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Assessing Greece's plans towards climate-neutrality under a water-energy-food-emissions modelling nexus: Ambitious goals versus scattered efforts

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ABSTRACT

Achieving climate-neutrality is a global imperative that demands coordinated efforts from both science and robust policies supporting a smooth transition across multiple sectors. However, the interdisciplinary and complex science-to-policy nature of this effort makes it particularly challenging for several countries. Greece has set ambitious goals across different policies; however, their progress is often debated. For the first time, we simulated a scenario representing Greece's climate-neutrality goals drawing upon its main relevant energy, agricultural and water policies, and compared it with a 'current accounts' scenario by 2050. The results indicate that most individual policies have the potential to significantly reduce carbon emissions across all sectors of the economy (residential, industrial, transportation, services, agriculture, and energy production). However, their implementation seems to be based on economic and governance assumptions that often overlook sectoral interdependencies, infrastructure constraints, and social aspects, hindering progress towards a unified and more holistic sustainable transition.

Keywords: Climate Neutrality; Energy-emissions modelling; LEAP; FABLE Calculator; MaritimeGCH; WaterReqGCH; Decarbonization; Greece.

Introduction

Becoming climate-neutral through strategies aimed at reducing greenhouse gas (GHG) emissions by 55% by 2030 (compared to 1990 levels) and ultimately achieving net-zero emissions by 2050 has been established as a top priority by the European Union (EU) (Den Elzen et al., 2022). These EU goals, as a unified Nationally Determined Contribution (NDC) under the Paris Agreement, highlight the urgency of action against climate change. Each Member-State's National Energy and Climate Plan (CNPP), as outlined in Regulation 2018/1999/EU on energy and climate action governance, sets out how each state can achieve these shared European climate targets. Climate-neutrality and clean energy affect directly and indirectly multiple sectors, including agriculture, food production, land uses, water resources, as well as the social and economic prosperity (Kılkış et al., 2020; Garcia & Alamanos, 2023). Although climate-neutrality is primarily defined as achieving net-zero GHG emissions, in practice, realizing this decarbonization transition requires that interconnected systems such as the economy, land use, food production, and water use become also more sustainable (Blackburn et al., 2017; Abram et al., 2022). International and European policy acknowledge that, making it particularly evident in the Sustainable Development Goals (SDGs) framework, where principles such as indivisibility, integration and universality are highlighted (Weitz et al., 2023). However, in reality, the scientific community exposes crucial weaknesses of policies in addressing a more holistic and sustainable progress. Merfort et al. (2023) explore the negative effects of fragmented land-energy policies. Fujimori et al. (2021) argue on the poor coordination and incompatible nature of national climate policies, revealing that there are individual challenges in energy system transformations and investment needs. Roelfsema et al. (2020) explain that even the implementation of current national policies fall short to close the GHG emissions gap needed to achieve the Paris Agreement's goals, while other studies even highlight national regulatory conflicts (Chen et al., 2024).

A key element in assessing different future climate-neutrality scenarios, evaluate and guide relevant policies, is the use of sound scientific tools (Zheng et al., 2024). There are several examples in the literature using modelling approaches for such purposes. Common cases are the integrated assessment models (IAMs) simulating effects across different sectors (Keppo et al., 2021), the deep decarbonization models (DDMs), which are bottom-up, engineering-economic models that minimize the costs of achieving net-zero emissions (Felder & Kumar, 2021), or custom combinations based on case-specific needs and concepts (Villamar et al., 2021). Several studies couple different models representing mainly the water-energy-food-land systems, as the core ones to climate-neutrality (Li & Zhang, 2023). For instance, Doelman et al. (2022) explored water-land-food-climate trade-offs by combining the MAgPIE and IMAGE models. Yue et al. (2021) designed an optimization-based decision support tool for water-food-energy-climate change-land nexus pathways. However, the use of such models to assess different existing climate-neutrality national policies is rarer. Kattelmann et al. (2021) combined the energy system model TIMES with the computational general equilibrium model NEWAGE to suggest efficient climate-neutrality strategies. Most approaches exploring climate-neutrality pathways usually are more focused on a specific system, e.g. energy, or land. Capros et al. (2019) used the PRIMES energy model to explore pathways towards climate-neutrality in the EU energy-system by 2050 and 2070. Duffy et al. (2022) developed and applied the GOBLIN model, focusing on land use, to identify national agriculture and land use pathways to climate-neutrality. Also, there are fewer publications using similar modelling approaches to evaluate actual policies across water-food-energy-land systems, assuming scenarios of their joint implementation. Most of the examples mentioned do not consider a detailed sectoral resolution in the energy-emissions modelled uses, but they are mainly focusing on the terrestrial energy processes and policies. To our knowledge, there is still no study doing such an analysis for Greece.

