators such as employment effects and electricity price effects are sometimes but not widely applied.

For this study, within the domain of costs and prices, our primary emphasis centres on materials costs. We thoroughly investigate the impact of materials expenditures on overall costs and pricing structures in both scenarios. This detailed exploration allows for a side-by-side comparison of how materials costs influence economic dynamics, providing valuable insights into the financial implications of each scenario. Prices for several critical materials will be analysed for the abovementioned scenarios. The interlinks between these prices and the scenario features are assessed, as costs of materials are likely to affect economy-wide prices.

Environmental effects

Energy system modelling and renewable energy system scenarios often emphasise energy-related aspects and indicators in the evaluation of scenarios, overlooking environmental and sustainability concerns. In this study, we expand on the traditional evaluation of energy systems by also considering effects outside of traditional energy indicators. In Table 7 an overview of existing literature on environmental indicators can be seen.

Table 7. Environmental effects indicators and characterisation identified in existing research.

Reference	System boundaries	Indicators/characterisation	Notes
Liu (2014)	Energy systems	- Resource quality, economic quality, environment quality, technological quality and social quality	Develops a framework for evaluating and quantifying sustainability in renewable energy systems.

		- Economic, institution, ecology, sociology and technology - Performance, market, environment and social indicators - Resource, environment, social and economic - Ecosystem and human system	
Santoyo-Castelazo and Azapagic (2014)	Energy systems	- Global warming - Abiotic depletion - Acidification - Eutrophication - Freshwater aquatic ecotoxicity - Human toxicity - Marine aquatic ecotoxicity - Ozone depletion - Photochemical ozone creation - Summer smog - Terrestrial ecotoxicity	Develops a framework for analysing sustainability in energy systems based on environmental, economic, and social indicators.
Kourkoumpas et al. (2018)	Energy systems (focus on PV and battery storage)	- Life cycle CO_2 emissions - Global warming potential - Avoided CO_2 emissions - Reduction of direct CO_2 emissions - Energy and carbon payback times - RE share	Proposes environmental and energy key performance indicators based on life cycle assessment and cradle-to-grave principles for transitioning energy systems.
Dorning et al. (2019)	Energy systems	- Air quality - Land use and quality - Waste - Resources - Water quality, quantity, toxicity	Reviews environmental indicators as represented in energy system studies.
Pata (2021)	Energy systems	- Ecological footprint - CO_2 emissions - Renewable energy generation - Globalisation - Agricultural value added	Analyses the integration and causality of key energy and environmental indicators, underlining the importance of transitioning to renewable energy to combat environmental degradation.
Rinaldi et al. (2023)	Energy systems	- Raw material demands	Presents a framework for assessing material demands in energy transition scenarios.

The literature review uncovered a broad range of environmental indicators applied in previous studies, ranging from material demands and resource usage to air and water quality, and various forms of CO_2 emission metrics.

In this study, environmental indicators assessment revolves around materials demand. We scrutinise the heightened demand for minerals, metals, and other resources, evaluating the environmental implications of increased materials consumption. This consistent approach ensures a parallel analysis of how each scenario affects materials demand, contributing to a holistic understanding of the environmental sustainability of their respective approaches.

3.4 Case description and scenario overview

This section introduces the investigated case studies of the EU and Greece, and the concrete scenarios included for the following evaluation and comparison. Case studies represent both an international and national scale, demonstrating the application of indicator-based scenario comparison for multiple planning scales.

3.4.1 Case description and scenarios for the EU

The EU has put forward a long-term target to be climate-neutral by 2050 (European Commission, 2020) as part of the European Green Deal (European Commission, 2023) and in alignment with the global climate action of the Paris Agreement. In response to the Russian invasion of Ukraine, the EU has launched the REPowerEU plan (European Commission, 2022), with the aim of increasing the deployment of renewable energy, saving energy, and diversifying the energy supply. All targets call for a concretisation of potential pathways for a transition of the energy system of the EU and secondly, exploring how to evaluate these pathways. The decarbonisation of the EU's energy system entails an array of significant changes, including improvements in energy efficiency and energy savings, large-scale expansion of variable renewable energy (VRE) capacity, and a complete conversion of transportation and industry.

In this study, we develop and evaluate three different scenarios for the future energy system of the EU. Scenarios are modelled in EnergyPLAN as an an aggregated energy system, i.e., without any geographical distinction. The aggregated approach to system modelling allows for significant modelling of sector integration measures and energy technologies at an hourly temporal resolution, but also means that network, transmission, and interconnection restrictions cannot be represented. The scenarios evaluated were first presented in Thellufsen et al. (2023) for a comparison of the role of sector integration in the PRIMES "A Clean Planet for All" scenarios (European Commission, 2018) compared to a scenario developed based on Smart Energy System Principles. The transition scenarios studies are:

- **"Baseline 2050":** The Baseline 2050 was developed to reflect the EU decarbonisation trajectory towards 2050 based on agreed policies and policies proposed by the Commission. The Baseline 2050 reflects macro-economic projections, fuel price projections, and technology assumptions.
- **"1.5 TECH 2050":** The 1.5 TECH scenario was developed as a climate-neutral scenario and as a pathway to stay within the 1.5°C ambition of the Paris agreement. This requires significant electrification and deployment of e-fuels and hydrogen, carbon capture and storage solutions largely for bioenergy, alongside strong penetration of VRE for a decarbonised power sector.
- **"Smart Energy Europe 2050":** The Smart Energy Europe scenario is developed as a 100% renewable energy system alternative based on the same technology catalogue as the PRIMES scenarios but designed according to Smart Energy System principles. Specifically, 1) energy efficiency first, 2) updated heating systems and expansion of district heating, 3) electrification of transport, 4) e-fuels for heavy parts of transport, and 5) replacing remaining fossil fuel demands in industry and power generation with biogas and biomass. Being a 100% renewable energy scenario the Smart Energy Europe 2050 scenario ialso complied with 1.5°C ambitions.

The ensuing analysis will elaborate on how the scenarios differ with regard to demands and capacities and the implications of these differences.

Case description and scenarios for Greece

Greece is a country with ambitious short- and long-term climate and policy objectives, moving away from its ongoing regime, which is defined by a limited capacity for interconnections and heavy reliance on imported fuels for electricity production (Kleanthis et al., 2022). One of its goals is to decarbonise the power sector by expanding the capacity of VRE and phasing out the highly polluting lignite power plants by 2028, while natural gas will be used as the transitional fuel during this process. The 2022 Russian invasion of Ukraine and the resulting energy crisis may temporarily hinder the lignite phase-out plan of Greece. However, in due course, the country will rely solely on progressively rising volumes of variable renewable energy (VRE) to meet its electricity requirements (Michas & Flamos, 2023). This will lead to a future power sector dominated by wind onshore, wind offshore, and solar PV technologies. According to the preliminary draft National Energy and Climate Plan, the target is to have a cumulative VRE capacity of 69 GW by 2050 (Hellenic Ministry of Environment and Energy, 2023a). This represents a growth of 1,190% compared to the installed capacity of 5.8 GW in 2020.

We explore least-cost energy mixes that lead to a fully decarbonised power sector but vary in terms of the year when: **(i).** carbon neutrality is achieved, and **(ii).** natural gas is phased out. We define a total of four different transition scenarios that achieve carbon neutrality either by 2042, according to a recent national energy planning document (Hellenic Ministry of Environment and Energy, 2023b), or by 2050, as indicated by older national long-term forecasts (Hellenic Ministry of Environment and Energy, 2019). The transition scenarios studied are summarised below and presented in detail in the following study "Deep dive into Greece's National Energy and Climate Plan":

- **"Early Neutrality 100% RE":** Carbon neutrality by 2042 focusing on variable renewable energy and energy storage. This scenario corresponds to the "Early Neutrality 1" scenario in Section 4.2.3.1.
- **"Early Neutrality CCS":** Carbon neutrality by 2042 with the use of Carbon Capture and Storage (CCS) for natural gas plants and biomass power plants. This scenario corresponds to the "Early Neutrality 2" scenario in Section 4.2.3.1.
- **"2050 Neutrality-2040 Gas":** Carbon neutrality by 2050 and forced shutdown of gas-fired plants by 2040. This scenariocorresponds to the "2050 Neutrality 1" scenario in Section 4.2.3.1.
- **"2050 Neutrality-2045 Gas":** Carbon neutrality by 2050 and forced shutdown of gas-fired plants by 2045. This scenario corresponds to the "2050 Neutrality 2" scenario in Section 4.2.3.1.

3.5 Evaluation of energy systems

This section constitutes the analysis and evaluation of energy system indicators for Greece and Europe, emphasising the characteristics of the power system. It is naturally not possible to make direct comparisons in absolute terms across national scenarios such as the included scenarios for Greece and scenarios for the entirety of the EU, hence these are predominantly considered separately. Including both a national and European case study does however demonstrate the relevance of such evaluation of energy system scenarios on both a national and European scale.

Energy security and resilience

It was previously established that the diversity of an energy system is an essential parameter for energy security. In the context of energy systems, diversity can both be considered from an energy consumption and energy generation perspective, i.e., the diversity of the fuel composition and the diversity of generation technologies. To compare and quantify diversity we apply the Shannon diversity index (Shannon, 1948), originally developed for information theory, but widely popular in ecological literature, and lately, also for quantifying diversity of energy systems (Ranjan & Hughes, 2014; Sun & Ren, 2021). It is a measure of the diversity of species in a community, or in this context, the diversity of the demand and supply of an energy system. In the Shannon index, the diversity of an energy system would increase as the number of flows or entities increases, and as the size of the flows or entities converge. It is calculated as seen in Equation 1, where pi is the proportion of the flow (or entity) made up of species I.

$$\mathbf{H = -\Sigma pi * ln(pi)} \quad \textit{(Eq. 6)}$$

A system with a single flow would have a Shannon index value of zero, the lowest possible value. As the number of flows increases, the theoretical maximum Shannon index value increases. The theoretical maximum value is obtained when flows are equally distributed, e.g., 10 flows each responsible for 10% of the total generation. The theoretical maximum Shannon diversity index for an increasing number of units/flows can be seen in Figure 9.

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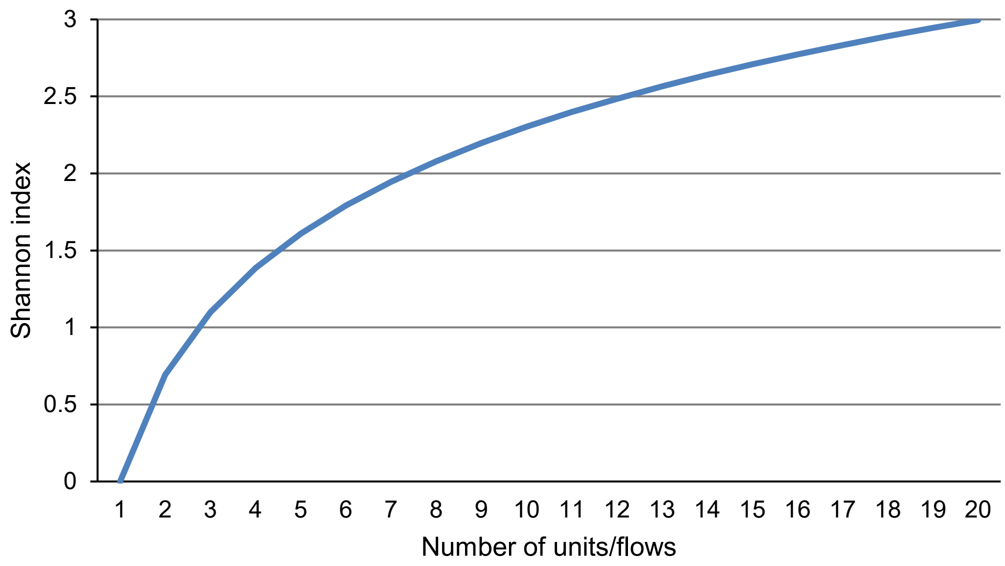

Figure 9. Theoretical maximum Shannon diversity index values.

The primary energy consumption and resulting Shannon diversity index values for the three EU scenarios can be seen in Figure 10. It is seen that the absolute primary energy consumption is highest for the Baseline scenario, followed by the 1.5 TECH scenario, and lowest in the Smart Energy Europe scenario as a result of the Energy Efficiency First Principle embedded in the scenario design. The Smart Energy Europe scenario is based on 100% RE, whereas the 1.5 TECH scenario manages a 90% CO_2 emission reduction, and substantial fossil fuel consumption remains in the Baseline scenario. To achieve this, the 1.5 TECH scenario introduces additional nuclear, offshore, and onshore wind power, as well as PV. The Smart Energy Europe Scenario omits nuclear energy, and to a larger extent prioritises onshore wind power and energy efficiency improvements.

The diversity of the primary energy consumption is highest for the Baseline Scenario caused by the variety of fuel types consumed, followed by the 1.5 TECH scenario, and lowest for the Smart Energy Europe scenario. A side-effect of the complete phase-out of oil, coal, and natural gas in the Smart Energy Europe scenario and the heavy inclination towards onshore wind power is the resulting lower diversity on the consumption side. As was seen in Figure 9, the Shannon diversity index is highly impacted by the number of flows included, i.e., the presence of additional fuel sources even if these constitute a small proportion of the total consumption increases diversity significantly.

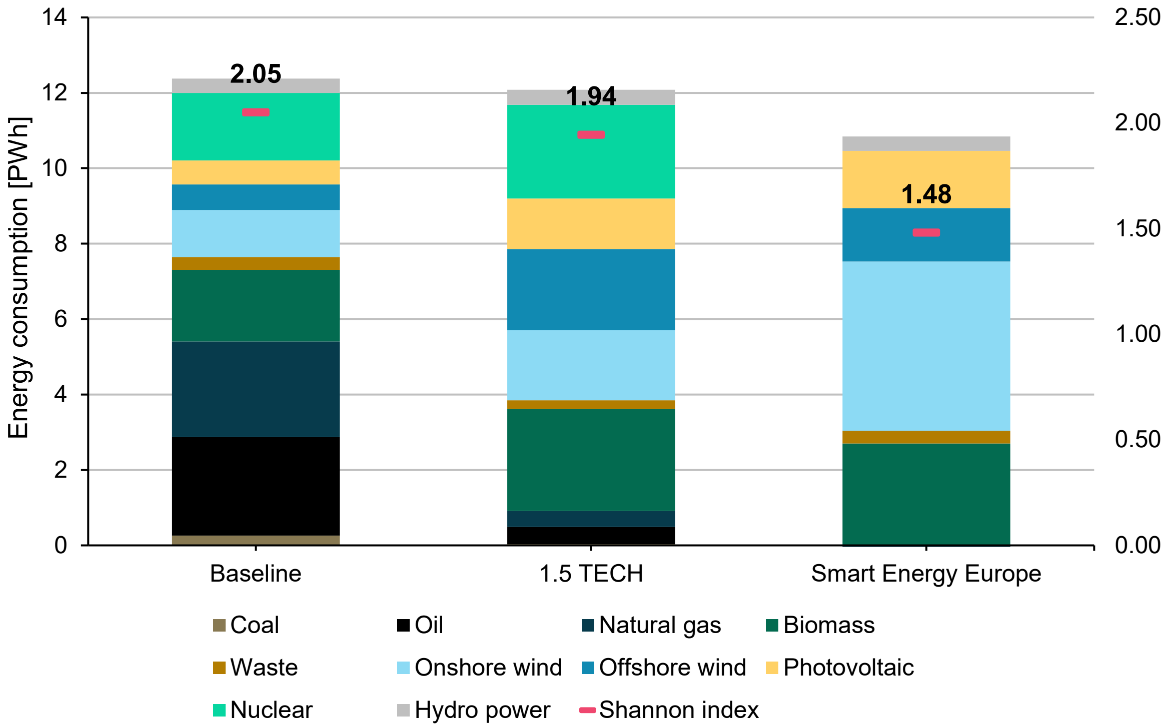

Figure 10. Primary energy consumption in EU scenarios.

The electricity and heat generation capacities and resulting Shannon diversity index values for the EU scenarios can be seen in Figure 11. The combined electricity generation capacity in the Smart Energy Europe scenarios is higher due to a larger VRE capacity, primarily in the form of onshore wind power. Like the results for primary energy demand, the Shannon diversity index value is highest for the Baseline scenarios, followed by 1.5 TECH, and lastly Smart Energy Europe. This is caused by the exclusion of nuclear power and the relatively large installed onshore wind power capacity.

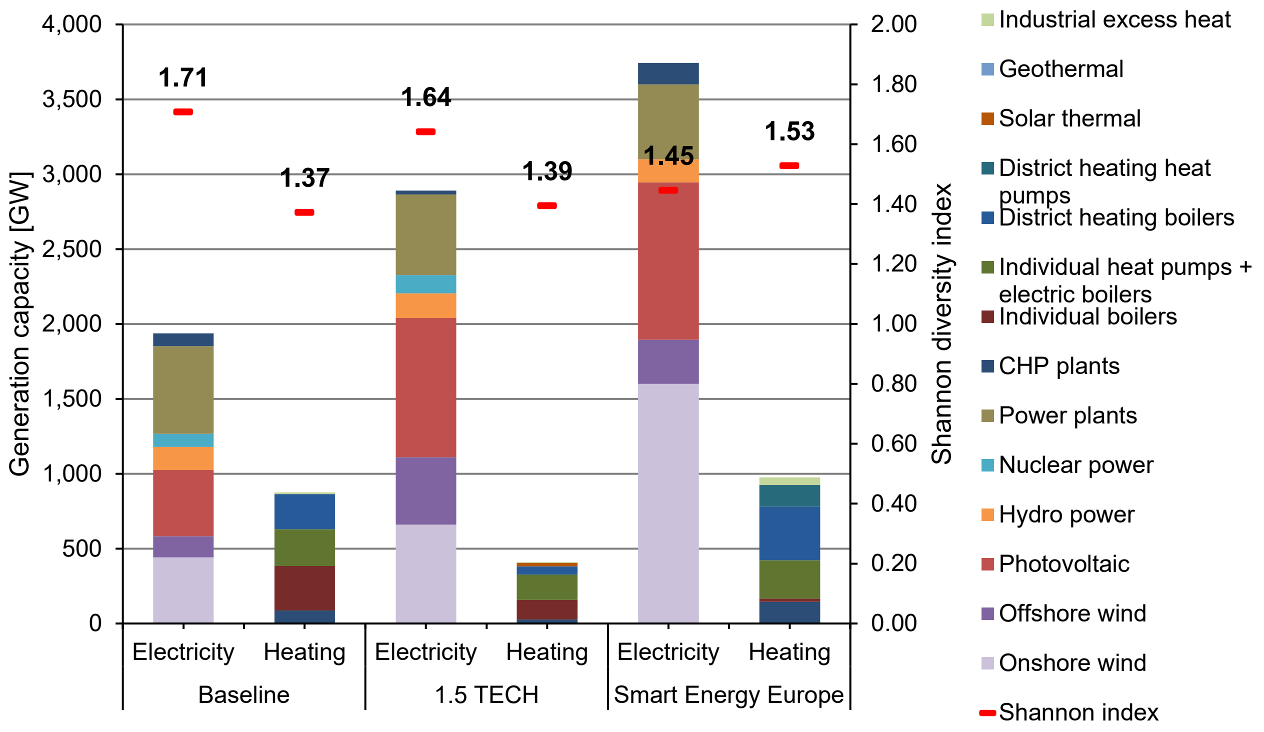

Figure 11. Generation capacities and Shannon diversity index for electricity and heat generation technologies in EU scenarios.

Electricity generation capacities and Shannon diversity index values can be seen for the scenarios for Greece in Figure 12.

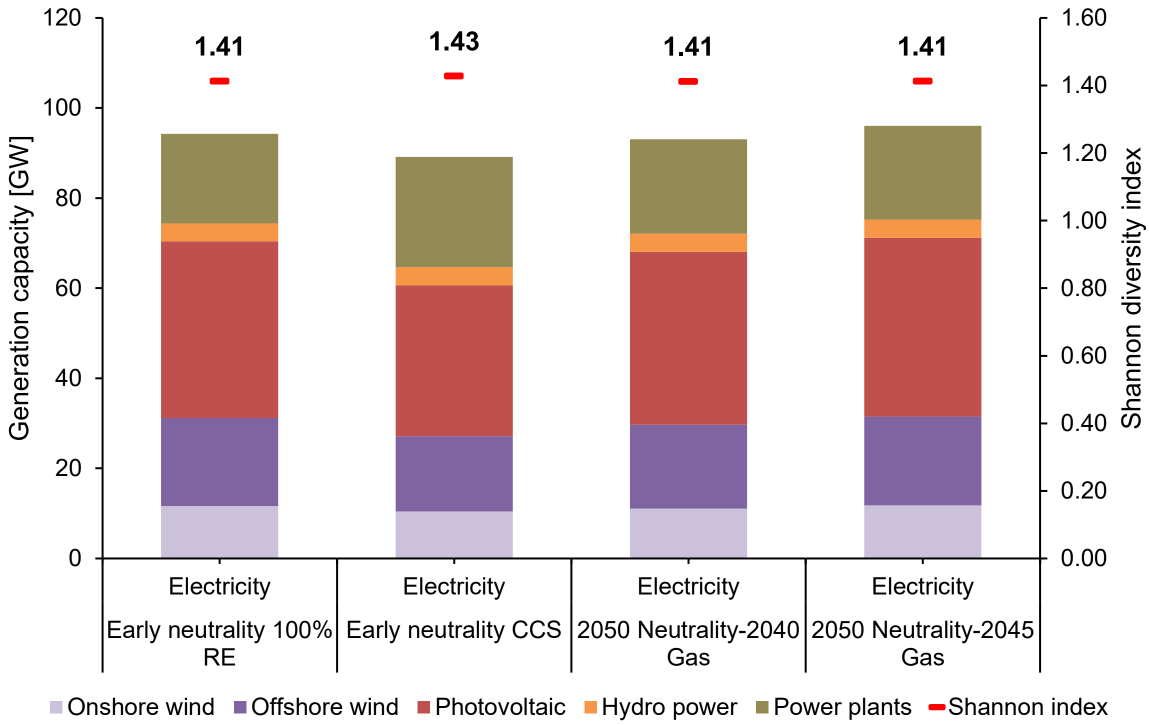

Figure 12. Generation capacities and Shannon diversity index for electricity and heat generation technologies in Greece scenarios.

The scenarios for Greece are relatively similar in terms of installed capacities for electricity generation, having the same technology mix across scenarios with variations in capacity. This naturally results in similar Shannon diversity index values, which are also comparably lower than the observed diversity in the EU scenarios.

From this comparison of diversity in energy systems for the EU and Greece, it is evident that it is worth considering as one aspect of scenario design, as with the transition to renewable energy there is a risk that energy systems become less diverse. However, energy security and diversity should also be considered from a qualitative perspective, considering the nature of the technologies included. The Shannon diversity index only considers the number of flows and their evenness, and thus does not evaluate the availability and geographical distribution of technologies. Wind power (onshore or offshore) is for example a distributed technology compared to e.g., nuclear power which is based on large individual plants, and hence less susceptible to outages. Furthermore, a system independent of foreign imports is arguably more secure than a system based on imports, and thus, having a lower Shannon diversity index value could be acceptable if all energy demands are sourced internally. Lastly, a consideration is the certainty that energy demands can be sourced in the future, which for renewable energy, due to the nature of being renewable and therefore replenishable would be high, while for fossil fuels due to depletion or potential scarcity would be lower. It may be that additional indicators are required in the future for comparing and designing 100% renewable energy systems as merely considering diversity comes with certain limitations.

As previously discussed, MARIO is used to calculate the backward linkages of electricity produced by different energy sources. The results serve as a proxy of how the power sector in the EU is dependent on foreign industrial activities. Figure 13 shows a comparison among the backward linkages of the electricity produced in the EU by the main energy sources. Nuclear, Biomass & Waste, Solar thermal, Geothermal, Hydro and Tide technologies are shown as a total backward linkage (dots on the left, under the "Others" label), while Coal, Natural gas, Oil, PV and Wind are also detailed in terms of dependence by origin supply chains (EU27 or Rest of the World, RoW). Moreover, a sensitivity analysis has been performed on technology performance (lifetime and capacity factors) for PV and Wind. These results come from a static application of MARIO and are referred to as the Baseline scenario. However, it is reasonable to state that the following considerations hold also for future years in case the supply chains of these electricity production technologies remain unchanged.

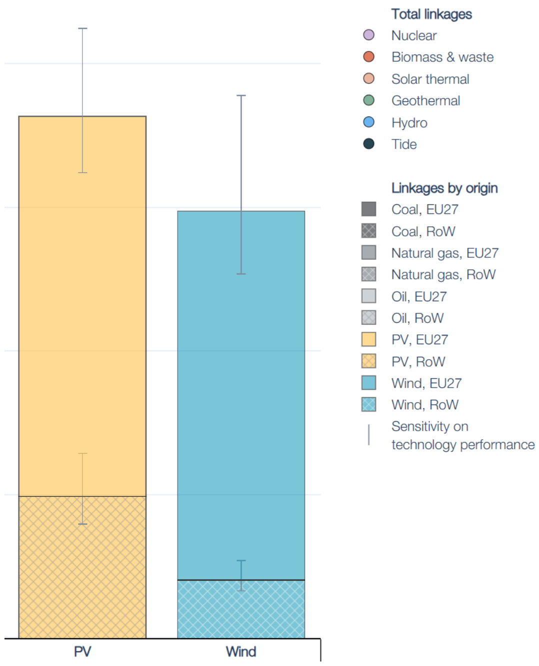

Figure 13. Backward linkages of electricity generation sources in EU27.

As evident, the dependency values (backward linkages) associated with electricity production from renewable sources closely resemble, and possibly exceed, those linked to other fossil sources. Geothermal, nuclear, hydro,

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and other less common sources exhibit the lowest values of backward linkages, excluding PV and wind. When compared to their fossil counterparts, PV and Wind show a comparable share in non-European economies, with PV having a similar share and Wind having a lower share. While the dependency on upstream supply chains for these two renewable technologies is comparable to that of fossil fuels, the notable difference lies in the predominantly European nature of the supply chains they rely on. For instance, in the case of wind, less than 15% of the backward linkage is attributable to non-European industries.

To conclude, this measure does not account for the evolution of the dependency: currently, the European energy system heavily relies on primary resources like Russian gas. However, in transitioning to PV and Wind, interconnection will be essential for generating new capacity. Nevertheless, once the plant is installed, operational dependency diminishes, as these technologies are characterised by very low operating costs. This issue gains even more significance as these technologies become more widespread in the economy and more enduring.

Flexibility

This section is divided into a discussion regarding electricity generation in comparison to electricity loads, and energy demands with a focus on flexibility and storage capacities.

As pointed to in the review on flexibility, it matters to discuss both types of generation and units and whether they are dispatchable or not. Furthermore, it is also important to show there is a difference in types of energy loads, where demand flexibility can help in the implementation of renewable energy. Figure 7 shows three types of electricity loads:

- Classical electricity demand, which only covers the normal electricity demand in households, as well as electricity demands in industry.
- Inflexible demands, which covers all in 1) but also 1-day flexible demands, electricity for heat pumps and boilers in households with individual heating solutions and inflexible electricity demands for transport (e.g., rail and heavy transport).
- Total demand includes all of 1) and all of 2), as well as flexible demand in electrolysis, heat pumps and electric boilers in district heating systems and smart charging of electric vehicles with batteries.

The key comparison here is that systems should have enough dispatchable electricity capacity to cover the inflexible loads. As Figure 14 shows, this is the case for all three European scenarios.

The peak load for the total demand increases in line with the increase in renewable capacity. This is the case to support the implementation of large shares of renewable energy. Here it is necessary for the system to be able to respond to hours of the day, week and year, with large productions, and by utilising high capacities in heat pumps, electrolysers and electric vehicles, to either use the energy directly in this hour, or integrate with energy storage and have the ability to move and match production with demand. Here research shows that by utilising energy storage in heating and fuel sectors, it is possible to avoid expensive electricity storage costs.

Figure 15 shows the electricity capacities for the Greek scenarios which indicate the same trend as the European system. The primary installed generation capacity is renewable, but there still is a significant dispatchable power plant capacity to ensure flexibility and production in hours with limited renewable energy generation.

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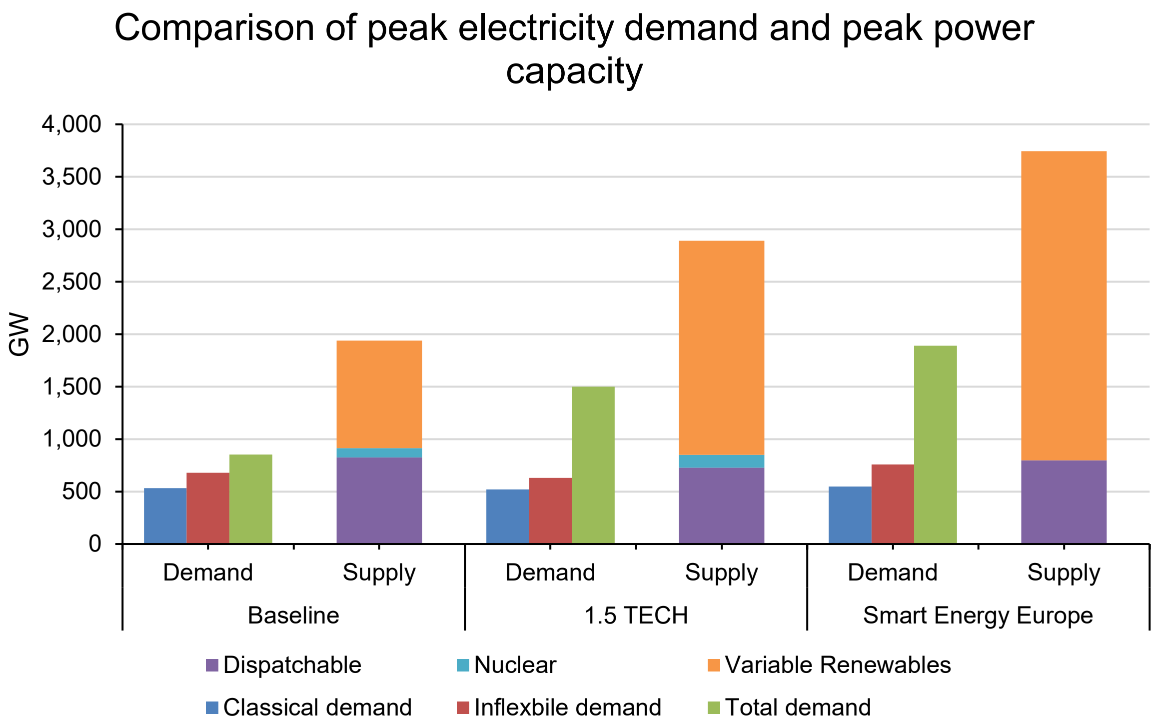

Figure 14. Electricity loads compared to dispatchable, nuclear, and variable renewable electricity capacity in the scenarios for EU.

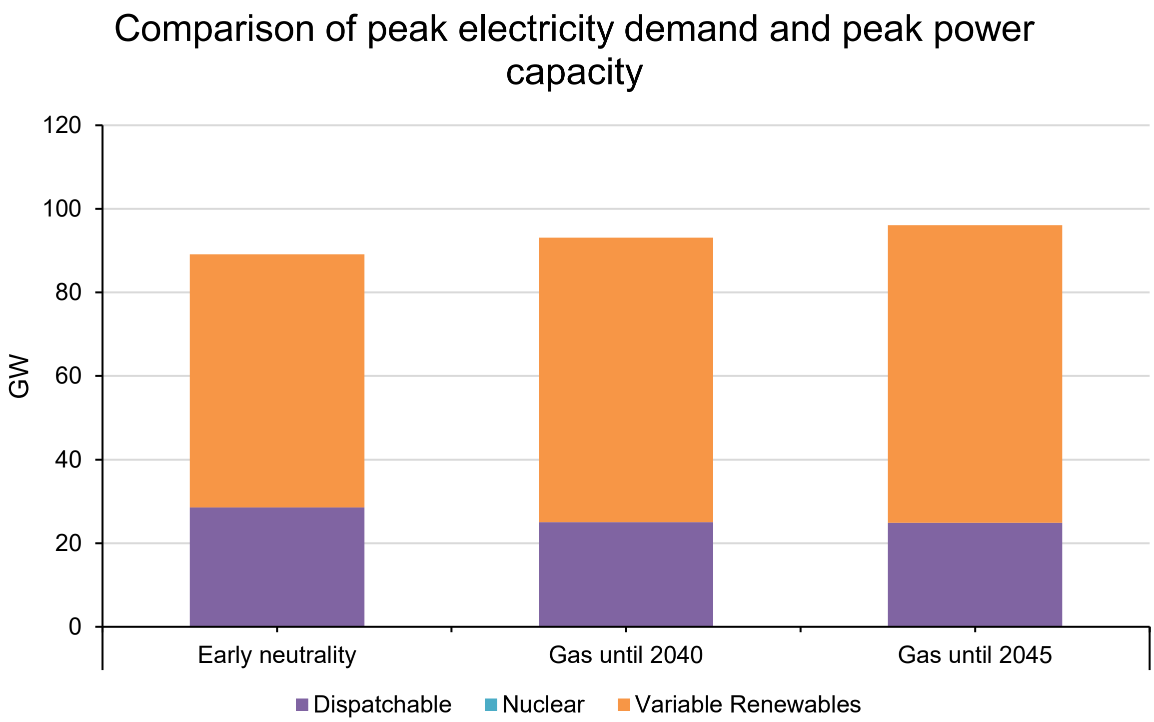

Figure 15. Power capacity in the scenarios for Greece.

Regarding energy demands, Figure 16 shows the electricity demands in the European energy systems. This highlights, in combination with the information from Figure 14, that in the transition towards CO_2 neutral energy system, increased electrification is needed and with higher electricity demands. It also shows that when comparing the baseline with 1.5 TECH and Smart Energy Europe scenarios, the non-flexible demands are rather similar

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across the different scenarios. Hence, to ensure flexibility, the electrification of the energy sectors needs a focus on flexibility in demands. These demands are especially tied to the electrification of transport, either through EVs or in hydrogen production for fuels and gas.

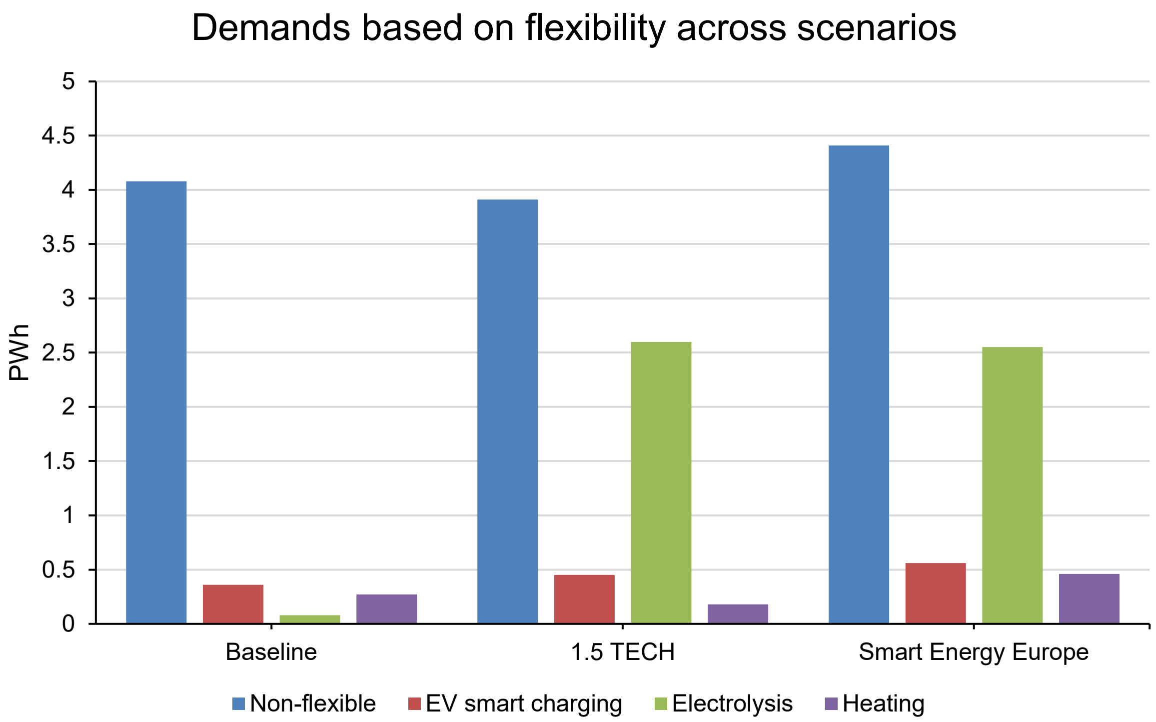

Figure 16. Overview of electricity demands in the scenarios for EU.

Storage is crucial to ensure the flexibility of the system, especially in the utilisation of flexible demands and flexible production units. Figure 17 shows installed storage capacities in the modelled European Scenarios. In general electricity storage is quite expensive compared to e.g., thermal storage, which also is indicated in the three European scenarios with quite low electricity storage, and here pumped hydro has the largest utilisation. However, the "hidden" electricity storage in EVs is quite important to ensure the smart charging and flexibility of transport demands. Hence, there is a quite large utilisation of electricity storage in electric vehicles in all three scenarios, but especially in the Smart Energy Europe scenario. Smart Energy Europe also have a significant amount of thermal storage, to be used in district heating systems. This allows for flexible use of heat pumps and electric boilers in the district heating grid. Finally, hydrogen storage plays an important role in the flexibility of electrolysis, which is why it is the biggest storage both in the 1.5 TECH and Smart Energy Europe scenario. By having sufficient hydrogen storage, it is possible to utilise electrolysers flexibly and handle large quantities of renewable energy by avoiding operation during peak demand hours. Smart Energy Europe has a significantly larger hydrogen storage than 1.5 TECH and the baseline. The primary reason is that Smart Energy Europe is completely self-sufficient, which means that there is an annual balance between gas demands and green gas (biogas and e-methane) production. To ensure this balance either import/export of gas is needed or gas storage plants of 110 TWh are needed. 1.5 TECH and the baseline scenario are dependent on imports of natural gas from other regions (e.g., Russia) outside the EU. Besides the storages illustrated here, dammed hydro is included as well as dispatchable power production.

Figure 18 shows the storage capacities for the Greek scenarios. This also highlights that hydrogen storage, in combination with flexible electrolysis capacity, is the biggest storage. However, in the Greek scenarios, direct electricity storage takes up a bigger space, which to some extent potentially can be explained by the synergies with a large capacity of solar PV and thereby predictable production profile and need for storage capacity during night periods, compared to the European scenarios with larger shares of wind energy production profile varying

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throughout both day and night periods.