Thus, we aim to fill this gap by developing a scenario assuming the joint implementation of various national policies aiming to climate-neutrality in Greece. We consider a combination of simulation models for food-land, water, and cross-sectoral energy systems (including residential, industrial, terrestrial, maritime and aviation transportation, and services sectors). Different agricultural, energy, shipping and water policy frameworks are assessed jointly, to provide useful insights on whether these plans can achieve the climate-neutrality goals, and what is missing to use them as opportunities for a broader sustainability transition.

Context and challenges in Greece

Greece's efforts towards climate-neutrality face several significant challenges, primarily its continued reliance on fossil fuels, which account for a substantial portion of energy supply (Tsoutsos et al., 2008). Despite notable progress in renewable energy adoption, fossil fuels still dominate. The government has set ambitious commitments to phase out lignite by 2028 and reduce overall GHG emissions to net-zero by 2050. However, the transition is complicated by the need for substantial investments in renewable infrastructure and energy-efficient technologies (Halkos & Tzeremes, 2012). The CNPP is the main policy instrument dealing with these challenges, proposing a pathway to climate-neutrality through the decarbonization of all sectors of the economy. The main idea is to use cleaner fuels and improve energy use efficiency, for all uses. While limited research so far explores specific sectors' decarbonization pathways, such as transportation (Tsita & Pilavachi, 2017), or macroeconomic impacts (Koutsandreas et al., 2021), there is no study exploring multiple sectors as a whole, in a single model, like the present paper.

Agriculture in Greece remains significant in terms of employment and output, contributing approximately 4% to the national GDP and employing around 11% of the workforce. Nonetheless, the sector faces key challenges, most importantly low productivity and tech adoption, aging farmers, and fragmented land holdings. Moreover, agriculture is challenged by resources limitations (e.g. water and soil conditions, energy), as well as natural hazards (droughts and floods). Scientists have been advocating for nexus approaches considering all those factors together, long ago, to avoid food security problems (Papadopoulou et al., 2022). While there are no substantial land use changes in Greece, the land degradation is a pressing issue for agriculture and food production (Karamesouti et al., 2015). In line with the decarbonization commitments, the transition to more sustainable diets with reduced carbon footprints is among the country's goals, with limited progress so far (Abeliotis et al., 2016; Varela, 2025). The CNPP does not have specific recommendations for agriculture though. The Common Agricultural Policy (CAP) is an overarching plan covering such concerns, aiming to a resilient and more sustainable food system. However, subpar performance in crop and livestock productivity is attributed to the marginal spread of cutting-edge technologies, stemming from the inherent attributes of the Greek agricultural sector as well as the poor functioning of national and subnational innovation systems.

The shipping sector is particularly important for Greece, stemming from a deep-rooted tradition of maritime expertise and a strategic focus on global shipping markets, positioning it as a crucial component of international trade and economic stability (Alexandropoulou et al., 2021). The country continues to be the global leader in deadweight tonnage (DWT), with approximately 18% of global capacity, and a fleet capacity of approximately 427 million DWT. At the moment, Greece must accommodate rising shipping demand while complying with the recent International Maritime Organization (IMO)'s targets and EU's FuelEU Maritime Regulation, adhering to the Emissions Trading System (ETS), which mandates an 80% reduction of the current emissions at EU-level by 2050. Obligations for alternative fuels and emissions-reduction technologies are expected to apply from 2030. Very few studies couple the terrestrial and the maritime energy systems (Fadiga et al., 2024). The review paper by Naghash et al. (2024) finds that most existing modelling approaches do not meet the IMO targets, and that integrated modelling frameworks with real policy scenarios are needed. This paper fills this gap, by providing such an integrated tool to address recent policies and achieve climate-neutrality goals.