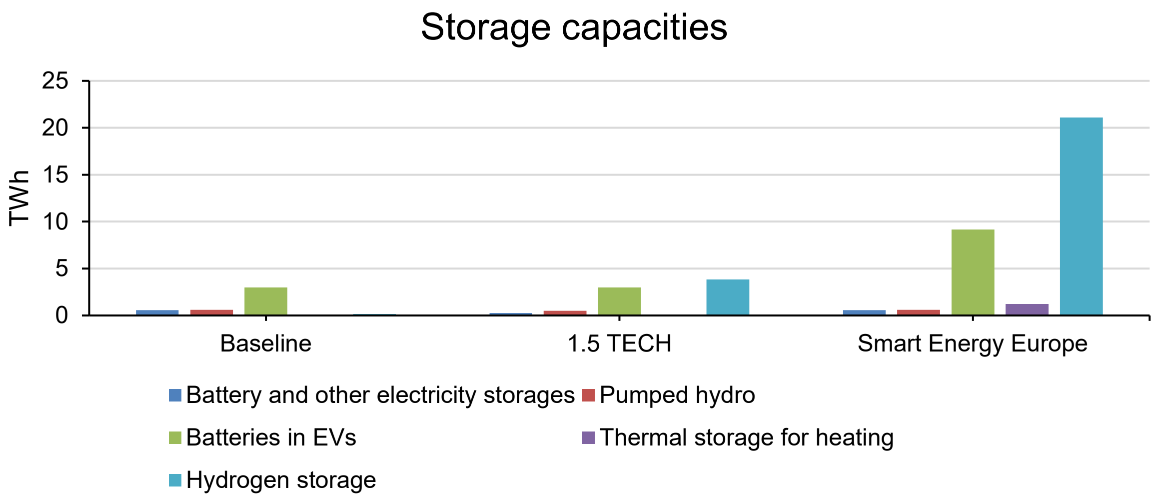

Figure 17. Storage capacities in the scenarios for EU.

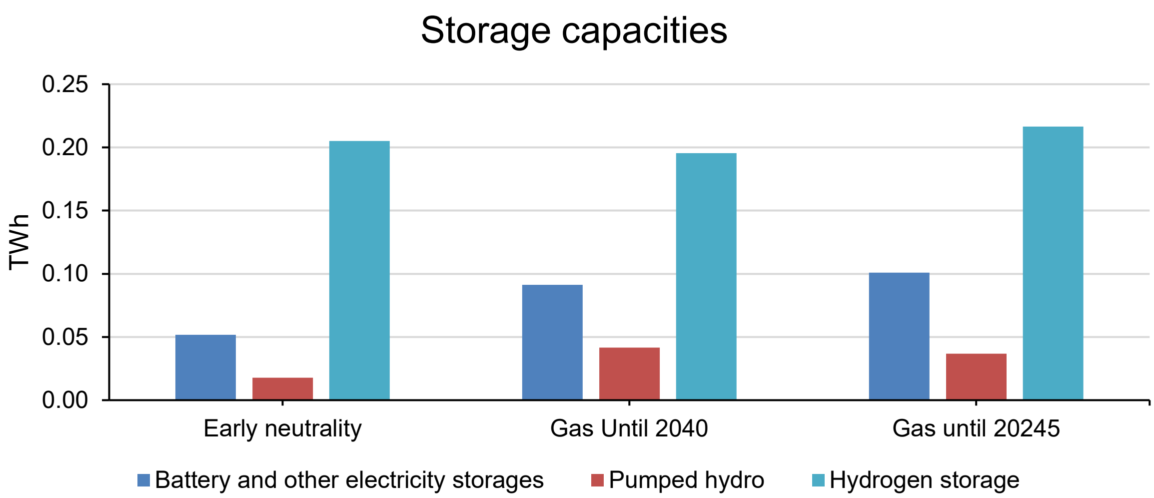

Figure 18. Storage capacities in the scenarios for Greece.

Costs and prices

In light of the achieved results within the 1.5 TECH scenario, several key outcomes have emerged, shaping the economic landscape in the pursuit of climate neutrality and adherence to the 1.5°C ambition of the Paris Agreement. The significant electrification and the deployment of e-fuels and hydrogen have led to transformative changes in energy costs. Increased reliance on renewable energy sources has influenced electricity prices, fostering a shift toward more sustainable and cost-efficient energy solutions. The costs associated with hydrogen production have seen notable shifts, impacting various sectors relying on hydrogen as a feedstock or energy source. The strong penetration of VRE sources has influenced the pricing dynamics of renewable energy. The decarbonisation of the power sector has resulted in varying electricity prices, impacting industries dependent on sustainable and resilient energy sources. The envisioned supply chain and infrastructure investments have materialised, leading to improved efficiency and sustainability across various sectors. However, there is a potential surge in materials demand that can lead towards an economy-wide increase in energy and even goods prices. The materials analysed in the study are copper (CU), aluminium (AL), nickel (AL), and iron (FE) given that they are essential for developing net-zero technologies, playing a pivotal role in key components. Growing demand for these materials could potentially lead to an increase in costs, eventually harming the energy transition. Understanding these dynamics is crucial for developing sustainable strategies and mitigating potential supply chain risks in the transition towards a net-zero future.

In the Smart Energy Europe scenario, the overarching principle of "energy efficiency first" has manifested in pronounced outcomes. The prioritisation of energy efficiency measures has resulted in optimized energy consumption patterns across various sectors, leading to reduced overall energy costs. The strategic update of heating systems and the expansive adoption of district heating have redefined the heating landscape. This has not only enhanced the resilience and sustainability of heating infrastructure but has also contributed to cost efficiencies in the provision of thermal energy. The electrification of the transport sector has ushered in a new era. Shifts toward electric vehicles and associated infrastructure development have influenced transport costs, with implications for industries reliant on efficient and sustainable transportation solutions. The integration of e-fuels for the heavy segments of transport has introduced resilience in the face of challenging energy demands. This strategic use of e-fuels has impacted both the costs and environmental footprint of heavy transportation, aligning with sustainability goals. The replacement of remaining fossil fuel demands in industry and power generation with biogas and biomass has marked a transformative phase. The use of renewable alternatives has influenced production costs and energy prices, contributing to a more sustainable and resilient energy matrix.

The results are shown below compared to the Baseline=100. Copper (Cu) prices significantly increase mid-simulation as the energy transition is unfolded (see Figure 19). The escalating demand for copper in the medium-term can be attributed to its indispensable role in the construction of renewable energy infrastructure, such as wind turbines, solar panels, and electric vehicle components, as part of the global net-zero transition. The increased need for copper, coupled with potential supply chain constraints is likely to drive copper prices up, reflecting the growing significance of this critical raw material in achieving sustainable energy goals. However, copper prices would potentially drop as the installation of new technologies decreases. That will probably be unavoidable even in the Smart Energy Europe scenario. Nevertheless, that scenario shows a better performance than the 1.5Tech one. This improved performance can be seen more notably when looking at Aluminium (Al), with a reduction in price 6 points higher than 1.5Tech. The same tendency is observed for other critical materials such as Nickel (Ni) and Iron (Fe). The divergence in material prices between the Smart Energy Europe and 1.5 TECH scenarios is pronounced -with the exception of copper-, primarily driven by the distinct assumptions underpinning each approach. In contrast with 1.5 TECH seario, the Smart Energy Europe scenario is anchored in comprehensive renewable energy principles with a focus on energy efficiency and sector-specific transitions. As a consequence, that scenario shows more moderate material price dynamics. These results show the importance, regarding critical raw materials, of targeting energy efficiency first. In fact, these efforts could potentially be insufficient to avoid a rapid increase in materials costs, suggesting the need to address further demand-sided policies to reduce materials demand, both for net-zero technologies and the rest of the economy.

Moreover, in WILIAM, the dynamism of materials supply through mining is contingent upon its relationship with materials demand. The overall (for all scenarios and materials) observed escalation in prices is related to the following dynamics through two interconnected facets: firstly, as a flow, the great augmentation in demand outpaces the capacity to increase the annual mining output. The substantial growth in demand for materials, driven by ambitious net-zero scenarios, surpasses the industry's ability to incrementally increase mining outputs, thereby generating an upward pressure on prices. Secondly, from a stock viewpoint, the prices increase is related to the fact that reserves remain constant. Consequently, if new reserves are either discovered or turned economically viable for extraction, the impact on prices shown in our results may be mitigated.

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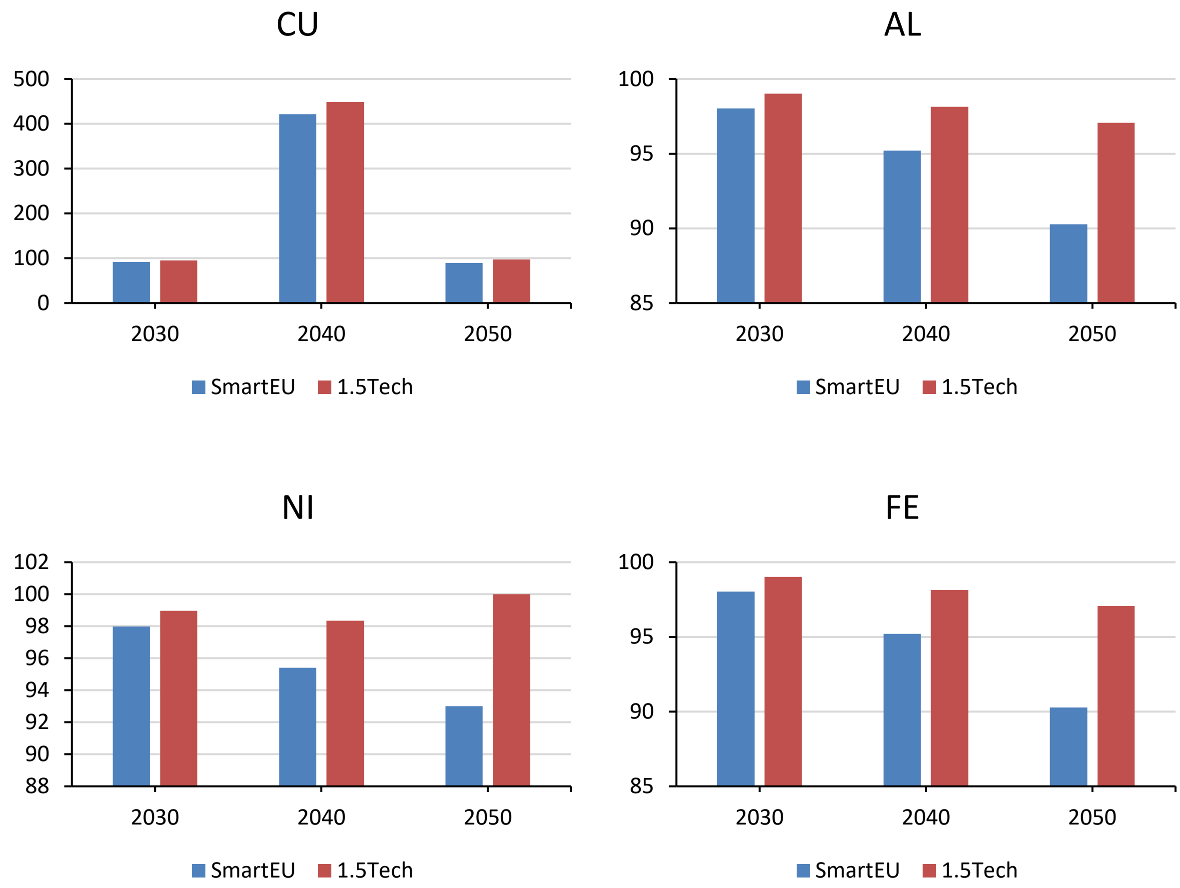

Figure 19. Material prices in Smart Energy Europe and 1.5 TECH relative to Baseline (Index 100).

Environmental effects

Within the environmental context of the 1.5 TECH scenario, the evaluation of crucial indicators, particularly materials consumption, reveals a profound impact on resource demand. The scenario, while aligning with ambitious climate targets, notably intensifies the demand for materials, signifying a pivotal shift in the environmental landscape. The implementation of the 1.5 TECH scenario, with its emphasis on technological innovation and electrification, has led to a significant surge in materials intensity. The heightened demand for resources, including minerals, metals, and rare earth elements crucial for renewable energy technologies, batteries, and electric infrastructure, underscores an intensified materials consumption pattern. T Elements such as lithium, cobalt, and copper, integral to the production of batteries and electric components, experience heightened demand, potentially leading to environmental concerns related to extraction practices and resource depletion. From extraction to production and disposal, the life cycle of materials becomes a focal point, with potential environmental impacts stemming from mining activities, energy-intensive manufacturing processes, and the management of electronic waste. The surge in materials demand within the 1.5 TECH scenario poses challenges to the principles of a circular economy. The increased consumption of materials, if not managed sustainably, may hinder efforts to reduce waste generation and promote recycling, contributing to a linear materials flow with potential ecological consequences. This tendency is especially intense in copper demand (see Figure 20). The results are compared with Baseline=100. None of the scenarios can avoid an important increase in copper demand. All other materials would potentially even decrease its consumption over time.

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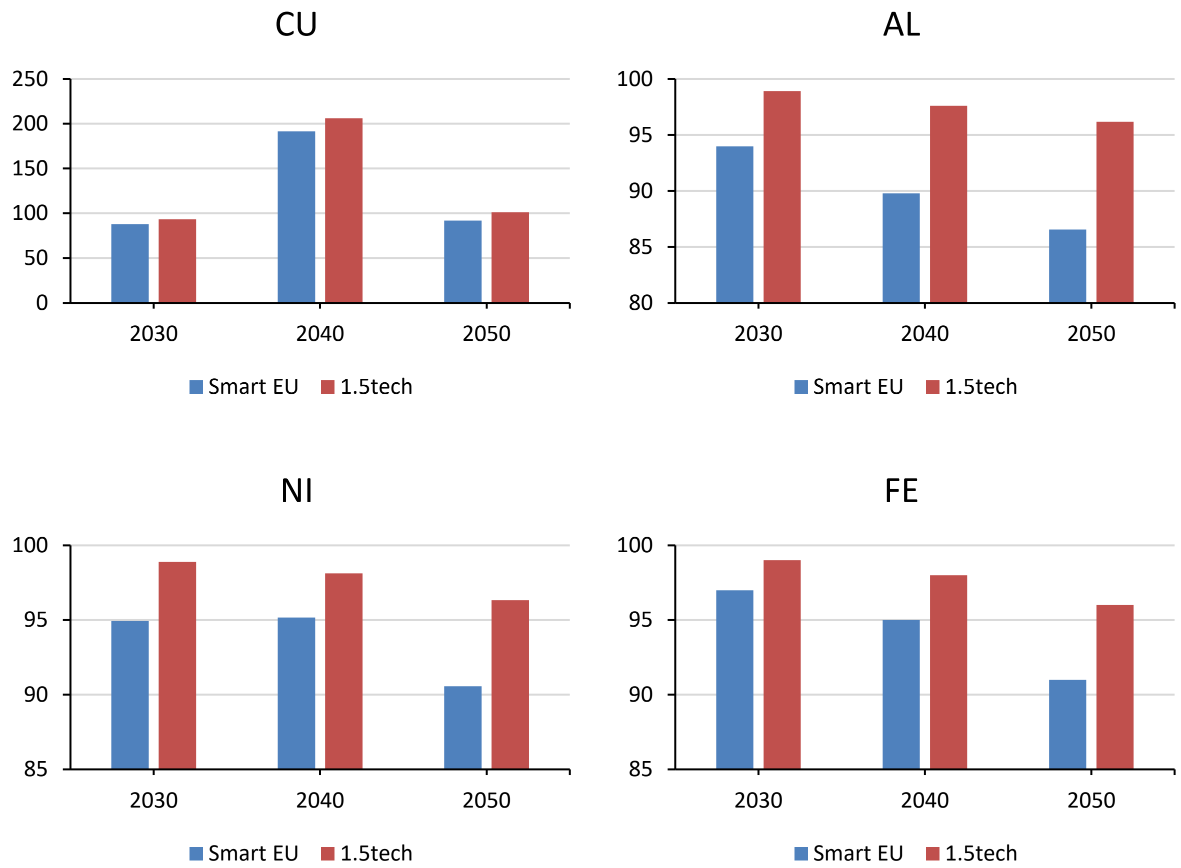

Figure 20. Material demand in Smart Energy Europe and 1.5 TECH relative to Baseline (Index 100).

In contrast to the heightened materials demand observed in the 1.5 TECH scenario, the Smart Energy Europe scenario presents a narrative of easing pressures on materials consumption within the environmental landscape. This scenario, rooted in Smart Energy System principles, introduces a range of strategies that contribute to a more sustainable and resource-efficient approach. The Smart Energy Europe scenario places a pronounced emphasis on "energy efficiency first," a principle that inherently alleviates materials demand. By prioritising efficiency measures across sectors, the scenario mitigates the need for extensive material consumption in the energy transition process. The strategic update of heating systems and the expansion of district heating in the scenario contribute to a more efficient use of materials in the energy sector. This optimisation minimises the demand for specific materials associated with traditional heating systems, thus easing pressures on material resources. While the scenario also involves electrification initiatives, the emphasis on a balanced and strategic approach mitigates the intensive demand for specific materials associated with electrification. This balanced electrification aligns with a sustainable resource management strategy. The scenario incorporates a diversified mix of renewable energy sources, contributing to a more distributed and balanced energy matrix. This approach lessens the concentration of material-intensive technologies, such as those associated with a heavy reliance on a single energy source. The replacement of remaining fossil fuel demands in industry and power generation with biogas and biomass introduces a sustainable alternative with potentially lower material intensity. This strategic shift in energy sources eases pressures on specific materials while aligning with renewable and environmentally friendly options. The Smart Energy Europe scenario aligns with circular economy principles, emphasizing a more sustainable approach to materials consumption. Strategies such as the utilisation of biogas and biomass contribute to a circular materials flow, promoting recycling and reducing overall environmental impact.

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3.6 Conclusion

In this study, we presented a review of energy system indicators and tools and methods for evaluating renewable energy system scenarios. Based on existing literature and insights from policymakers and other stakeholders, indicators and parameters for evaluating renewable energy systems were established and categorised according to four main topics: 1) Energy security and resilience, 2) Flexibility, 3) Costs and prices, and 4) Environmental effects. We modelled renewable energy systems for Greece and Europe in OSeMOSYS and EnergyPLAN respectively, providing a number of insights into the functioning of concrete, tangible renewable energy scenarios for the future. The input-output model MARIO was used to calculate the backward linkages of electricity produced by different energy sources based on the energy system scenario outputs generated in EnergyPLAN. The integrated assessment model WILLIAM was applied to model material cost and material demand projections for different energy systems, based on the energy system scenario outputs from EnergyPLAN.

Based on the review of energy system indicators in existing research, key indicators and aspects for each main topic to be assessed in the study were determined. For energy security and resilience, the diversity of energy systems both from a consumption and generation perspective, and the backward linkage reliance of commodities and upstream supply chains, split between domestic and foreign supply chains were assessed. For flexibility, dispatchable and variable generation capacity relative to demand flexibility and the availability of storage solutions in energy systems as indicators of system flexibility. For costs and prices, impact of materials expenditures on overall costs and pricing structures for critical material were assessed. Finally, for environmental indicators, the heightened demand for minerals, metals, and other resources were assessed, evaluating the environmental implications of increased materials consumption.

In this study we show how it is feasible to design 100% renewable energy system scenarios for the EU without foreign fuel imports, underlining that it is possible to develop a functioning independent energy system. The scenarios for Greece demonstrated potential pathways for a functioning energy system with and without natural gas power plants, meeting and negating the recent challenges of the energy crisis and limited natural gas availability.

Applying the Shannon diversity index to quantify the diversity of energy systems it is found that the diversity of 100% renewable energy systems arguably decreases relative to systems with a combination of renewable and fossil fuel resources. However, it is pertinent to consider not only diversity index values but also the nature of energy demands and generation technologies, including their availability and distribution, where renewable energy technologies could be considered an improvement over fossil fuel technologies.

An assessment of backward linkage effects for energy technologies was conducted, finding that the dependency values (backward linkages) associated with electricity production from renewable sources closely resemble, and possibly exceed, those linked to fossil fuels. While the dependency on upstream supply chains for PV and Wind power is comparable to that of fossil fuels, the notable difference lies in the predominantly European nature of the supply chains they rely on, while fossil fuel-based technologies to a greater extent rely on non-European industries. For instance, in the case of wind, less than 15% of the back-ward linkage is attributable to non-European industries.

For energy system flexibility substantial differences in dispatchable generation capacity relative to variable generation capacity and flexible demands relative to residual demands were observed for different scenarios. It is pivotal that future renewable energy systems are designed in a way that enables the exploitation of large variable renewable electric generation capacities through flexible electricity demands, while at the same time having a sufficient dispatchable generation capacity for flexibility and covering the residual demand. Having this flexibility on both the supply and demand side is what renders 100% renewable energy systems feasible without overly relying on external markets and imports.

Modelling of material prices in future energy scenarios demonstrated that increased sector integration, strategic use of e-fuels, and biogas generation as demonstrated in the Smart Energy Europe scenarios results in lower

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material prices for copper, aluminium, nickel, and iron. This indicates that the transition to renewable alternatives can positively influence production costs and energy prices, contributing to a more sustainable and resilient energy matrix.

For material consumption it is found that a profound prioritisation of energy efficiency improvements, electrification, and strategic expansion of district heating can ease pressures on material consumption within the environmental landscape, contributing to a more sustainable resource management strategy.

A relevant limitation of the study is that electricity transmission within Europe is not considered, which may provide both opportunities in terms of flexibility for balancing VRE, and limitations in terms of bottlenecks. Further exploring this would be relevant in future studies. A second limitation is the emphasis on the power sector in both the scenarios of Greece and Europe. In future work, it would be relevant to explore the full extent of the EnergyPLAN scenario and all effects and impacts from sectors beyond the power sector. Future work could explore additional developments to energy security indicators for renewable energy systems which to a higher degree encompass and value the nature of fluctuating renewable energy technologies.

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4 Deep dive into Greece's National Energy and Climate Plan

4.1 Introduction

Greece is a country with a significant renewable energy potential and presents a case of a significant shift in planning for its future energy system's development. In 2019, the Greek government decided to terminate by 2028 domestic lignite mining and lignite-fired electricity generation and set ambitious climate and policy goals, including the decarbonisation of its power sector by expanding the capacity of renewable energy sources (RES). This decision prompted a need for additional studies into the potential impacts of phasing out lignite on the future growth of Greece's energy system. Consequently, the National Energy and Climate Plan (NECP) was created to specify goals, policy priorities, and targets with regards to energy and climate by 2030 (Ministry of Environment and Energy, 2019b). The revised draft NECP, in accordance with the European Commission's (EC) new energy and climate objectives, was publicly presented in January 2023 (Hellenic Ministry of Environment and Energy, 2023b) and initially submitted to the EC for review, while the updated and revised draft NECP was prepared and re-submitted to the EC at the beginning of November 2023 (Hellenic Ministry of Environment and Energy, 2023a). It is anticipated that the revised NECP's final version will become publicly available in June 2024.

However, more modelling applications are required to determine whether the full decarbonisation of the national energy system, as articulated by the NECP, is a viable option, while maintaining or even improving Greece's economic standards and cultivating a just society without "*winners and losers*" for an energy transition where "*no one being left behind*".

The work outlined in this section has been carried out as a component of PRM-1 of the IAM COMPACT project under Theme 2: "Electrification" (see *Deliverable D2.2 "Scoping Relevant Research Questions"*). The topic of how the implementation of the updated draft NECP compares to the cost optimal approach at the European level was recognised as an issue of high concern for high-level policymakers from national governments and the EC. Consequently, the following overarching research question (RQ) was selected for the Greek case study:

RQ: "How do residential and power sector development projections, as articulated by the revised draft version of the Greek NECP, compare to the (cost-optimal) transition pathways derived from sectoral models?"

To answer this RQ, we use two (2) energy system models, namely, an electricity supply cost optimisation model and a demand-side management model.

Policy background and targets

Figure 21 displays Greece's national targets for the energy transition by 2030 and 2050, as established in the framework of the NECP's updated and revised draft version. To attain these targets, the revised NECP consists of specific strategic policy priorities:

- **Rapid growth of RES:** Development of solar and wind power (and acceleration of development of offshore wind power) with the addition of >12GW by 2030 and exploitation of the remaining hydraulic capacity of the country.
- **Energy storage:** The high penetration of RES should also be accompanied by the development of the required storage capacities for balancing and stabilising the system (e.g., batteries, pumped hydro, etc.).
- **Energy efficiency:** Energy upgrading of buildings (insulations, appliances, heat pumps), smart management of energy consumption and change of behaviour to reduce energy requirements or even demand profile.
- **Electrification of light road transport:** Electrification in light/medium-sized vehicles with simultaneous development of charging infrastructure. A large part of the required investments will be in vehicles and their batteries.
- **Creation of green hydrogen economy:** Development of infrastructure and production of hydrogen from

RES and use in heavy-duty transport, shipping, aviation, industry, and long storage in electricity generation.

- **Development of climate-neutral alternative fuels:** Use of Renewable Fuels of Non-Biological Origin (RFNBO) in heavy-duty transport, shipping, and aviation.
- **Gaseous fuel system:** Maintaining the gas system in the country given that the gas mix can quickly become low carbon using renewable gases.
- **Bioeconomy:** Creation of a national production system in agriculture and industry to produce advanced biofuels and biomethane that can be injected into the gas grid.
- Innovation in **carbon capture and storage** (**CCS**) for industry (e.g., oil refining, fertilizers, etc.).

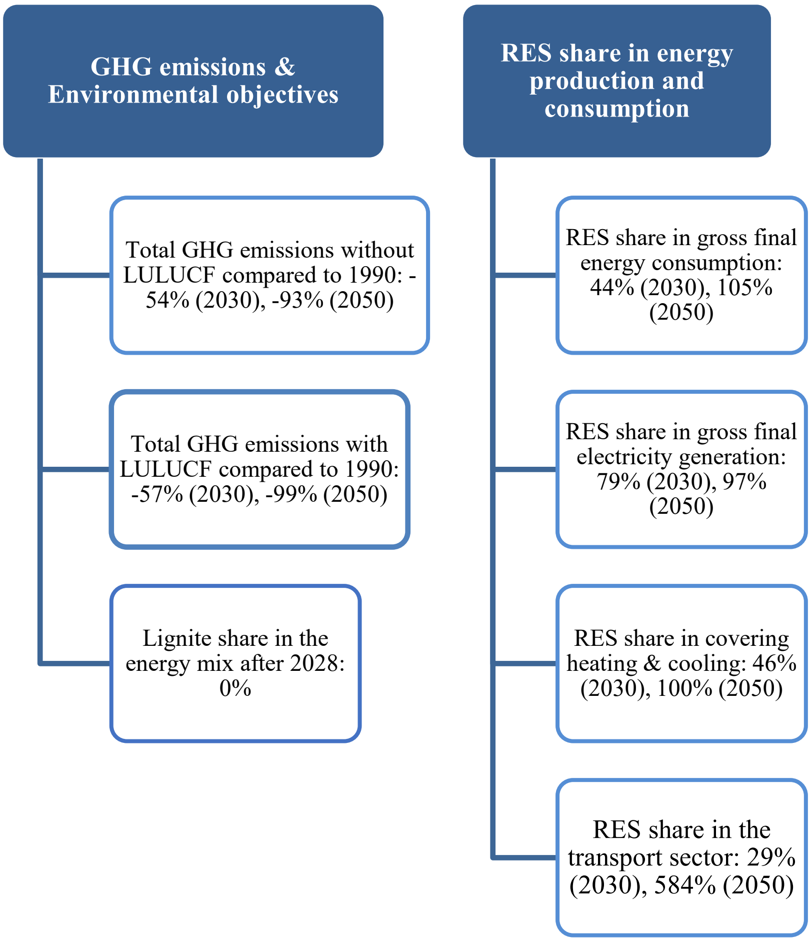

Figure 21. GHG emissions, RES, and energy efficiency targets in Greece by 2030 and 2050 according to the updated and revised draft NECP. Source: (Hellenic Ministry of Environment and Energy, 2023a).

Scenarios & Specifications of the National Energy and Climate Plan

In this study, we have considered the country's recent climate commitments and key data projections for the power and residential sectors, as these have been, partially, articulated in the revised draft version of the NECP. In this regard, the scenario of the revised draft NECP is used to provide comparability with the results from the sectoral models used. The revised draft NECP scenario towards 2030 and 2050 considers the development of all economy sectors and seeks to assess the barriers to meeting the country's energy and climate goals.

The decarbonisation of the power sector is achieved by reducing the utilisation of carbon-intensive generating resources and encouraging the use of RES. The net electricity production in 2030 will be equal to 71.5 TWh, while in 2050, it will amount to 173.7 TWh. RES will become the predominant source of electricity production generation, amounting to 80% and 93.5% of the net electricity generation in 2030 and 2050, respectively. The total RES capacity for electricity production will amount to 28.7 GW in 2030 and will rise to 69.8 GW in 2050. In 2030, hydro plants' capacity will consist of 4 GW, onshore and offshore wind capacity will reach 7.1 GW and 2.7 GW, i.e., a total of 9.8 GW of wind capacity, and photovoltaics (PV) plants will increase to 14.1 GW. Therefore, the total wind and PV capacity will total to 23.9 GW. In 2050, onshore and offshore wind capacity will increase to 10.5 GW and 17.3 GW, meaning that the wind capacity will amount to 27.8 GW, and PV will reach 34.5 GW. As such, the sum of wind and PV capacity will total to 62.3 GW. In 2030, pumped hydro and battery energy storage systems (BESS) will reach 2.5 GW and 5.6 GW, respectively, i.e., a total of 8.1 GW of electricity storage. In 2050, pumped hydro and BESS will total to 5.2 GW and 23.3 GW, amounting to 28.5 GW of electricity storage.

Hydrogen production will require electrolyser capacity of 1.2 GW in 2030 and 14.7 GW in 2050. This will result in 0.2 Mt of hydrogen in 2030 and 2.3 Mt of hydrogen in 2050. Synthetic fuels production will reach 0.2 Mtoe in 2030 and 2.8 Mtoe in 2050. All the lignite-fired generating units will stop operating by 2025, with the exception of the 'Ptolemaida 5' unit, which will be adapted to generate power from natural gas in 2028. Consequently, the lignite's share in electricity production will be zero in 2030 and 2050. As an intermediate fuel of the energy transition, natural gas has a capacity of 6.9 GW in 2030 and 5.1 GW in 2050. Specifically, electricity generation from natural gas power plants is projected to reach 12 TWh in 2030 and 10.7 TWh in 2050. Strengthening of interconnections with bordering countries will boost power capacity to satisfy demand and reduce costs during peak demand periods.

It is projected that RES will account for 45% of the gross final energy consumption in 2030. By 2050, the final energy consumption will decrease to 11.5 Mtoe from 15.3 Mtoe in 2030. In 2030, RES is predicted to account for 47% of the gross final consumption for heating and cooling (geothermal 42%, bioenergy 32.2%, and solar 24.8%). Energy intensity in the residential sector will be decreased by 27% between 2005 and 2030, and further reduced by another 27% between 2030 and 2050 (a total of 54% between 2005 and 2050). Electrification in houses will increase to 50% by 2030 and 61% by 2050 compared to 26% in 2005. Until 2030, 19% of residential buildings and 59% of tertiary buildings will be deeply renovated. 20% of residential buildings and 67% of tertiary buildings will use heat pumps for heating by 2030.

In addition, the share of RES in the gross final consumption for transport will be 32% (biofuels 60%, RFNBO 21.8%, and electricity from RES 18.2%) in 2030. Electrification of cars will increase to 20% by 2030 and 98% by 2050 compared to 0% in 2005. Electrification in road transport is promoted by increasing sales of passenger electric vehicles (Battery Electric Vehicles and Plug-in Hybrid Electric Vehicles), 32% of the total new sales of light-duty vehicles by 2030. This will lead to private electric vehicles holding a share of 20% of the total passenger-km in 2030, which is projected to increase to 85% in 2050, while the rest of private mobility will mostly be covered by hydrogen (13%). Energy intensity in the industrial sector will be reduced the least across demand sectors, namely 6% between 2005 and 2030, and further decreased by 28% between 2030 and 2050 (a total of 34% between 2005 and 2050).

Finally, emission reduction targets for the energy-related CO_2 emissions by 2030 and 2050 are provided in Table 8. Overall, the energy-related CO_2 emissions are expected to be mitigated by 71.4% by 2030 and 99.6% by 2050 compared to 2005 . GHG emissions will total to 49.2 $MtCO_2eq$. in 2030 and 9.1 $MtCO_2eq$. in 2050.

Table 8. Energy-related CO_2 emission reduction targets per sector for 2030 and 2050 compared to the 2005 levels.

Sector	CO_2 emission reduction 2030	CO_2 emission reduction 2050
Power	89%	100.5%
Transport	32.4%	98%
Buildings & Agriculture	76.1%	100%
Industry	40.9%	100%

4.2 Working approach

To explore the feasibility of the different targets as set by the latest official version of the Greek NECP and provide answers to the overarching RQ of this study, we use two (2) energy system models. The models used, the sectoral deep-dives, and the scenario definitions are outlined in the subsections below.

Models used

In this study, we use two (2) energy system models[2], which belong to the Technoeconomics of Energy Systems laboratory (TEESlab) Modelling (TEEM) suite, namely, an energy system linear cost optimisation model and a dynamic high-resolution demand-side management model. A short presentation of each model's characteristics is presented below.

OSeMOSYS-GR

The Open Source energy MOdelling SYStem (OSeMOSYS) is an open-source energy system linear cost optimisation model generator for medium- to long-term energy planning (Howells et al., 2011). OSeMOSYS is utilised to determine the most economically efficient pathway by minimising the discounted cost of the system. This is achieved by optimising the capacity and electricity generation of each technology to meet the predefined final energy demand. Optimisation considers various technological factors such as costs and lifetimes, as well as system constraints like emission limits and RES targets. The standard version of OSeMOSYS is developed in GNU MathProg, an open-source modelling language in which coded equations resemble their algebraic form. It is available as a text file on GitHub[3].

In this study, we use OSEMOSYS-GR, a specific and detailed implementation of the original OSeMOSYS modelling framework, developed and adjusted by TEESlab in the context of the IAM COMPACT project, to accurately model the unique characteristics of the Greek power system from 2021 to 2050. In OSEMOSYS-GR, the electricity supply system is represented by importing and extraction technologies, fossil-fired power plants using lignite, natural gas, oil, RES power plants (i.e., hydro, wind onshore and offshore, solar PV, biomass, and geothermal), electricity storage (i.e., battery and pumped hydro), hydrogen production and consumption (namely electrolysers and fuel cells), transmission, and distribution systems, as well as interconnections with neighbouring countries. The reference energy system of OSEMOSYS-GR is depicted in Figure 22.

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[2] It should be noted that no soft-linking between the three models took place in the context of this modelling excersice.
[3] https://github.com/OSeMOSYS

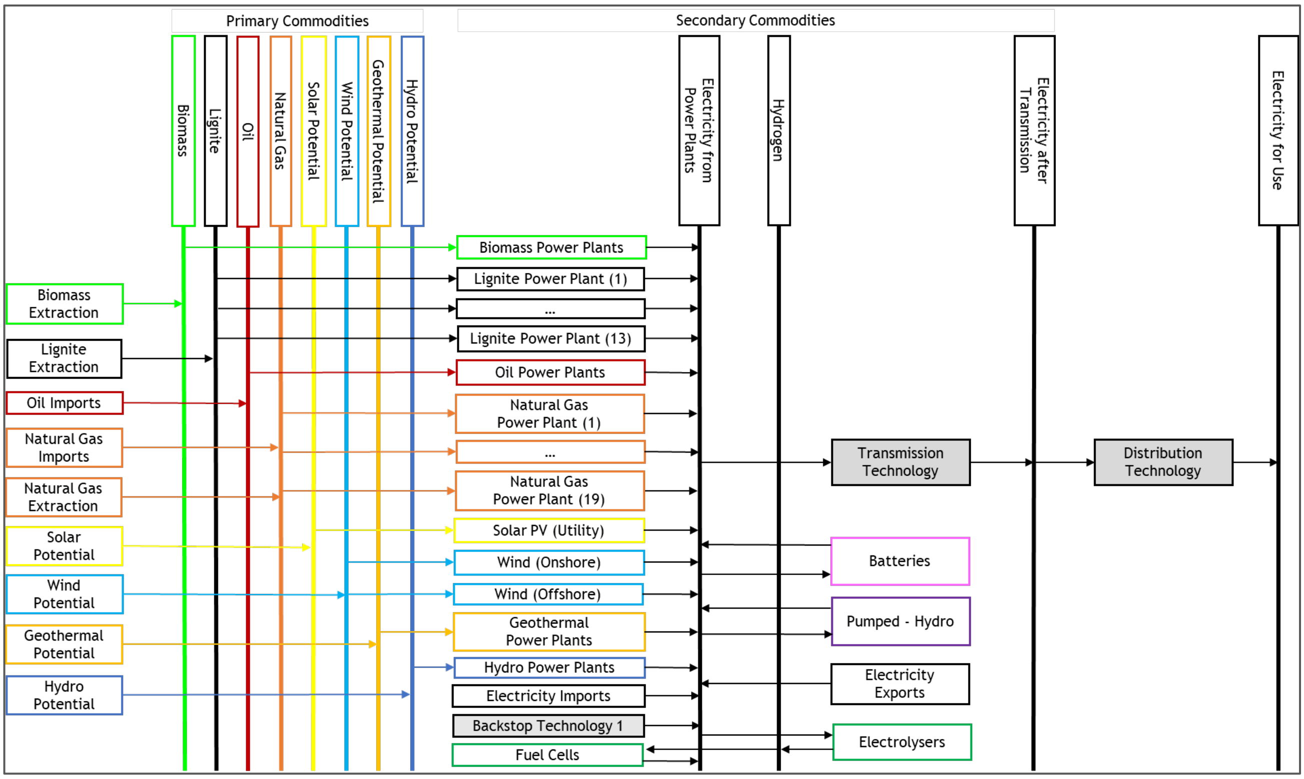

Figure 22. The Reference Energy System of the OSEMOSYS-GR modelling framework as it currently stands.

DREEM

The Dynamic high-Resolution dEmand-sidE Management (DREEM) model is a fully integrated energy demand and demand-side management simulation model, focusing on the building sector, which enhances the computational capabilities of the current Building Energy Systems (BES) and demand-side models, by not solely calculating energy demand, but by also assessing the benefits and limitations of demand flexibility, primarily for the main end-users (e.g., consumers, citizens, etc.), and, then for other relevant energy system stakeholders (e.g., suppliers, retailers, DSOs, TSOs, etc.) (Stavrakas & Flamos, 2020).

The fundamental idea driving the development and the implementation of the DREEM model is that for end-users to actively participate in the energy transition, they must initially gain awareness of the benefits from investing in new energy products and services. In this context, the model's novelty lies in its potential to be used in a wide range of applications, not only to assess the existing technological infrastructure, but also to support the development of business models and regulatory innovations, which maximise the value of energy products and services, and monetise them, to fairly compensate end-users and other energy market actors. Overall, the DREEM model:

- Embodies key features towards the simulation of renewable energy, energy efficiency, and other demand-flexibility actions, like demand response, in the building sector.
- Builds on the concept of modularity consisting of sevelal components, each of which consists of additional modules, permitting greater flexibility in potential system configurations and computational efficiency (i.e., high time resolution and quick simulations), towards a broad spectrum of scenarios, to study different end-use scenarios (Figure 23).
- Enables the integration of upcoming technological advancements in a comprehensive manner, including the adoption of innovative technologies like heat pumps and electric vehicles, aligning with energy transition scenarios that anticipate the complete electrification of the heating and the transportation sectors.
- Produces outputs for a group of buildings, for example, a neighbourhood, a district, a municipality, or an

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energy community.

- Serves as a basis for modelling domestic energy demand scenarios within the broader field of local, regional, and national energy systems in different geographical/climate and socioeconomic contexts, within and beyond the European Union (EU), based on the availability of historical data and observations.