Water management in Greece is also grappling with critical issues, in several fronts. These include water scarcity, particularly exacerbated by climate change and increasing demand (e.g. tourism) (Alamanos, 2021); competing water uses over the over-reliance on groundwater resources, which in turn has resulted in over-extraction and salinization, further compromising water quality and availability (Stefanidis et al., 2019; Angeli et al., 2020). Water governance is often fragmented across various authorities, leading to inefficiencies and poor coordination, which is evident in several sectors, but mainly in the residential and the agricultural ones (Sfyris et al., 2019; Kourgialas, 2021). The Water Framework Directive WFD 2000/60/EC is the EU policy dealing with these challenges, and each Member-State develops River Basin Management Plans (RBMPs) with sets of measures for the restoration and protection of water bodies, and a more responsible and efficient demand management. The importance of tracking water consumption by sector is increasingly recognized as the core target of water use efficiency improvements (Keramitsoglou & Tsagarakis, 2011). It is also relevant for climate-neutrality goals, as it allows for a more complete assessment of resource use efficiency in general, and helps identify potential conflicts or synergies between water use and decarbonization efforts (Karavitis & Oikonomou, 2024). Most studies explore the effects on specific sectors or regions of Greece (Shan et al., 2015), with limited research on a cross-sectoral basis, like in this paper.

Each sector of the economy also faces unique challenges. The residential sector is the largest energy consumer and second-largest water user, faces significant resource pressures and aging infrastructure. Agriculture must address competing water and energy needs, environmental pressures, and productivity gaps, along its transition to cleaner fuels and modernization of current practices. Industrial decarbonization is also challenged by resource limitations, outdated technologies, and high reliance on fossil fuels (Giannitsis & KastelliI, 2014). Moreover, Greek industry being not as big as in other EU Member-States, is an overlooked issue with limited research. The transportation sector, as a whole, struggles with reliance on conventional fuels, inefficiencies, and policy gaps, hindering its decarbonization efforts (Kyriakopoulos et al., 2023). The transition of the transportation sector to cleaner fuels is still at a preliminary stage, and the sector often appears to be “isolated” from the broader future energy planning (Kouridis & Vlachokostas, 2022). While sector-specific challenges are critical, comprehensive nexus approaches assessing all these sectors as a whole, and each one at a fine-resolution, are still lacking. The interdisciplinary and complex science-to-policy nature of such cross-sectoral climate-neutrality efforts make their simulation particularly challenging. This applies particularly for countries that are not traditionally used to such holistic governance (Martin et al., 2023; Koundouri et al., 2024). Greece is such an example, and this research aims to fill a critical gap in terms of cross-sectoral fine-resolution modelling approaches, and in terms of its national climate-related policy assessment.

Methodology

A systems-nexus modelling approach was followed to simulate all sectors described in the previous section. This approach consists of: the FABLE Calculator (Mosnier et al., 2020) for the potential evolution of food and land-use systems; the Low Emissions Analysis Platform (LEAP) (Heaps, 2022) for the simulation of the energy consumption and the associated GHG emissions of multiple pollutants; the MaritimeGCH model for the simulation of the shipping sector’s climate-neutrality (Alamanos et al., 2024); the WaterReqGCH accounting tool (Alamanos & Koundouri, 2024) for the estimation of the water requirements of the studied sectors; and the LandReqCalcGCH tool to estimate the land requirements for any potentially additional renewable energy production units. These models were linked through specific outputs becoming inputs elsewhere, and tools (e.g. the BiofuelGCH Calculator), as illustrated in Figure 1.