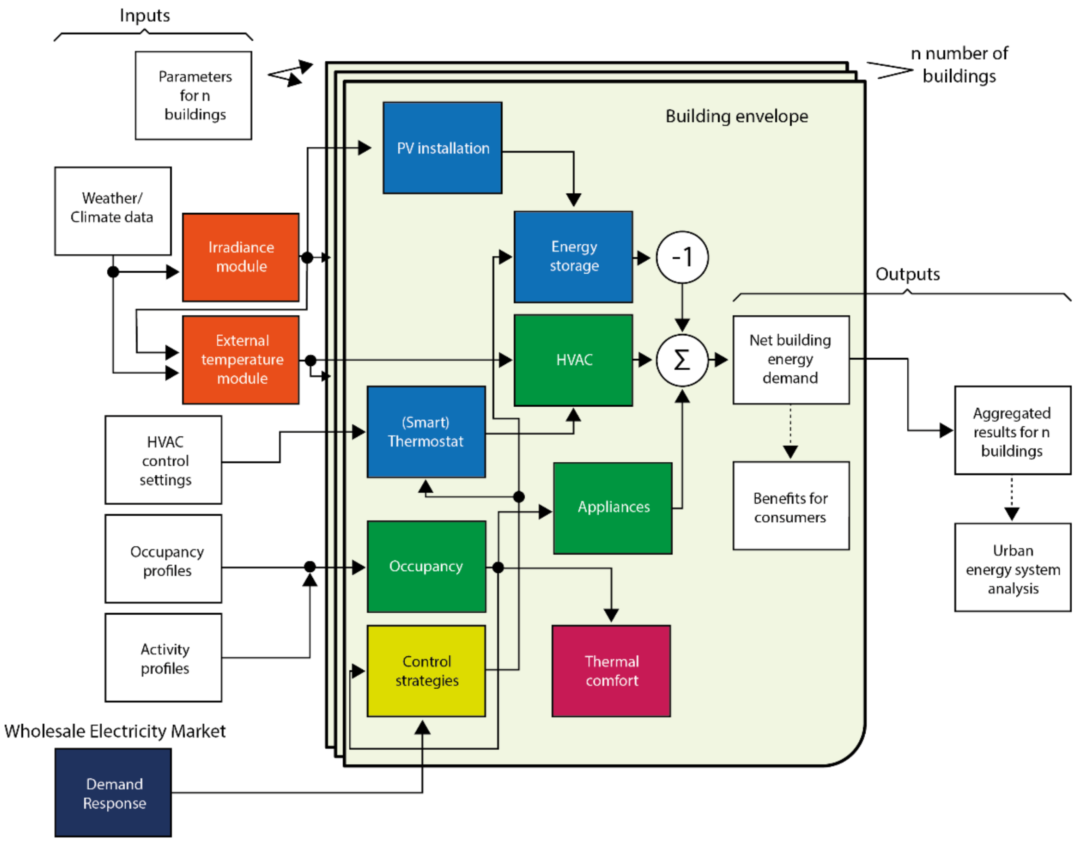

Figure 23. The architecture of the DREEM model as it currently stands (Stavrakas & Flamos, 2020).

DREEM is developed using the "Buildings" library, an open-source Modelica library dedicated to building energy and control systems. In addition to the Modelica models, Python scripts have also been developed to simulate specific components of the model and facilitate interaction with the Dymola simulation environment. The DREEM model is open access under the "GNU AFFERO GENERAL PUBLIC LICENSE[4]" and is available on GitHub[5].

Sectoral deep dives

In this section, we provide current and future trends with regard to the energy transition in the power and residential sectors in Greece.

Energy transition in the power sector by 2050

Between 2005 and 2021, the utilisation of fossil fuels in Greece's energy supply has significantly decreased, owing primarily to the decreased use of lignite, and resulting in lower shares of lignite-fired power generation, i.e., from 60% in 2005 to 10% in 2021, thus lowering the carbon intensity of electricity generation (IEA, 2023). The decrease in lignite-fired electricity generation was mainly offset by higher gas-fired generation and onshore wind

[4] https://www.gnu.org/licenses/agpl-3.0.txt
[5] https://github.com/TEESlab-UPRC/DREEM

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and solar PV capacity additions.

Natural gas has been given a significant role in eliminating the lignite-fired generation in key policy documents authorised before 2021 (Ministry of Environment and Energy, 2019b). However, natural gas, in contrast to lignite, is not a domestic fossil fuel and Greece is heavily reliant on Russia for gas imports. In fact, Russia contributed 41% of gas imports in 2021 (Statista Research Department, 2023). After the energy crisis of the past couple of years, the Greek government is currently reconsidering the role of natural gas in the national energy planning, which still remains uncertain. On the one hand, the country is taking significant steps to a lower dependence on Russian gas imports in order to meet its security and climate goals, while, on the other hand, significant expenditures are scheduled to expand gas infrastructure concurrently, which could increase the domestic demand for gas.

Moreover, Greece's electricity generation remains heavily reliant on oil, accounting for 7% of the total power production in 2021 compared to the IEA average of 2% in 2020 (IEA, 2023). Since most the oil-fired electricity is produced on islands, the government intends to gradually phase it out until 2030 by installing RES and connecting the most populous islands to the mainland's electricity grid.

Aiming to create a carbon-neutral power sector, the national energy planning will emphasise the use of RES for power generation. In an effort to guarantee affordable electricity prices and boost deployment rates, Greece recently made significant changes to its scheme supporting the development of renewable electricity. The country is also working on shortening the time required to license and permit RES, electricity infrastructure, and energy storage projects. August 2022 saw the enactment of its first offshore wind law, which aims to achieve 2 GW of offshore wind capacity by 2030 (HEREMA, 2022).

Greece also plans to invest significantly in its domestic electricity infrastructure. This includes improving its interconnection capacity to promote integration with Europe's electricity market, aiming at becoming a net electricity exporter (Kleanthis et al., 2022). The government has declared plans to triple the interconnection capacity with Albania, double the interconnection capacity with North Macedonia, Bulgaria, and Italy, and initiate an interconnection with Egypt (Hellenic IPTO, 2023). Significant investments are also planned to expand the domestic transmission and distribution capacity to accommodate increased wind, solar, and hydroelectric power.

In the context of all the abovementioned recent developments, and in view of the expected final version of the revised NECP, in this study, we aim at addressing the following RQ:

RQ_1: "What will be the required power and storage capacity, as well as the cost of transitioning to a RES-based future rather than continuing to rely on natural gas, be in order to meet carbon neutrality?"

Energy transition in the Greek residential sector by 2050

The European Union (EU)'s building sector accounts for approximately 40% of the final energy consumption and nearly one-third of the total CO_2 emissions. This underscores the significant imperative to decrease the sector's energy consumption and improve its environmental impact (Ruusu, Cao, Manrique Delgado, & Hasan, 2019). In this direction, various strategies, regulations, and directives have been been designed and implemented at the EU level, emphasising the pivotal role of energy-efficiency actions (Buildings Performance Institute Europe (BPIE), 2020). The significance of such actions has been underscored even more in light of the unexpected and extraordinary events of the past three (3) years, namely, the COVID-19 pandemic and the energy crisis resulting from Russia's invasion of Ukraine, which have raised considerable apprehensions regarding elevated energy prices and energy security (European Commission, 2022).

To address the implications of these events, the EU has formulated the "REPowerEU" plan, coupled with the "Fit for 55" package (2021), demonstrating the imperative need to gradually eliminate fossil fuels, including oil products and natural gas, from the building sector (European Commission, 2022). The objectives of these policy initiatives are primarily centered around: **(i).** reducing the EU's reliance on Russian natural gas, **(ii).** enhancing energy efficiency, **(iii).** progressively eliminating fossil-fuel boilers in buildings, and **(iv).** establishing a parallel Emission Trading System (ETS) for heating fuels in the building sector. This context is anticipated to exert additional pressure on the investments in alternatives to fossil fuels, such as electrification, in the upcoming years (European Commission, 2021, 2022). Eventually, the latter could not leave the EU Member States' energy transition planning and strategies, like their NECPs, unaffected.

In this context, the building sector in Greece, and specifically the residential sector, consumes almost one-quarter of the final energy consumption, and, therefore, is considered more than critical for the achievement of Greece's energy transition and security (IEA, 2020). Moreover, following the latest developments on the EU's energy landscape, Greece also amended its NECP, a final revised version of which is expected to be published by June 2024.

The current Greek NECP aims to achieve 60,000 household upgrades annually by 2030, focusing on enhancing energy efficiency either partially or full. Concurrently, the plan also aims to boost natural gas consumption, thereby increasing the country's energy dependency (Ministry of Environment and Energy, 2019b).

It is evident that this evolving energy policy framework in the EU will also impact the energy policy context in Greece. In this respect, and in view of the expected amendment of the Greek NECP, in this study, we seek to answer the following RQs:

RQ$_{2.1}$: "*Can the existing national planning lead to decarbonisation by 2050 in the residential sector?*"

RQ$_{2.2}$: "*Should Greece proceed with the current national planning, focusing on natural gas as a transition fuel in the residential sector, also increasing its energy dependence on fossil fuels?*"

RQ$_{2.3}$: "*What changes in the current national planning should take place in order for the residential sector to meet more effectively developments in the EU's energy policy landscape?*"

Scenario design and model parametrisation

In this section, we present the application of the OSeMOSYS-GR and DREEM models to the case of Greece in terms of the scenarios that the models were used to simulate, and their parameterisation based on the case study's characteristics and scenario specifications.

Note that input assumptions used in the two (2) models have been updated to match the specifications provided by the "**Deliverable 4.3: Broad scenario logic**" of the IAM COMPACT project. Specifically, technology data (i.e., capital costs, fixed and variable operating and maintenance costs, efficiencies, capacity factors, etc.) for the power and residential sectors have been retrieved from the EU Reference Scenario 2020 database (European Commission et al., 2021) and IEA's World Energy Outlook 2022 (IEA, 2022). Moreover, price projections were visually extracted from the World Energy Outlook 2022 report (IEA, 2022).

OSeMOSYS-GR

We explore least-cost capacity and electricity mixes that lead to a carbon-neutral power sector but differ in terms of the year that: **(i).** carbon neutrality is attained, and **(ii).** natural gas is phased out. According to Greece's recent climate commitments and key data projections, as these have partially been articulated in the revised draft NECP, carbon neutrality in the power sector can be achieved by 2042 (Hellenic Ministry of Environment and Energy, 2023b). Previous national long-term forecasts, such as the Long-term Strategy (LTS) of Greece, presented pathways that achieved full decarbonisation of the power sector by 2050 (Ministry of Environment and Energy, 2019a). Therefore, we included both scenarios with an earlier decarbonisation timeframe and others that achieve carbon neutrality at the end of the modelling horizon (i.e., 2050).

Furthermore, all scenarios include the current national energy planning with regard to phasing out lignite by 2028. Considering the uncertainty of the future of natural gas in the energy system, we opted for analysing scenarios with different assumptions regarding the use of natural gas for electricity generation. As such, we have included scenarios in which natural gas contributes to the electricity mix until 2050, either with the use of Carbon Capture and Storage (CCS), or not, and others in which natural gas is phased out due to the fast adoption rate of green technologies, or the natural gas phase out is enforced exogenously. Furthermore, all scenarios include the

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interconnections with Albania, North Macedonia, Bulgaria, Italy, and Cyprus. With regard to electricity imports from neighbouring countries, it is assumed that complete electricity independence (i.e., zero electricity imports) is achieved by 2050. This scenario design leads to differences in the technological configurations required to attain carbon neutrality. Based on the above, we define a total of four (4) different carbon-neutrality scenarios:

- "**Early Neutrality 1":** Carbon neutrality is attained by 2042 according to the emission target of the revised draft NECP. This scenario focuses on the capacity expansion of variable renewable energy (VRE), i.e., solar PV, wind onshore, and wind offshore, electricity storage, namely batteries and pumped hydro, and electrolysers for hydrogen production. Other RES technologies included in this scenario are geothermal, biomass, and hydro. In this scenario, the achievement of natural gas phase-out happens before 2042 due to the high adoption rate of green technologies.
- "**Early Neutrality 2":** This scenario also achieves carbon neutrality by 2042, following the same emission target as the "Early Neutrality 1" scenario. However, this scenario leads to carbon neutrality using CCS for natural gas and biomass power plants until 2050, assuming that all remaining natural gas and biomass power plants are retrofitted with CCS. It should be noted that despite aiming at reaching carbon neutrality by 2042 in the power sector, the revised draft NECP includes gas-fired power plants in the capacity and electricity mix by 2050, however, without explicitly mentioning the use of CCS, or carbon dioxide removal (CDR) technologies. This motivated us to explore a future power system with a different technological configuration than the "Early Neutrality 1" scenario. Besides the use of CCS, this scenario also invests in VRE, electricity storage, and hydrogen production technologies but at a lower rate compared to the "Early Neutrality 1" scenario. Other RES technologies assumed are the same as the "Early Neutrality 1" scenario.
- "**2050 Neutrality 1":** This scenario attains carbon neutrality by 2050, considering the different emission trajectories of the scenarios provided by the Greek LTS. However, in this scenario, we explore what would happen if a phase-out decision regarding the use of natural gas for electricity generation was taken. Specifically, in this scenario, we assume that the forced exogenous shutdown of gas-fired plants happens by 2040, while, oil and biomass power plants continue to operate after the shutdown of gas-fired plants. This scenario also includes VRE, electricity storage, hydrogen production, and other RES technologies, as in the previous two (2) scenarios.
- "**2050 Neutrality 2":** This scenario assumes the same emission limit projections as the "2050 Neutrality 1" scenario. The only difference is that the shutdown of the gas-fired plants happens by 2045 and is calculated endogenously. Investments in VRE, electricity storage, hydrogen production, and other RES technologies assumed are the same as in the previous scenarios.

DREEM

To investigate the energy transition in the Greek residential sector up to 2050, we simulated six (6) scenarios (Table 9). "**Scenarios 1-4**" are grounded in the existing NECP's renovation rate, specifying a total of 60,000 renovations per year. More specifically, "**Scenario 1**" is based on the current NECP's targets, mainly focusing on using natural gas as a mid-transition fuel, while "**Scenario 2**", "**Scenario 3**", and "**Scenario 4**" focus on investing in electrification, differing in the timeline of the natural gas' phase out (i.e., starts in 2036, starts in 2031, or starts in 2023, respectively).

On the other hand, for the "**Scenario 5**" and the "**Scenario 6**", a reverse engineering approach is applied. In particular, in all these four (4) scenarios (i.e., "**Scenario 5_a**", "**Scenario 5_b**", "**Scenario 6_a**", and "**Scenario 6_b**"), decarbonisation by 2050 and 2040, respectively, in the Greek residential sector is the main target; so, the annual renovation rate required is investigated. In addition, for all these scenarios, a further investigation is conducted regarding the environmental and financial impacts of investing in natural gas and electrification. Financial aspects include among others, fuel, renovation, and parallel Emissions Trading System/Scheme (ETS) costs.

Table 9*.* Scenarios for the energy transition in the Greek residential sector in Greece by 2050.

Scenarios	Period	Interventions foreseen
1. "Existing national planning"	(2023-2030)	Yearly penetration of natural gas in alignment with the existing NECP's 2030 targets, constituting 15.1% of the total consumption. Annual adoption rates to achieve a 300% increase in heat pump installations.
	(2031-2035)	Replacement of new natural gas boilers with heat pump installations.
	(2036-2050)	Phase out of the existing natural gas boilers throught the adoption of heat pump installations.
2. "Focusing on electrification #1"	(2023-2050)	60,000 yearly oil boiler substitutions with heat pump installations.
	(2036-2050)	Phase out of the existing natural gas boilers throught the adoption of heat pump installations.
3. "Focusing on electrification #2"	(2023-2050)	60,000 yearly oil boiler substitutions with heat pump installations.
	(2030-2050)	Phase out of the existing natural gas boilers throught the adoption of heat pump installations.
4. "Interdependence from natural gas"	(2023-2050)	Phase out of the existing oil and natural gas boilers throught the adoption of heat pump installations.
"Reverse engineering" scenarios		
5_a. "Decarbonisation by 2050: Focusing on natural gas by 2030"	(2023-2030)	Yearly penetration of natural gas in alignment with the existing NECP's 2030 targets, constituting 15.1% of the total consumption. The remaining dwellings substitute their oil boilers with heat pump installations.
	(2031-2050)	Phase out of the existing oil and natural gas boilers throught the adoption of heat pump installations.
5_b. "Decarbonisation by 2050: Focusing on electrification"	(2023-2050)	Replacement of oil and natural gas boilers with heat pump installations.
6_a. "Decarbonisation by 2040: Focusing on natural gas by 2030"	(2023-2030)	Yearly penetration of natural gas in alignment with the existing NECP's 2030 targets, constituting 15.1% of the total consumption.

	(2031-2040)	The remaining dwellings substitute their oil boilers with heat pump installations. Phase out of the existing oil and natural gas boilers throught the adoption of heat pump installations.
6b. "Decarbonisation by 2040: Focusing on electrification"	(2023-2040)	Replacement of the existing oil and natural gas boilers with heat pump installations.

In all the scenarios, for the dwellings built before 2010, and whose heating systems are replaced, renovation actions regarding energy performance upgrades to their building envelope and windows also take place, as follows: **(i).** Dwellings constructed prior to 1981: Exterior wall insulation & window upgrades, and (ii). Dwellings constructed during the period 1981-2010: Exterior wall insulation.

4.3 Results

This section presents and discusses the resulting changes in energy supply and demand, including critical trade-offs, energy system costs, and diversification of import sources, as documented in the case study and scenario specifications presented in the sections above.

Energy transition by 2050 in the Greek power sector

We present modelling results on carbon emissions, power and storage capacity additions, electricity dispatch, as well as capital, operating, and variable costs, while adhering to the emission and RES generation targets.

Between 2025 and 2035, we observe a steep emission reduction in the "Early Neutrality" scenarios, while "2050 Neutrality" scenarios follow a more linear emission reduction trend (Figure 24). In 2025, lignite will maintain a large share of the total CO_2 emissions (39.5% in "Early Neutrality 1", 36.5% in "Early Neutrality 2", 36% in "2050 Neutrality 1", and 36.5% in "2050 Neutrality 2"). However, in 2025 and 2030, natural gas will become the predominant source of CO_2 emissions (54.6% and 84.5% in "Early Neutrality 1", 58.1% and 84% in "Early Neutrality 2", 58.5% and 94.4% in "2050 Neutrality 1", 58% and 91.8% in "2050 Neutrality 2"). In 2030, the CO_2 emission reduction is more than 90% compared to the 2005 level in the "Early Neutrality" scenarios (90.3% in "Early Neutrality 1" and 90.6% in "Early Neutrality 2") and more than 80% compared to the 2005 levels in the "2050 Neutrality" scenarios (81% in "2050 Neutrality 1" and 80.2% in "2050 Neutrality 2"). Therefore, only the "Early Neutrality" scenarios achieve the target of 89% CO_2 emission reduction in 2030 compared to the 2005 levels, as outlined by the revised draft NECP.

In 2035, there is a sudden drop in the CO_2 emissions from natural gas and biomass in the "Early Neutrality 2" scenario, owing to retrofitting CCS to the existing natural gas and biomass power plants. On the contrary, CO_2 emissions owing to natural gas remain at relatively high levels, i.e., ~6.7 $MtCO_2$ in the "2050 Neutrality" scenarios. After 2035, we see an abrupt drop in the emissions of the "2050 Neutrality 1" scenario due to the forced shutdown of the gas-fired power plants. It should be noted that the use of CCS for natural gas and biomass power plants in the "Early Neutrality 2" scenario will not eliminate carbon emissions on its own, considering that the CCS units can only capture ~90% of the CO_2 of combustion fuels. This means that carbon dioxide removal technologies should also be implemented to absorb the remaining carbon emissions of the power sector. In 2050, all four (4) scenarios under study achieve the target of a carbon-neutral power sector compared to the 2005 levels.

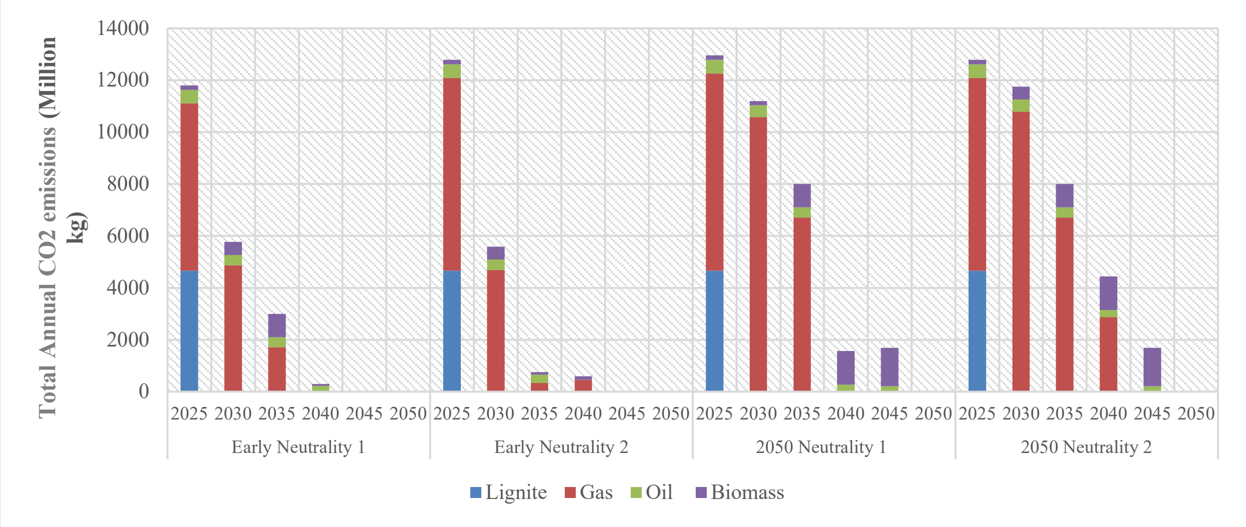

Figure 24. Total annual CO_2 emissions for the "Early Neutrality 1", "Early Neutrality 2", "2050 Neutrality 1", and "2050 Neutrality 2" scenarios.

Our findings indicate that the scenarios that achieve degasification before 2050 (i.e., "Early Neutrality 1", "2050 Neutrality 1", and "2050 Neutrality 2") can only be realised through the faster adoption of RES and storage technologies when compared to the scenario without degasification (i.e., "Early Neutrality 2") (Figure 25). In fact, the "Early Neutrality 1" scenario has the highest average adoption rate of VRE and storage technologies, which allows degasification to be completed by 2037, three (3) years before the "2050 Neutrality 1" scenario. By 2030, more than 20 GW of VRE technologies will be installed among the four (4) scenarios under study (24 GW in "Early Neutrality 1", 22.8 GW in "Early Neutrality 2", 21.8 GW in "2050 Neutrality 1", and 20.4 GW in "2050 Neutrality 2"). By 2040, the VRE capacity will increase to more than 45 GW among the four (4) scenarios (50.6 GW in "Early Neutrality 1", 45.9 GW in "Early Neutrality 2", 46.5 GW in "2050 Neutrality 1", and 45.5 GW in "2050 Neutrality 2"). At the same time, the capacity of electricity storage and hydrogen production technologies will grow significantly to match the high VRE capacity expansion (27.8 GW in "Early Neutrality 1", 21.6 GW in "Early Neutrality 2", 27.3 GW in "2050 Neutrality 1", and 23.2 GW in "2050 Neutrality 2").

By 2050, the VRE capacity will increase to 70.4 GW in the "Early Neutrality 1" scenario, 60.5 GW in the "Early Neutrality 2" scenario, 68.1 GW in the "2050 Neutrality 1" scenario, and 71.2 GW in the "2050 Neutrality 2" scenario, respectively. In parallel, energy storage capacity will increase to 47.4 GW in the "Early Neutrality 1" scenario, 29.3 GW in the "Early Neutrality 2" scenario, 41.6 GW in the "2050 Neutrality 1" scenario, and 44.9 GW in the "2050 Neutrality 2" scenario. The difference between the installed VRE and energy storage capacities among the "Early Neutrality" scenarios highlights the importance of the baseload capacity to the operation of the power system. Interestingly, the "2050 Neutrality 2" scenario, which achieves shutdown of the gas-fired plants by 2045, requires slightly more VRE and battery storage and electrolyser capacity than the "2050 Neutrality 1" scenario, which assumes forced gas-fired plants shutdown five (5) years earlier. This can be attributed to the lack of pumped hydro storage capacity addition between 2035 and 2040 and to the lower geothermal capacity addition between 2045 and 2050 due to the slowed-down gas-fired plant shutdown in this scenario.

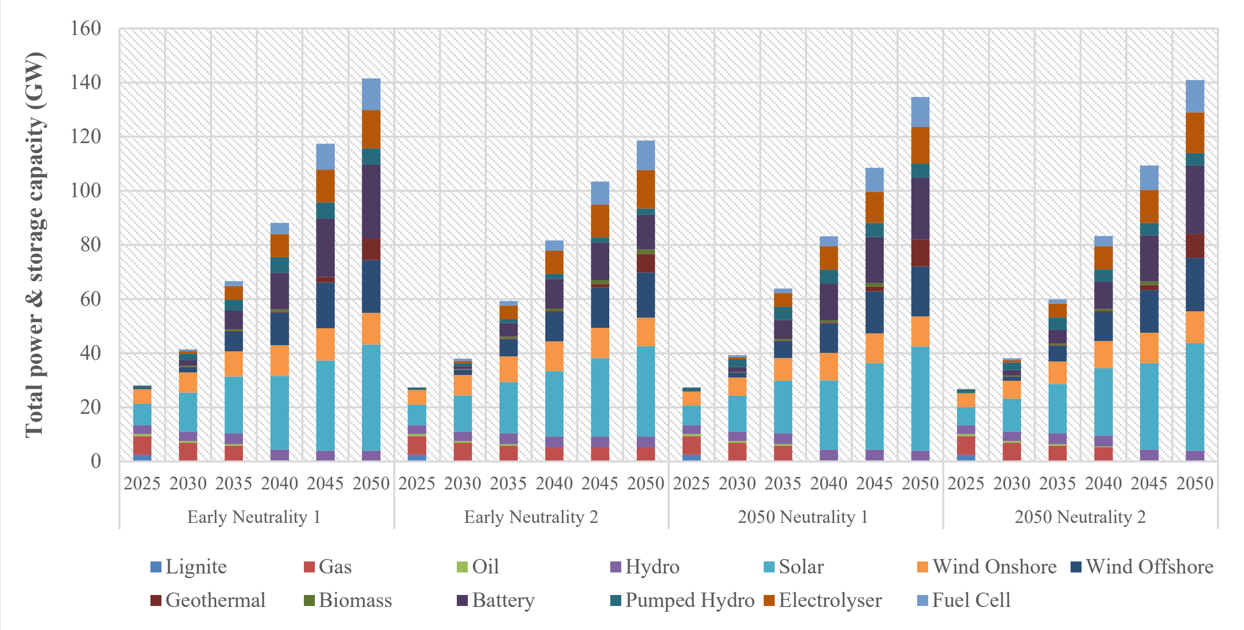

Figure 25. Least-cost total power and storage capacity mixes for the "Early Neutrality 1", "Early Neutrality 2", "2050 Neutrality 1", and "2050 Neutrality 2" scenarios.

Modelling results also show that RES, electricity storage, and fuel cell technologies cover at most ~70% of the total annual electricity generation in 2030 (70.2% in "Early Neutrality 1", 69.5% in "Early Neutrality 2", 57.9% in "2050 Neutrality 1", and 55.9% in "2050 Neutrality 2") (Figure 26). This means that none of the four (4) scenarios reaches the ambitious target of 80% RES share in the net electricity generation by 2030, as outlined by the revised draft NECP. These shares increase significantly by 2040 (93.7% in "Early Neutrality 1", 88.3% in "Early Neutrality 2", 93.3% in "2050 Neutrality 1", and 88.8% in "2050 Neutrality 2") due to the rapid decrease of the fossil-fired electricity generation between 2030 and 2040 (-16% in "Early Neutrality 1", -10.8% in "Early Neutrality 2", -28.8% in "2050 Neutrality 1", and -26.3% in "2050 Neutrality 2").

By 2050, the share of RES, electricity storage, and fuel cell technologies covers 100% of the electricity mix in all the scenarios except for the "Early Neutrality 2" scenario (94.8%). All the scenarios achieve the target of 93.5% RES share in the net electricity generation by 2050, as articulated by the revised draft NECP. Fossil fuels cover the remaining share of the total annual electricity generation (electricity imports are assumed to be zero in 2050). Therefore, in the "Early Neutrality 2" scenario, the use of CCS will allow natural gas to contribute with a 5.2% share to the electricity mix in 2050. Furthermore, in 2050, curtailment and/or electricity exports from VRE technologies amount to 12% in "Early Neutrality 1" scenario, 5.8% in the "Early Neutrality 2" scenario, 11.2% in the "2050 Neutrality 1" scenario, and 12.4% in the "2050 Neutrality 2" scenario. The differences between the scenarios show the importance of dispatchable power plants, as in the "Early Neutrality 2" scenario, which achieves the lowest curtailment, and storage capacity, considering that the "2050 Neutrality 2" scenario has less storage than the "2050 Neutrality 1" scenario.

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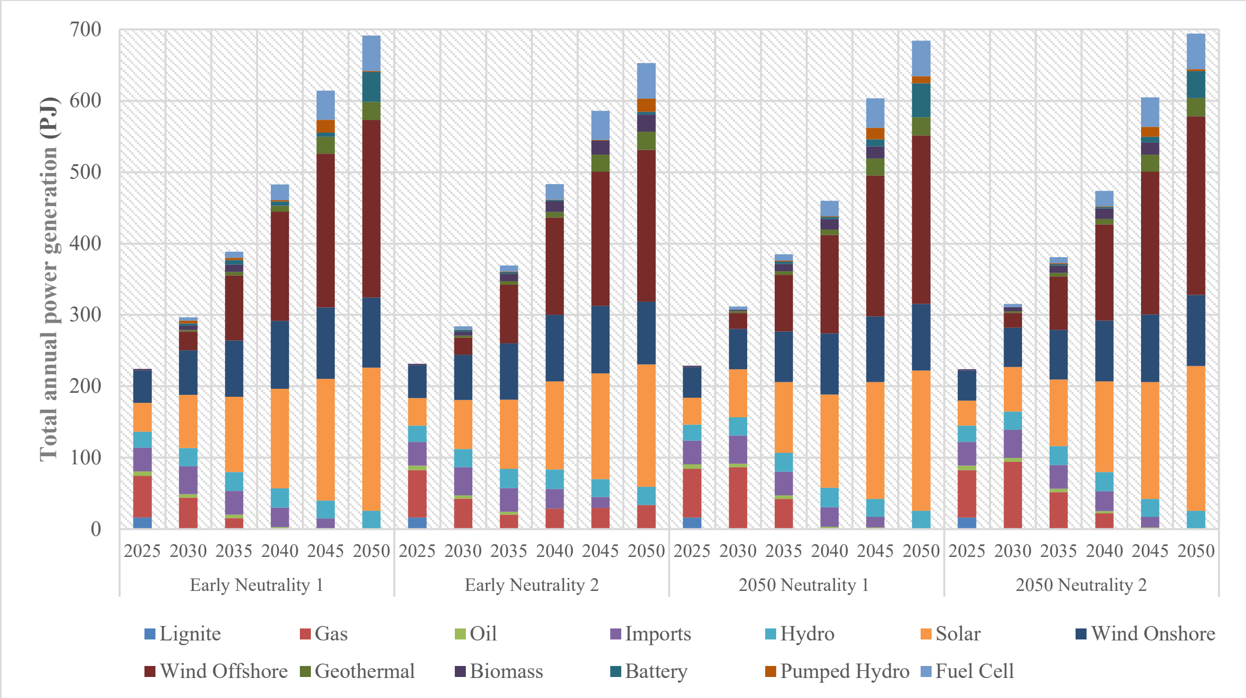

Figure 26. Least-cost total annual power generation mixes for "Early Neutrality 1", "Early Neutrality 2", "2050 Neutrality 1", and "2050 Neutrality 2" scenarios.

Furthermore, results from all four (4) scenarios under study suggest that a carbon-neutral and ~100% RES-based power sector will require significant investments in multiple RES and storage technologies (Figure 27). Specifically, the capital investment share in the accumulated total levelised electricity cost will be less than 17.8% by 2025 and more than 50% by 2050 across all the scenarios, reaching 58.5% by 2050 for the "Early Neutrality 1" scenario. Respectively, the sum of the variable operating cost and emission penalty shares in the accumulated total levelized electricity cost is more than 69.2% in 2025 and less than 27.4% in 2050 across all the scenarios. This means that the energy transition will alter the cost structure of the power sector, cutting the variable operating costs as well as the costs owing to the emission penalties of the fossil-fired power plants, while boosting capital expenditures for green technologies.

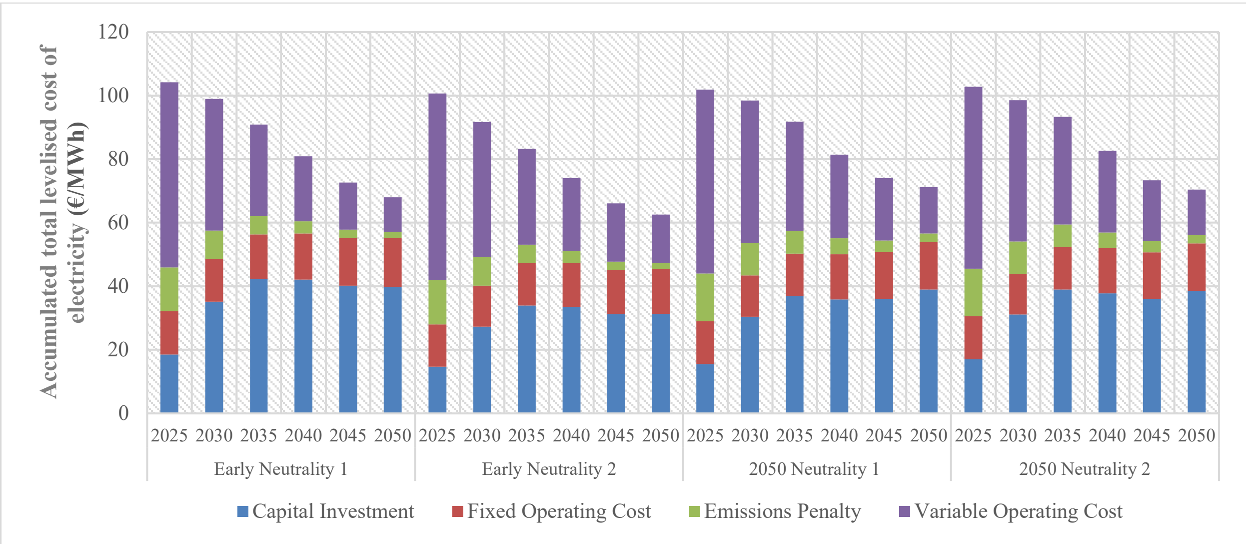

Figure 27. Accumulated total levelized cost of electricity for the "Early Neutrality 1", "Early Neutrality 2", "2050 Neutrality 1", and "2050 Neutrality 2" scenarios.

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Energy transition in the Greek residential sector by 2050

Simulation results for "Scenarios 1-4" (renovation rate of 60,000 dwellings, equivalent to approximately 1.3% annually), indicate that accomplishing decarbonisation in the Greek residential sector by 2050 is not viable. As shown in Figure 28, none of the first four (4) scenarios lead to the elimination of fossil fuels (i.e., heating oil and natural gas) from the final energy mix by 2050, while when the focus is mainly on the use of natural gas as a transition fuel (i.e., "Scenario 1"), the overall amount of the energy coming from fossil fuels is increased compared to the "Scenarios 2-4".

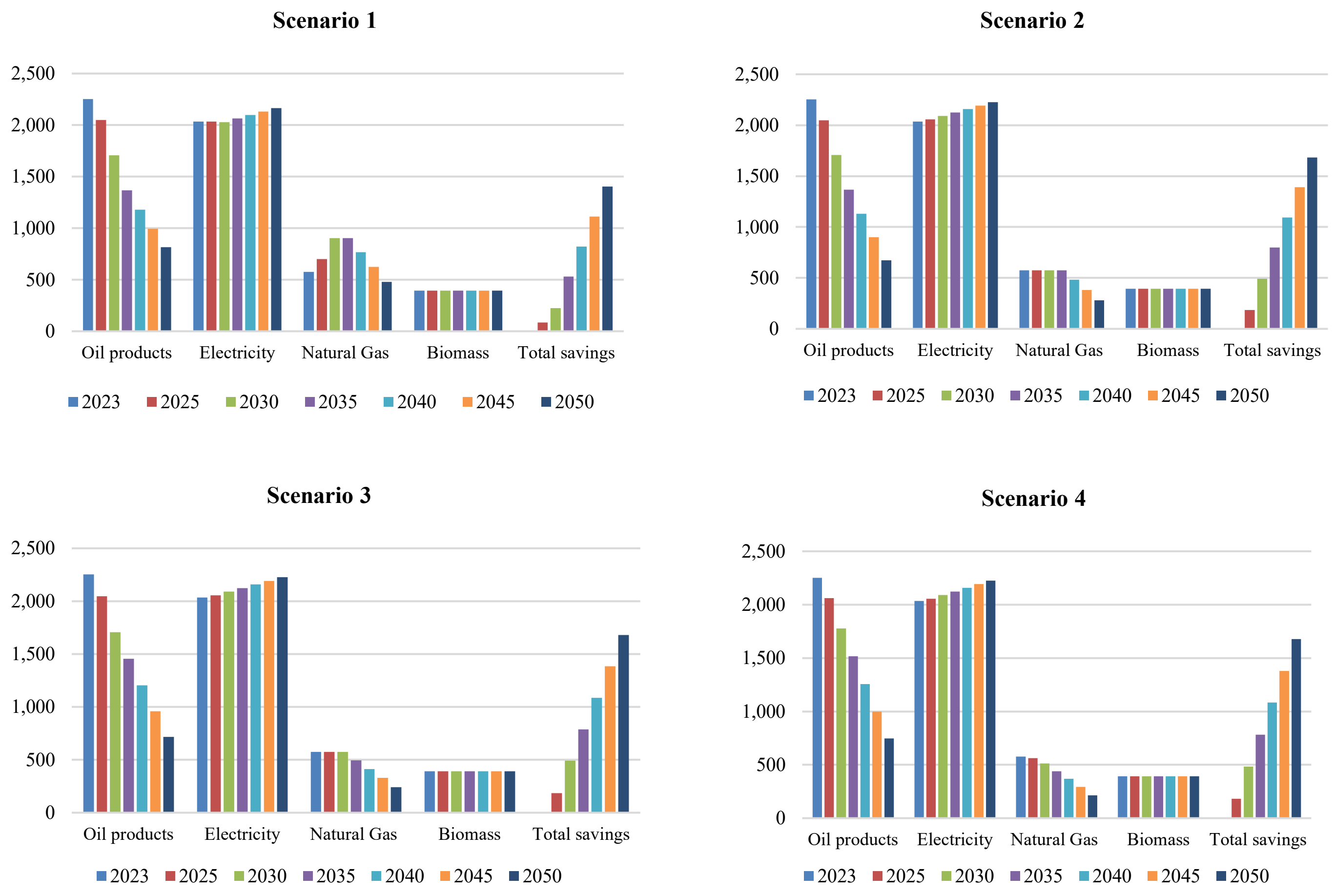

Figure 28. Final energy mix and energy savings in the Greek residential sector by 2050, under "Scenarios 1-4".

Considering these findings, we applied a reverse engineering approach in the DREEM model to identify the required renovation rate in order towards decarbonisation in the residential sector by 2050 and 2040, respectively (Figures 29-30). We find that in order to achieve complete decarbonisation by 2050, around 100,000 dwellings should be renovated annually (or roughly a 2.5% annual renovation rate); in contrast, if complete decarbonisation by 2040 is the goal, 145,000 dwellings must be renovated annually (or roughly a 3.5% annual renovation rate).