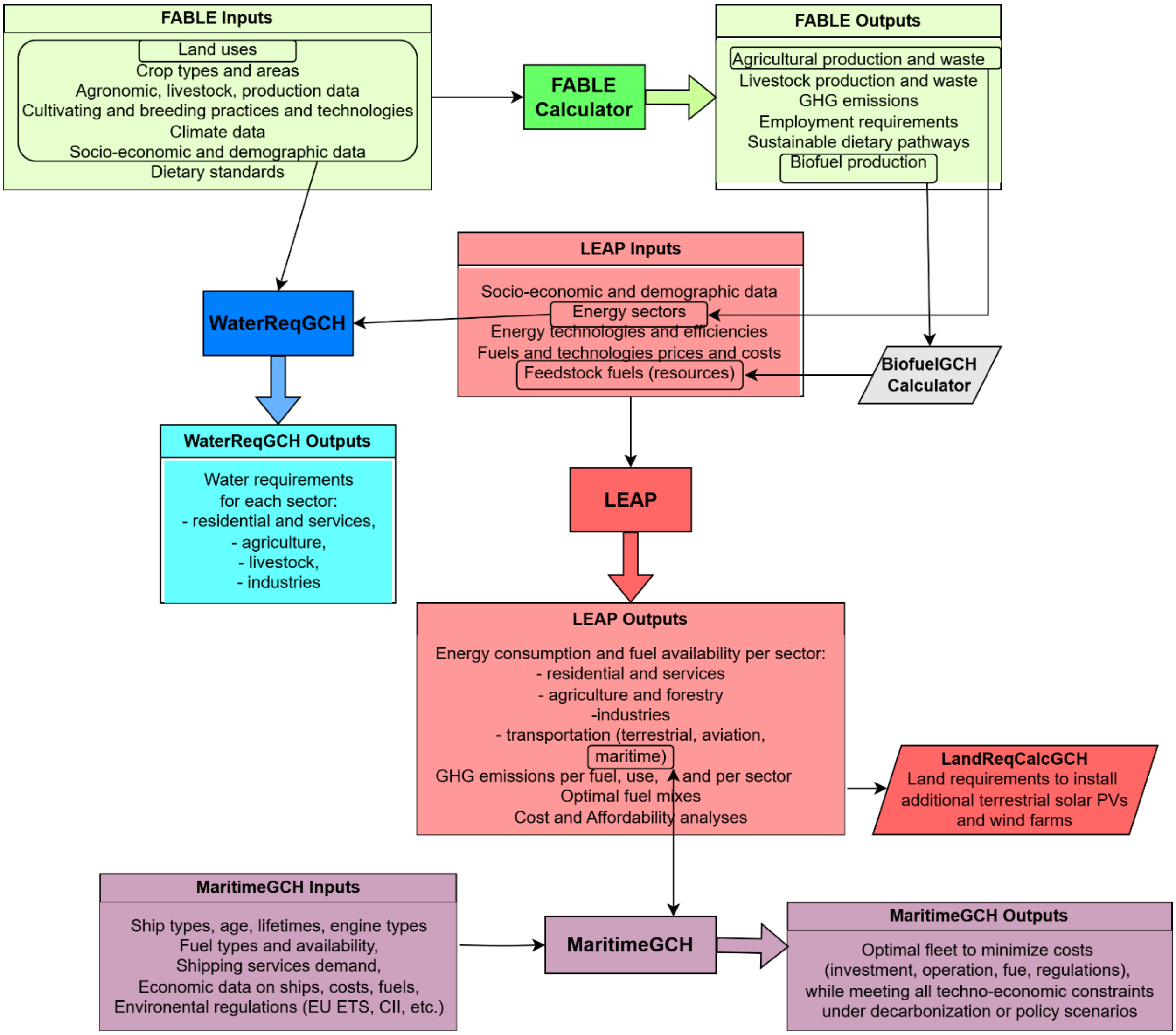

Figure 1. The modelling framework, with the tools, their inputs and outputs, and their connections.

Food-Land system

The FABLE (Food, Agriculture, Biodiversity, Land Use, and Energy) Calculator is a sophisticated simulation tool performing scenario analyses. FABLE Calculator uses primarily land use and crop data, agronomic, livestock, climate and socio-economic data from the FAOSTAT and the CORINE databases. Utilizing different scenarios for the human demand of food products for all uses, it calculates targeted land for the required agricultural production. This, in turn, is constrained by land availability and regulatory restrictions and determines the "feasible land area" for various uses, such as crop cultivation, livestock grazing, forestry, and bioenergy production (Mosnier et al., 2020). The FABLE Calculator offers a portfolio of more than 1.5 billion pathways (a combination of in-build scenarios through changing different variables) through assumptions covering aspects of climate conditions, economic and agricultural policy, regulation and demographics.