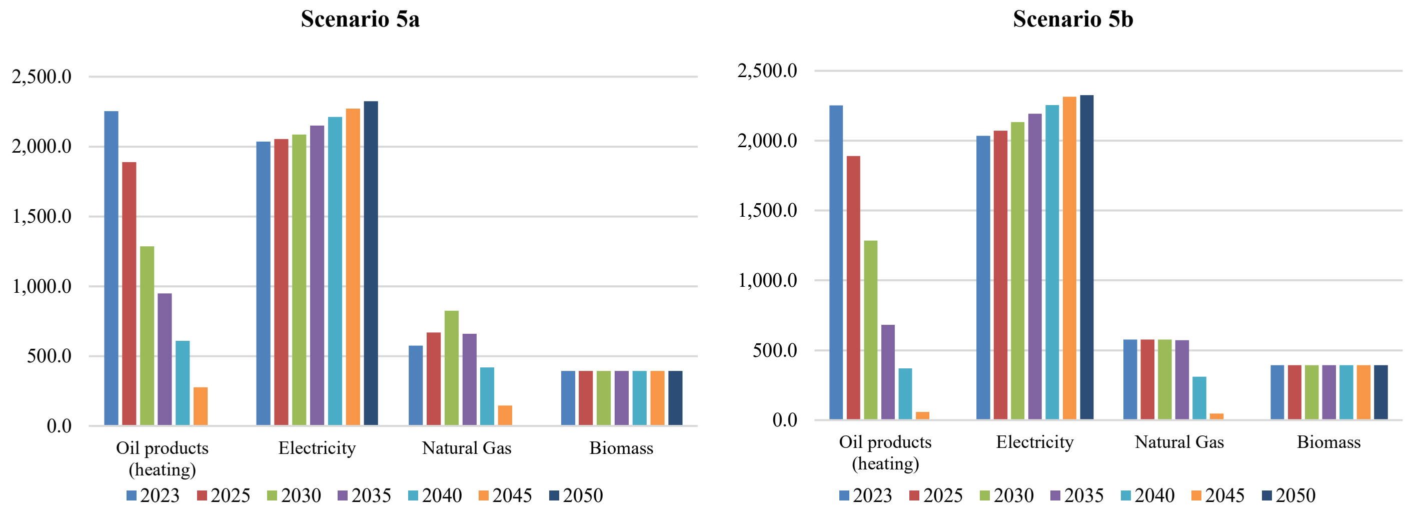

Figure 29. Final energy mix (ktoe) in the Greek residential sector by 2050 for the "Scenario 5a: Decarbonisation by 2050: Focusing on natural gas by 2030" and the "Scenario 5b: Decarbonisation by 2050: Focusing on electrification".

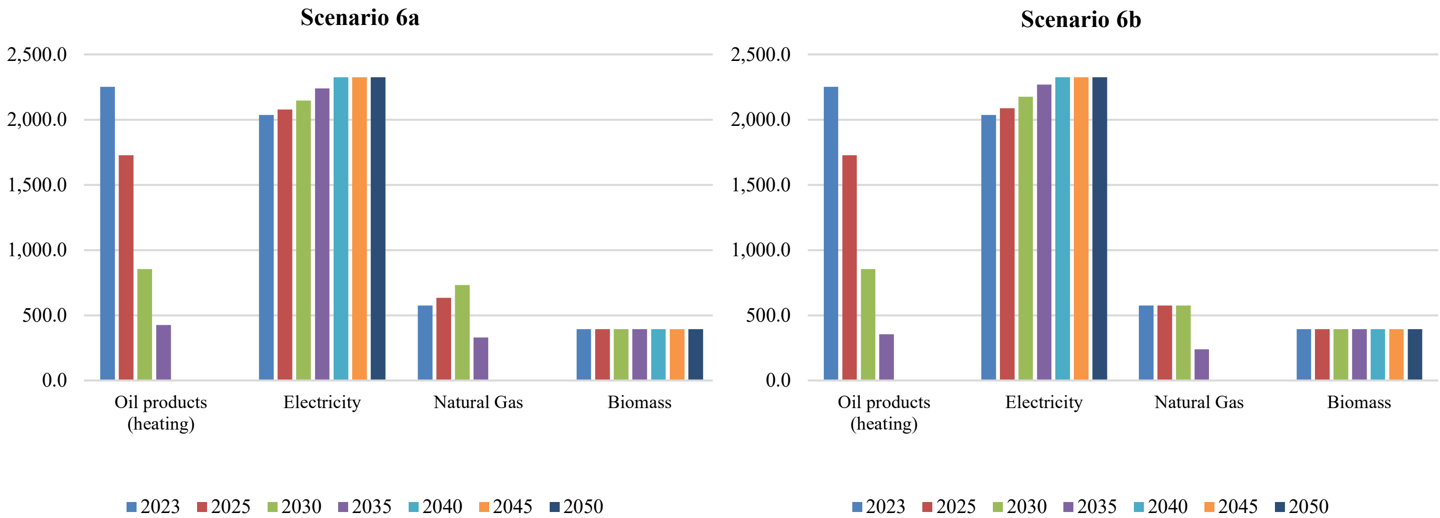

Figure 30. Final energy mix (ktoe) in the Greek residential sector by 2040 for the "Scenario 6a: Decarbonisation by 2040: Focusing on natural gas by 2030" and the "Scenario 6b: Decarbonisation by 2040: Focusing on electrification".

Following the calculation of the final energy mix, simulation results extracted useful findings regarding each scenario's environmental footprint and economic implications when it comes to the expected inclusion of the EU's building sector in a parallel ETS. As presented in Figures 31-32, towards decarbonisation, the adoption of heat pump installation results in reduced environmental impact and, thus, ETS-relevant costs, as less tonnes of CO_2 are emitted. Finally, when comparing the two different decarbonisation scenarios (i.e., "Scenario 5_a", "Scenario 5_b", "Scenario 6_a", and "Scenario 6_b"), decarbonisation in the Greek residential sector by 2040 also leads to a better environmental footprint, with less ETS-relevant costs than decarbonisation by 2050.

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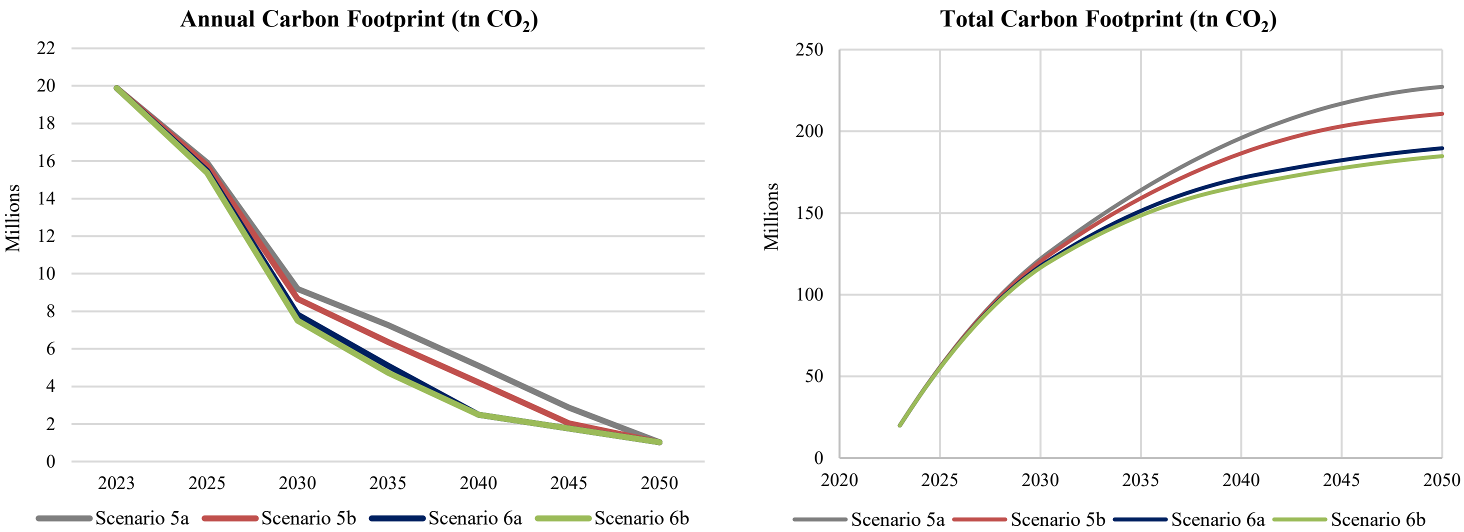

Figure 31. Environmental footprint under the decarbonisation scenarios (i.e., "Scenario 5a", "Scenario 5b", "Scenario 6a", and "Scenario 6b"): Annual and total carbon footprint (tn CO2) in the Greek residential sector by 2050.

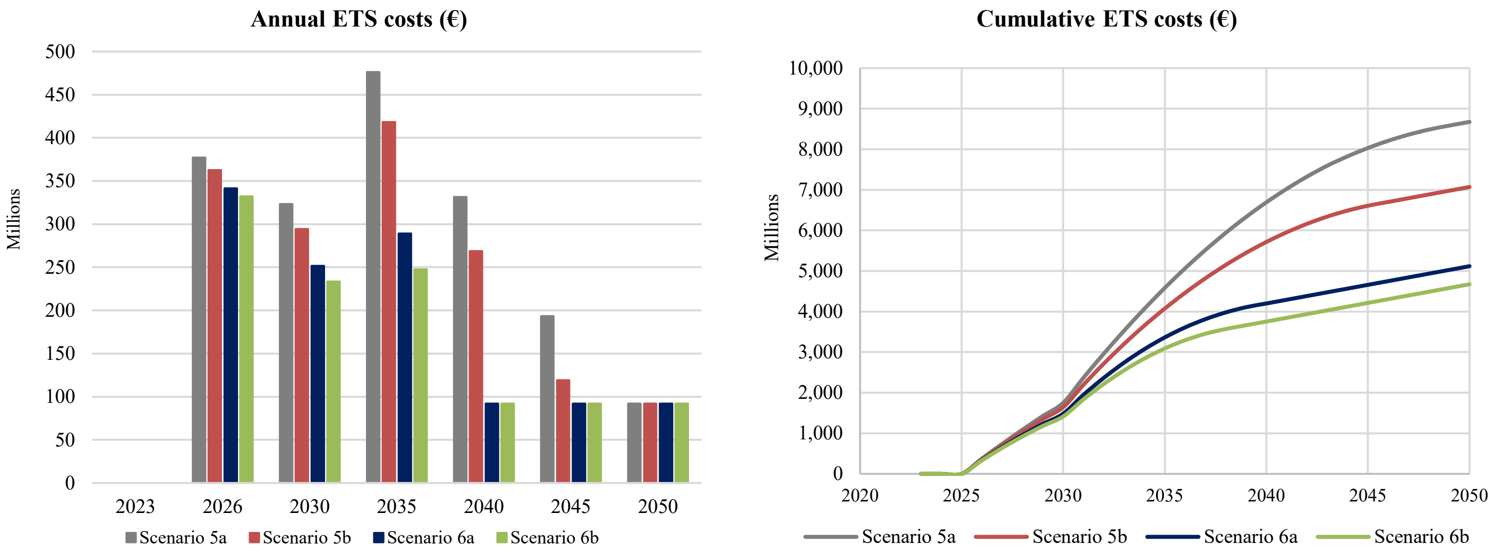

Figure 32. Costs (millions of €) by 2050 due to the Greek residential sector's inclusion to the Emissions Trading System/Scheme under the decarbonisation scenarios (i.e., "Scenario 5a", "Scenario 5b", "Scenario 6a", and "Scenario 6b").

In terms of the economic implications within each decarbonisation scenario, as shown in Figure 33, scenarios focusing on decarbonisation by 2040 (i.e., "Scenario 6_a" and "Scenario 6_b"), as well as on electrification (i.e., "Scenario 5_b" and "Scenario 6_b") lead to higher renovation costs.

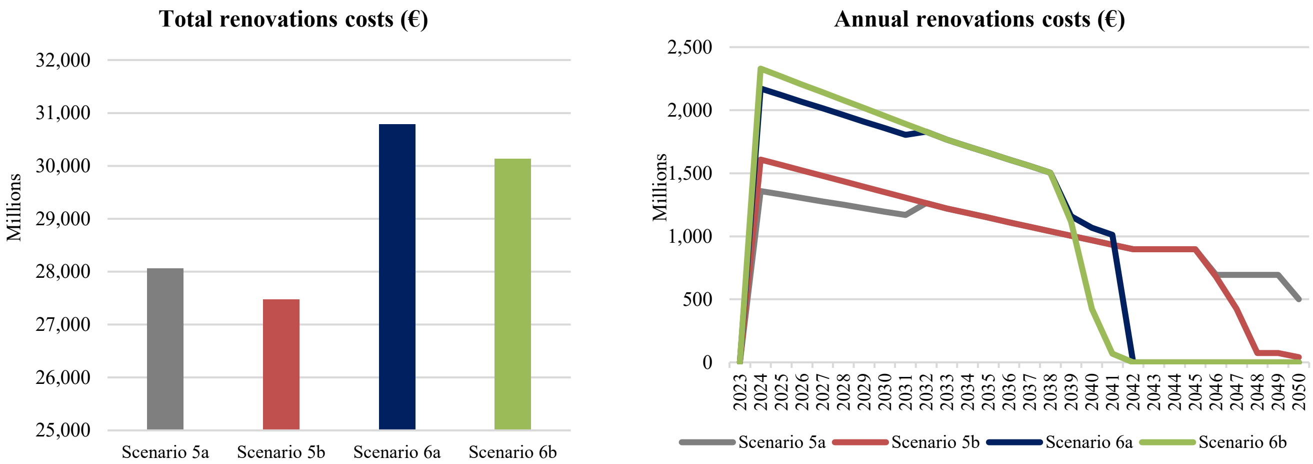

Figure 33. Total renovation costs by 2050 under the decarbonisation scenarios (i.e., "Scenario 5a", "Scenario 5b", "Scenario 6a", and "Scenario 6b").

Finally, we calculate the total energy transition costs (i.e., ETS-relevant, renovation, and fuel costs) by 2050, both at the household and the national level, for both decarbonisation by 2050 (i.e., "Scenario 5_a" and "Scenario 5_b") and decarbonisation by 2040 (i.e., "Scenario 6_a" and "Scenario 6_b"), respectively (Table 10). Results indicate that despite higher renovation costs, overall, earlier decarbonisation and electrification lead to more economic benefits both at the household and the national level, as they lead to lower annual extra charges and fuel costs in all potential price evolution cases.

Table 100*.* Total energy transition costs, both at the household and the national level, in the case of decarbonising the Greek residential sector by 2050 (i.e., "Scenario 5_a" and "Scenario 5_b") and 2040 (i.e., "Scenario 6_a" and "Scenario 6_b"), respectively.

Total costs by 2050 (€)	**Household level**	**National level**
Scenario 5_a	46,033-78,715	187.6-320.9 billion
Scenario 5_b	44,331-74,305	180.7-302.9 billion
Scenario 6_a	42,925-70,421	175.0-287.0 billion
Scenario 6_b	42,416-68,753	172.9-280.2 billion

In summary, our research illuminates diverse energy transition patways in the Greek residential sector by 2050, with the aim to offer policymakers and other key stakeholders valuable insights and recommendations, particularly in light of the recent developments in the EU's energy market and the upcoming finalisation of the revised draft Greek NECP. Our results underscore the necessity of setting more ambitious goals to achieve the EU's decarbonisation targets and prioritising investments in electrification over natural gas.

4.4 Conclusion

Policy recommendations for the Greek power sector

When it comes to the energy transition by 2050 in the Greek power sector, our simulation results imply that the government should accelerate pending reforms to accomplish a just and cost-efficient green energy transition while securing electricity supply. Simulation results also suggest that significant investments in VRE will be required among all the scenarios under study to achieve decarbonisation. This will request for a transparent and stable regulatory environment that enables the timely implementation of RES and electricity infrastructure projects.

In this regard, spatial planning and licencing procedures should be expedited to encourage timely project deployment on time. At the local level, where people are more sensitive to the effects of climate change and opposition to VRE projects emerges, efforts should be made to raise public understanding and awareness on policies promoting VRE technologies. Therefore, collaborating with communities and power sector stakeholders is critical in defining priority areas for the further deployment of RES technologies to facilitate rigorous and speedy licencing and grid connections, while balancing environmental and cultural challenges, land uses, and grid costs.

As shown by our findings, decarbonisation in the Greek power sector will also necessitate additional investments in energy storage technologies so that high VRE penetration levels can be handled by the electricity system. In this context, national policymaking should prioritise the establishment of VRE plants combined with storage. Furthermore, hydrogen storage and production using VRE electricity could be an effective solution for non-interconnected systems; considering hydrogen storage and production applications, the coupling of electricity and gas networks should be examined. The required legal and regulatory framework for offshore wind, energy storage, renewable hydrogen, and smart grids should be developed and put in place for the years to come.

Furthermore, according to the derived decarbonisation pathways, we find that there will be a path dependency on natural gas at least until 2037. Greece's decision to phase out lignite by 2028 is projected to sustain its reliance on gas, rather than accelerate the transition to a 100% RES-based power sector. This is owing to national planning decisions that have prioritised natural gas as the main energy source that can cost-effectively replace lignite on a large scale in the short and medium term. Considering this outcome and the 2022 energy crisis' implications, Greece should improve its energy security by diversifying gas supplies by origin and path of delivery, as well as reducing gas demand through increased deployment of RES.

In addition, modelling results also show that natural gas could be phased out between 2037 and 2044 at the latest. Thus, it is probable that newly built natural gas power plants will become stranded assets. In this respect, policymakers should evaluate the necessity for investments in new fossil-fuel infrastructures, taking into account the risk of stranded assets and the need to redirect funds towards initiatives that facilitate the energy transition. If the decision of phasing out natural gas is not taken, CCS and CDR technologies would be required to offset the carbon emissions from natural gas. However, there has been some scepticism against CCS investments in Greece due to economic viability concerns, regulatory hurdles, and public acceptance.

Policy recommendations for the Greek residential sector

Our work illuminates the energy transition by 2050 in the Greek residential sector, also considering the upcoming finalisation of the revised draft NECP by June 2024. The initial set of scenarios under study focused on the current renovation rate (60,000 dwellings/year) foreseen by the NECP, all of which, according to simulation results fail to achieve the target for decarbonisation and independence from fossil fuels by 2050, also considering the respective EU's policy planning.

In this context, new scenarios were investigated to identify the required renovation rate in order to achieve decarbonisation by 2050 and 2040. Simulation results on these new scenarios showed that if the goal is to achieve complete decarbonisation in the Greek residential sector by 2050, the renovation rate should increase to around 100,000 dwellings/year (40,000 dwellings more than the current provision, i.e., ~2.5% of the housing stock), while, if more ambitious targets are to be set (considering recent political announcements) for decarbonising the residential sector by 2040, then the renovation rate should increase to around 145,000 dwellings/year (85,000 dwellings more than the current provision, i.e., ~3.5% of the housing stock).

In this regard, our findings second a potential turn towards a more ambitious policy planning, i.e., a decarbonisation target by 2040 and a focus on electrification, rather than on natural gas as a transition fuel in the residential sector too, as is the current national planning. In particular, we find that scenarios towards decarbonisation by 2040 lead to lower final energy consumption earlier in comparison to scenarios towards decarbonisation by 2050, which also leads to a more positive environmental footprint. Additionally, investing in electrification results in lower annual and cumulative CO_2 emissions, as natural gas is phased out much earlier from the final energy mix.

Simulation results also suggest that ambitious policy planning could also lead to lower costs; decarbonisation by 2040 and investing in electrification eventually lead to reduced total annual extra charges and fuel costs for households. These costs include charges from the expected expansion of the EU's ETS to the building sector, building intervention costs (e.g., heating systems' replacement, building envelopes' upgrades, etc.) and fuel costs/prices. This means that despite the heavier upfront investment costs foreseen in the case of electrification due to the higher installation costs of heat pumps compared to the other technologies', these costs are counterbalanced over time, by the significantly lower ETS and fuel costs induced by more efficient heating systems, also considering the expected radical decrease in the heat pumps' capital costs over the next decade, as also envisaged by the European Heat Pump Association (EHPA).

In this context, our modelling results suggest two (2) main recommendations for the next round of revisions of the NECP: **(i).** increase in the annual renovation rate to achieve decarbonisation by 2050 or 2040 (~2.5% and ~3.5% of the housing stock, respectively) and **(ii).** a strategic focus on electrification as early as possible.

Doing so is of great necessity for another reason too; Greece is ranked among the countries with higher energy poverty rates in the EU, as more than one quarter of the Greek households are considered unable to keep their homes adequately warm in winter, while the arrears in utility bills are high (more than 38% of households) (Papada & Kaliampakos, 2020). Therefore, national planning needs to focus on provisions that address societal needs to a greater extent, leading to more financial benefits for consumers. In this respect, Greece should choose increased renovation rates and electrification, instead of investments in fossil-fuel infrastructures, to reduce energy poverty, also promoting sustainability and environmental awareness.

Moreover, considering the latest experience from the Russian-Ukraine war, it is evident that sticking to the current planning, i.e., focusing on natural gas as a transition fuel and not investing in electrification and energy efficiency, increases the domestic energy dependency, making the country more vulnerable to the risk of being prone to geopolitical games with all the subsequent dangerous consequences for the economy and the society.

Finally, the EC's technical guidance for climate-proofing infrastructural projects between the period 2021-2027 and the adoption of the "*Energy Efficiency First*" principle as a guiding criterion for evaluating investments may pose a risk to investments towards the expansion of the natural gas infrastructure in Greece. Nevertheless, despite the new climate policy framework established by the EC, Greece, along with other Member States, still takes advantage of a legislative "window" that allows the financing of new fossil-fuel infrastructure from public or EU's funding, i.e., the unspent amounts from the previous 2014-2020 Operational Programmes, as evident in the case of the new natural gas grid infrastructure in the Peloponnese region. The latter can lead to stranded assets given that they will need to be refinanced within their payback period (typically 15-20 years). Therefore, public funding will be once again required to move to cleaner fuels in alignment with the EU's energy transition objectives.Hence, to mitigate these uncertainties and protect households- especially those most vulnerable to energy poverty- national planning should shift towards an approach that prioritises energy efficiency and electrification. In this direction, Greece could use available funding from packages like the National Strategic Reference Framework and the National Recovery and Resilience Plan (NRRP) to develop new, or upgrade existing national subsidy programmes and finance investments that focus mainly on electrification (e.g., replacing oil boilers with heat pump installations, etc.) as well as to increase the allocated budget on residential energy-efficiency programmes, like in the case of the "Saving at home" programme.

Further research

Additional research should examine the key issues and challenges related to the Greek energy transition, such as just transition in areas affected by the lignite phaseout, energy poverty and vulnerable households, market reforms, etc., as well as look into transport and industry, which were not investigated in this study and have the most hard-to-abate segments like aviation, shipping, steel making, cement, etc. Furthermore, future modelling work should capture the interdependencies between the power and the residential sector, considering that the electrification of the residential sector, which requires heat pumps, and its transition to onsite generation technologies, such as rooftop PV, can significantly affect the evolution of electricity demand and the electricity

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mix. In this regard, a soft-linking process between the two (2) models would further elicit these trends and provide additional useful policy insights to decision-makers and other policy-relevant actors.

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5 Annex A: Energy system scenario data for EU

Parameter	Unit	Scenario	Model	Value
Power plant and CHP capacity	GW	Smart Energy Europe (2050)	EnergyPLAN	644.00
Damned hydropower	GW	Smart Energy Europe (2050)	EnergyPLAN	154.00
Nuclear	GW	Smart Energy Europe (2050)	EnergyPLAN	0.00
Dispatchable power capacity	GW	Smart Energy Europe (2050)	EnergyPLAN	798.00
Electrolysis	GW	Smart Energy Europe (2050)	EnergyPLAN	502.00
Offshore wind	GW	Smart Energy Europe (2050)	EnergyPLAN	295.00
Onshore wind	GW	Smart Energy Europe (2050)	EnergyPLAN	1,600.00
Photovoltaics	GW	Smart Energy Europe (2050)	EnergyPLAN	1,050.00
Total electricity demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	7.980
Total inflexible electricity demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	4.41
Traditional and additional electricity demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	3.40
Peak total electricity demand	GW	Smart Energy Europe (2050)	EnergyPLAN	1,890.00
Peak inflexible electricity demand	GW	Smart Energy Europe (2050)	EnergyPLAN	757.00
Peak Traditional and additional electricity demand	GW	Smart Energy Europe (2050)	EnergyPLAN	548.00
Total heat demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	2.29
Total individual heat demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	1.02
Total district heating demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	1.27
Peak individual heating demand	GW	Smart Energy Europe (2050)	EnergyPLAN	277.00
Peak district heating demand	GW	Smart Energy Europe (2050)	EnergyPLAN	298.00
Power plants and CHP (Coal)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Power plants and CHP (Natural gas)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.19
Power plants and CHP (Biomass)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Damned hydropower	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.38
Nuclear	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Offshore wind	PWh	Smart Energy Europe (2050)	EnergyPLAN	1.41
Onshore wind	PWh	Smart Energy Europe (2050)	EnergyPLAN	4.49
Photovoltaics	PWh	Smart Energy Europe (2050)	EnergyPLAN	1.52
Thermal storage	TWh	Smart Energy Europe (2050)	EnergyPLAN	1.20
Electricity storage	TWh	Smart Energy Europe (2050)	EnergyPLAN	0.56
Hydro storage	TWh	Smart Energy Europe (2050)	EnergyPLAN	0.59
Hydrogen storage	TWh	Smart Energy Europe (2050)	EnergyPLAN	21.10
Rockbed storage	TWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Methanol storage	TWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Electric vehicle battery (smart charge)	TWh	Smart Energy Europe (2050)	EnergyPLAN	9.16
Hydrogen demand	PWh	Smart Energy Europe (2050)	EnergyPLAN	1.79
Electricity for electrolysis	PWh	Smart Energy Europe (2050)	EnergyPLAN	2.55
Flexible electricity demand (1 day)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.24
Flexible electricity demand (1 day) Max effect	GW	Smart Energy Europe (2050)	EnergyPLAN	24.96
Electric vehicles (dump charge)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.408
Electric vehicles (smart charge)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.560
Electric vehicles smart charge max effect	GW	Smart Energy Europe (2050)	EnergyPLAN	762.00

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Electric vehicles dump charge max effect	GW	Smart Energy Europe (2050)	EnergyPLAN	134.792
Electric vehicles discharge (V2G)	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Electrolysis	GW	Smart Energy Europe (2050)	EnergyPLAN	502.00
Heat pumps (district heating)	GW	Smart Energy Europe (2050)	EnergyPLAN	36.00
Heat pumps (district heating) elec. consumption	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.46
Electric boiler (district heating)	GW	Smart Energy Europe (2050)	EnergyPLAN	0.00
Electric boiler (district heating) elec. consumption	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.00
Power to heat (individual heating)	GW	Smart Energy Europe (2050)	EnergyPLAN	93.00
Power to heat (individual heating) elec. consumption	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.34
CO2 hydrogenation electricity	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.03
CO2 hydrogenation electricity max effect	GW	Smart Energy Europe (2050)	EnergyPLAN	5.00
Curtailment of VRE	PWh	Smart Energy Europe (2050)	EnergyPLAN	0.40
Power plant and CHP capacity	GW	1.5 TECH (2050)	EnergyPLAN	565.00
Damned hydropower	GW	1.5 TECH (2050)	EnergyPLAN	163.00
Nuclear	GW	1.5 TECH (2050)	EnergyPLAN	121.35
Dispatchable power capacity	GW	1.5 TECH (2050)	EnergyPLAN	849.35
Electrolysis	GW	1.5 TECH (2050)	EnergyPLAN	478.00
Offshore wind	GW	1.5 TECH (2050)	EnergyPLAN	451.38
Onshore wind	GW	1.5 TECH (2050)	EnergyPLAN	658.73
Photovoltaics	GW	1.5 TECH (2050)	EnergyPLAN	930.77
Total electricity demand	PWh	1.5 TECH (2050)	EnergyPLAN	7.140
Total inflexible electricity demand	PWh	1.5 TECH (2050)	EnergyPLAN	3.91
Traditional and additional electricity demand	PWh	1.5 TECH (2050)	EnergyPLAN	3.25
Peak total electricity demand	GW	1.5 TECH (2050)	EnergyPLAN	1,499.00
Peak inflexible electricity demand	GW	1.5 TECH (2050)	EnergyPLAN	630.00
Peak Traditional and additional electricity demand	GW	1.5 TECH (2050)	EnergyPLAN	520.00
Total heat demand	PWh	1.5 TECH (2050)	EnergyPLAN	1.42
Total individual heat demand	PWh	1.5 TECH (2050)	EnergyPLAN	1.18
Total district heating demand	PWh	1.5 TECH (2050)	EnergyPLAN	0.24
Peak individual heating demand	GW	1.5 TECH (2050)	EnergyPLAN	320.00
Peak district heating demand	GW	1.5 TECH (2050)	EnergyPLAN	56.00
Power plants and CHP (Coal)	PWh	1.5 TECH (2050)	EnergyPLAN	0.00
Power plants and CHP (Natural gas)	PWh	1.5 TECH (2050)	EnergyPLAN	0.32
Power plants and CHP (Biomass)	PWh	1.5 TECH (2050)	EnergyPLAN	0.21
Damned hydropower	PWh	1.5 TECH (2050)	EnergyPLAN	0.40
Nuclear	PWh	1.5 TECH (2050)	EnergyPLAN	0.96
Offshore wind	PWh	1.5 TECH (2050)	EnergyPLAN	2.16
Onshore wind	PWh	1.5 TECH (2050)	EnergyPLAN	1.85
Photovoltaics	PWh	1.5 TECH (2050)	EnergyPLAN	1.34
Thermal storage	TWh	1.5 TECH (2050)	EnergyPLAN	0.00
Electricity storage	TWh	1.5 TECH (2050)	EnergyPLAN	0.27
Hydro storage	TWh	1.5 TECH (2050)	EnergyPLAN	0.51
Hydrogen storage	TWh	1.5 TECH (2050)	EnergyPLAN	3.82

Rockbed storage	TWh	1.5 TECH (2050)	EnergyPLAN	0.00
Methanol storage	TWh	1.5 TECH (2050)	EnergyPLAN	0.00
Electric vehicle battery (smart charge)	TWh	1.5 TECH (2050)	EnergyPLAN	3.00
Hydrogen demand	PWh	1.5 TECH (2050)	EnergyPLAN	1.82
Electricity for electrolysis	PWh	1.5 TECH (2050)	EnergyPLAN	2.60
Flexible electricity demand (1 day)	PWh	1.5 TECH (2050)	EnergyPLAN	0.23
Flexible electricity demand (1 day) Max effect	GW	1.5 TECH (2050)	EnergyPLAN	21.97
Electric vehicles (dump charge)	PWh	1.5 TECH (2050)	EnergyPLAN	0.174
Electric vehicles (smart charge)	PWh	1.5 TECH (2050)	EnergyPLAN	0.450
Electric vehicles smart charge max effect	GW	1.5 TECH (2050)	EnergyPLAN	618.00
Electric vehicles dump charge max effect	GW	1.5 TECH (2050)	EnergyPLAN	57.485
Electric vehicles discharge (V2G)	PWh	1.5 TECH (2050)	EnergyPLAN	0.01
Electrolysis	GW	1.5 TECH (2050)	EnergyPLAN	478.00
Heat pumps (district heating)	GW	1.5 TECH (2050)	EnergyPLAN	0.00
Heat pumps (district heating) elec. consumption	PWh	1.5 TECH (2050)	EnergyPLAN	0.18
Electric boiler (district heating)	GW	1.5 TECH (2050)	EnergyPLAN	0.00
Electric boiler (district heating) elec. consumption	PWh	1.5 TECH (2050)	EnergyPLAN	0.00
Power to heat (individual heating)	GW	1.5 TECH (2050)	EnergyPLAN	67.00
Power to heat (individual heating) elec. consumption	PWh	1.5 TECH (2050)	EnergyPLAN	0.24
CO2 hydrogenation electricity	PWh	1.5 TECH (2050)	EnergyPLAN	0.02
CO2 hydrogenation electricity max effect	GW	1.5 TECH (2050)	EnergyPLAN	5.00
Curtailment of VRE	PWh	1.5 TECH (2050)	EnergyPLAN	0.39
Power plant and CHP capacity	GW	Baseline (2050)	EnergyPLAN	671.40
Damned hydropower	GW	Baseline (2050)	EnergyPLAN	154.00
Nuclear	GW	Baseline (2050)	EnergyPLAN	87.00
Dispatchable power capacity	GW	Baseline (2050)	EnergyPLAN	912.40
Electrolysis	GW	Baseline (2050)	EnergyPLAN	18.00
Offshore wind	GW	Baseline (2050)	EnergyPLAN	142.86
Onshore wind	GW	Baseline (2050)	EnergyPLAN	440.87
Photovoltaics	GW	Baseline (2050)	EnergyPLAN	441.49
Total electricity demand	PWh	Baseline (2050)	EnergyPLAN	4.790
Total inflexible electricity demand	PWh	Baseline (2050)	EnergyPLAN	4.08
Traditional and additional electricity demand	PWh	Baseline (2050)	EnergyPLAN	3.28
Peak total electricity demand	GW	Baseline (2050)	EnergyPLAN	853.00
Peak inflexible electricity demand	GW	Baseline (2050)	EnergyPLAN	680.00
Peak Traditional and additional electricity demand	GW	Baseline (2050)	EnergyPLAN	531.00
Total heat demand	PWh	Baseline (2050)	EnergyPLAN	2.43
Total individual heat demand	PWh	Baseline (2050)	EnergyPLAN	2.00
Total district heating demand	PWh	Baseline (2050)	EnergyPLAN	0.43
Peak individual heating demand	GW	Baseline (2050)	EnergyPLAN	543.00
Peak district heating demand	GW	Baseline (2050)	EnergyPLAN	100.00
Power plants and CHP (Coal)	PWh	Baseline (2050)	EnergyPLAN	0.00
Power plants and CHP (Natural gas)	PWh	Baseline (2050)	EnergyPLAN	0.58

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Power plants and CHP (Biomass)	PWh	Baseline (2050)	EnergyPLAN	0.19
Damned hydropower	PWh	Baseline (2050)	EnergyPLAN	0.38
Nuclear	PWh	Baseline (2050)	EnergyPLAN	0.69
Offshore wind	PWh	Baseline (2050)	EnergyPLAN	0.68
Onshore wind	PWh	Baseline (2050)	EnergyPLAN	1.24
Photovoltaics	PWh	Baseline (2050)	EnergyPLAN	0.64
Thermal storage	TWh	Baseline (2050)	EnergyPLAN	0.00
Electricity storage	TWh	Baseline (2050)	EnergyPLAN	0.56
Hydro storage	TWh	Baseline (2050)	EnergyPLAN	0.59
Hydrogen storage	TWh	Baseline (2050)	EnergyPLAN	0.14
Rockbed storage	TWh	Baseline (2050)	EnergyPLAN	0.00
Methanol storage	TWh	Baseline (2050)	EnergyPLAN	0.00
Electric vehicle battery (smart charge)	TWh	Baseline (2050)	EnergyPLAN	3.00
Hydrogen demand	PWh	Baseline (2050)	EnergyPLAN	0.06
Electricity for electrolysis	PWh	Baseline (2050)	EnergyPLAN	0.08
Flexible electricity demand (1 day)	PWh	Baseline (2050)	EnergyPLAN	0.24
Flexible electricity demand (1 day) Max effect	GW	Baseline (2050)	EnergyPLAN	24.96
Electric vehicles (dump charge)	PWh	Baseline (2050)	EnergyPLAN	0.210
Electric vehicles (smart charge)	PWh	Baseline (2050)	EnergyPLAN	0.360
Electric vehicles smart charge max effect	GW	Baseline (2050)	EnergyPLAN	327.00
Electric vehicles dump charge max effect	GW	Baseline (2050)	EnergyPLAN	69.378
Electric vehicles discharge (V2G)	PWh	Baseline (2050)	EnergyPLAN	0.04
Electrolysis	GW	Baseline (2050)	EnergyPLAN	18.00
Heat pumps (district heating)	GW	Baseline (2050)	EnergyPLAN	0.45

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6 Annex B: Energy system scenario data for Greece

Parameter	Unit	Scenario	Model	Value
Power plants	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	19.85
Damned hydropower	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	4.03
Dispatchable power capacity	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	23.88
Electrolysis	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	14.02
Offshore wind	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	19.54
Onshore wind	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	11.67
Photovoltaics	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	39.17
Total annual electricity demand	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.1605
Power plants and CHP (Coal)	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.00
Power plants and CHP (Natural gas)	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.00
Other power plants	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0209
Damned hydropower	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0071
Offshore wind	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0690
Onshore wind	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0273
Photovoltaics	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0557
Electricity storage	TWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.1087
Hydro storage	TWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0487
Hydrogen storage	TWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.2019
Hydrogen demand	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.023
Electrolysis	GW	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	14.02
Curtailment of VRE	PWh	Early Neutrality 100% RE (2050)	OSeMOSYS-GR	0.0169
Power plants	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	24.52
Damned hydropower	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	4.03
Dispatchable power capacity	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	28.55
Electrolysis	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	14.24
Offshore wind	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	16.73
Onshore wind	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	10.43
Photovoltaics	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	33.43
Total annual electricity demand	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.1605

Power plants and CHP (Coal)	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.00
Power plants and CHP (Natural gas)	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0094
Power plants and CHP (Biomass)	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0067
Other power plants	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0209
Damned hydropower	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0071
Offshore wind	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0591
Onshore wind	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0244
Photovoltaics	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0475
Electricity storage	TWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0517
Hydro storage	TWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0178
Hydrogen storage	TWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.2050
Hydrogen demand	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.023
Electrolysis	GW	Early Neutrality CCS (2050)	OSeMOSYS-GR	14.24
Curtailment of VRE	PWh	Early Neutrality CCS (2050)	OSeMOSYS-GR	0.0071
Power plants	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	20.99
Damned hydropower	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	4.03
Dispatchable power capacity	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	25.02
Electrolysis	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	13.57
Offshore wind	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	18.55
Onshore wind	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	11.11
Photovoltaics	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	38.40
Total annual electricity demand	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.1605
Power plants and CHP (Coal)	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.00
Power plants and CHP (Natural gas)	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.00
Other power plants	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0209
Damned hydropower	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0071
Offshore wind	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0655
Onshore wind	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0260
Photovoltaics	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0546
Electricity storage	TWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0913
Hydro storage	TWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0415

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Hydrogen storage	TWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.1955
Hydrogen demand	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.023
Electrolysis	GW	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	13.57
Curtailment of VRE	PWh	2050 Neutrality-Gas until 2040 (2050)	OSeMOSYS-GR	0.0151
Power plants	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	20.88
Damned hydropower	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	4.03
Dispatchable power capacity	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	24.91
Electrolysis	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	15.03
Offshore wind	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	19.69
Onshore wind	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	11.82
Photovoltaics	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	39.66
Total annual electricity demand	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.1605
Power plants and CHP (Coal)	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.00
Power plants and CHP (Natural gas)	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.00
Other power plants	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0209
Damned hydropower	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0071
Offshore wind	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0695
Onshore wind	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0277
Photovoltaics	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0564
Electricity storage	TWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.1009
Hydro storage	TWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0369
Hydrogen storage	TWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.2164
Hydrogen demand	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.023
Electrolysis	GW	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	15.03
Curtailment of VRE	PWh	2050 Neutrality-Gas until 2045 (2050)	OSeMOSYS-GR	0.0176

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