It dynamically allocates land to these different purposes based on agronomic conditions, yield potentials, regulatory restrictions, and socio-economic drivers. In this way, the model simulates land use changes over time, accounting for constraints like limited land availability and policy-driven land allocation decisions (Mosnier et al., 2020). For food and livestock production, the FABLE Calculator employs a demand-based approach that estimates production targets based on consumption projections while considering resource constraints. It integrates crop yields, livestock productivity, and agronomic practices to simulate the production of various food commodities (Mosnier et al., 2020).

The associated agricultural production-based GHG emissions refer to direct emissions from production activities and processes, agronomic practices, and non-energy uses (e.g. livestock emissions). They are calculated by linking production processes to emission factors, and cover emissions from fertilizer use, enteric fermentation from livestock, manure management, and other agricultural practices (Mosnier et al., 2020).

Cross-sectoral Energy-Emissions Analysis

LEAP is at the core of the modelling suite, as it simulates the energy demand (consumption) across various sectors, the fuel supply and their production, as well as the associated GHG emissions for each process. The energy demand (D) has been calculated as the product of an activity level (AL) and an annual energy intensity (EI, energy use per unit of activity), according to LEAP's Final Energy Demand Analysis method (Equation 1).

$$D_{sector,scenario} = AL_{sector,scenario} \cdot EI_{sector,scenario} \quad (1)$$

LEAP's energy supply-side module simulates the resources (representing the availability and characteristics of primary and secondary energy forms), and transformation processes (simulating how energy is converted, transmitted, and distributed through technologies like power plants, refineries, and grids). The supply system ensures alignment with the per sector demand-side inputs and can simulate constraints, imports, exports, and system losses, offering detailed insights into energy flows (Table 1).

The GHG emissions are then estimated automatically, based on the emission coefficients of the IPCC's Fifth Assessment Report (IPCC, 2014) per sector, per use and per fuel type for the demand side, and per process for the supply side.

Table 1. The main types of inputs in the LEAP model, for each sector.

Energy Demand			**Data sources**
Sectors	**Activity Level (AL)**	**Energy uses (and energy intensity, EI)**	
Residential	Population (distinguished between urban and rural)	Lighting, cooking, space heating, space cooling, water heating, and other appliances	World Bank (2023); ELSTAT (2024)
Industry	Value Added of each industry product, or tons of product	Food and tobacco, textiles and leather, wood products, paper pulp and printing,	IEA (2023a)

		chemicals and chemical products, rubber and plastic, non-metallic minerals, basic metals, machinery, transport equipment, other manufacturing, mining, cement and steel production	
Agricultural energy use	Agricultural products (FABLE Calculator's output)	Energy used for the agricultural and livestock products	FABLE Calculator
Transportation	Passengers and freight in passenger/km or tons/km	Cars, light trucks, motorcycles, buses, trains, domestic airplanes, shipping, freight trucks and trains	IEA (2023a); ELSTAT (2024)
Services	Number of public buildings	Tertiary sector services	IEA (2023a); ELSTAT (2024)
Energy Supply (fuels' production processes to cover the demand)			
Primary Resources	Solar, crude oil, coal lignite, hydropower, wind, coal, municipal solid waste, biofuels		EUROSTAT (2022); IEA (2023a); ELSTAT (2024)
Secondary Resources	Diesel, petroleum coke, refinery feedstocks, residual fuel oil, kerosene, CNG, LPG, gasoline, Hydrogen, biogas, oil, heat, electricity, synthetic fuels		
Transformation processes	Transmission and distribution, synthetic fuel production, generation of hydrogen, electricity, heat, oil refining – with the associated losses		
GHG emissions			
Types of pollutants	CO_2, CH_4, N_2O, PM2.5, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), Black Carbon (BC), Organic Carbon (OC)		IPCC (2014)

Agriculture's residuals potential for biofuels production

Another stage worth mentioning is a simple intermediate mode we developed, as a link between the FABLE Calculator and LEAP: the BiofuelGCH Calculator. One of FABLE Calculator's outputs is the crop and livestock products. The most common crops that can be used for biofuels production were selected, according to FABLE Consortium data for Greece (Koundouri et al., 2023): these are corn, sugarbeet, sunflower, olive, and wheat. Based on the production of each crop, a percentage of their residues (generated during agricultural production) can be estimated based on typical values from the literature (Elbehri et al., 2013; Yang et al., 2023). The fraction of those residues is typically available for biofuel use, without affecting food production. So, the biofuel production potential from those specific residues can be calculated (FAO, 2010; Talebnia et al., 2010; IEA Bioenergy, 2011).

$$Biofuel\ production\ potential_{\text{biofuel type}} = Residual\ Availability_{\text{selected crop}} \cdot Biofuel\ Production\ Coefficients_{\text{biofuel,crop}} \tag{2}$$

Equation 2 describes the estimation of the biofuel production potential, per biofuel type (in liters of biofuel), occurring as the product of the available residuals per crop (in tons of residues) and the respective biofuel production coefficients per biofuel and per crop [liters of biofuel/ ton of residues].

Providing policymakers with this additional insight (e.g. liters of bioethanol and/or biodiesel that can be produced per ton of existing crop residues) is crucial for investments in domestic biofuel production units, potential reductions of imported biofuels, or even exporting them.

Needs for additional renewable energy infrastructure

National policies often require explicable actions and trade-offs. The efforts towards climate-neutrality require an increase of renewable energy shares in the total fuel mix of each use. One additional answer to this energy planning problem that can be provided by this nexus modelling approach, is the land requirements for additional solar panels and onshore wind farms installation. This is achieved by the LandReqCalcGCH model, which receives inputs from LEAP regarding the future energy mix. Based on the information of the required capacity of renewable solar and wind power, excluding the existing production capacity, this model informs on the land requirements and implementation costs.

$$\begin{aligned} & Land\ Requirements_{\text{renewable source}} = (Required\ production\ capacity_{\text{renewable source,onshore}} - \\ & Current\ production\ capacity_{\text{renewable source,onshore}}) \cdot \\ & Area\ Conversion\ Coefficient_{\text{renewable source,land use type,project type}} \end{aligned} \qquad (3)$$

Equation 3 describes how this model estimates the land requirements (in km^2) that will be needed for additional solar panels and for wind farms, considering their additional future energy production requirements (their onshore portion). The area conversion coefficients (in km^2/MW) are typical values from the literature, considering the land use types and the most common types of solar panel and wind farm projects. Moreover, the LandReqCalcGCH model calculates the expected costs (in million €) for the installation of the additional solar panel and wind farm areas, based on typical installation cost values.

Shipping sector

This sector includes both the Greek ports, and the Greek shipping fleet operating internationally, so a combination of its modelling in LEAP and the MaritimeGCH model is followed.

The LEAP model estimates the energy use and GHG emissions from domestic and international maritime operations. This refers to the fuel supplied to ships engaged in domestic, and international navigation, namely voyages between ports within Greece and in different countries (or international waters), regardless of the ship's flag, as long as they are supplied by fuels in Greek ports. The LEAP model is focused on port-related fuel flows and policy, helping ports and regulators understand the broader fuel supply and environmental impacts of domestic and international shipping supplied in Greece. On the other hand, the MaritimeGCH model is aimed at ship owners, providing insights into fleet investment and operational decisions under the Greek flag. This separation allows each model to be tailored to its “target audience’s” needs. Thus, the two models offer complementary perspectives providing a more complete picture, and enabling coordinated policies at Greek ports while guiding individual Greek fleet strategies.

The MaritimeGCH model is an Investment Decision Support Tool (IDST), based on dynamic linear programming optimization (Alamanos & Koundouri, 2024; Alamanos, 2025b). Its objective function (Equation 4) aims to minimize the total cost of fleet operations over a user-defined planning horizon (in years, from 2020 to 2050 in this case). The total cost includes investments for new-build ships, operational costs of the fleet, fuels costs, and any allowance that must be purchased in the case of excess emissions, according to the EU’s Emissions Trading System (ETS).

$$min \sum_{y=2020}^{2050} (total\_cost_y), \text{ where} \qquad (4)$$

$$\begin{aligned} total\_cost_y = & \sum_s (new\_ship_{y,s} \times invest\_cost_s) + \sum_s (stock\_ship_{y,s} \times op\_cost_s) + \\ & \sum_s (fuel\_demand_{y,f} \times fuel\_cost_f) + (excess\_emissions_y \times ETS\_price_y) \end{aligned}$$

The model's constraints include a fleet capacity constraint, where the total stock of ships each year must be sufficient to meet the demand for shipping services; a ship production constraint; a fleet stock update constraint where the total stock for a given year is the sum of surviving ships for the year and new ships built, fuel demand constraints subject to fuel availability; an emissions constraint, dictated by emissions factors for each fuel, and the ETS emissions threshold where excess emissions are penalized. The fleet should also not exceed a performance metric as defined by the Carbon Intensity Indicator (CII) constraint, according to the IMO targets. For the input data, we used a mix of datasets retrieved from various sources, including Clarksons Research, UNCTAD, MarineTraffic and information from legal frameworks such as FuelEU as well as the European Union Emissions Trading System (EU ETS) and information from legal frameworks like FuelEU (UNCTAD, 2023; Clarksons, 2024; European Commission, 2024b; MarineTraffic, 2024).

Water Requirements

Finally, the water requirements of all sectors studied in LEAP, are calculated by the WaterReqGCH accounting tool (Alamanos & Koundouri, 2024). The estimation of water requirements refers to calculating the amount of water needed for a specific sector, in this case, following the same approach with the energy demand, assuming an AL and typical water consumption values. For instance, the residential water requirements (W) are estimated by multiplying the AL (population) with an average consumption rate per person per day (CR), which is then increased by a losses coefficient (LC) expressing the water lost in various stages (pumping, transmission, distribution), according to Equation 5. The CR can range from 120-150lt/cap/day for Greece, while the LC was assumed to be 40%, reflecting most Greek cities conditions (Kolokytha, 1998; Kolokytha et al., 2002; Alamanos et al., 2019; Stathi et al., 2023).

$$W_{sector} = AL_{sector} \cdot CR_{sector} \cdot LC_{sector} \tag{5}$$

The water requirements for industry were estimated (for each one of 15 different manufacturing and industrial processes considered also within LEAP), based on typical water consumption values per industrial product. Similarly, the water requirements for agriculture and livestock were considered based on the crops and animal populations per species, and their typical CRs.

This is a straightforward calculation approach that requires minimal data processing. The resulting estimate provides a reasonable approximation of urban water requirements, as the typical consumption rates include the effects of various socio-economic parameters on water requirements (Khilchevskyi & Karamushka, 2020; Alamanos & Koundouri, 2024).

Results

All the models described run under a common simulation period, from 2020 to 2050, at an annual time-step. Also, the simulation considered two scenarios: The 'current accounts' or do-nothing scenario (business-as-usual - BAU), which assumes that the current trends (the 2000-2020 observed trends per sector) will continue applying until 2050; The climate-neutrality planned pathway (CNPP). The CNPP assumes that the different policies per sector, that are relevant to climate-neutrality are applied and implemented together (Table 2). Thus, it simulates the pathway for Greece's climate-neutrality across all sectors, as it is currently planned/described in its respective sectoral policies.

Table 2. The description of the climate-neutrality planned pathway (CNPP) scenario, according to each sectoral policy.

Sectors	Planned pathway according to sector-specific policies
Residential, Industry, Transportation, Services	The Greek National Energy and Climate Plan (CNPP), as defined by the Greek Ministry of Energy and Environment (2024), assumes certain interventions per sector. These refer to improvements of energy use efficiencies and cleaner energy mixes. So, for all sectors, the CNPP's expected energy consumption led to the respective energy intensities assumed in this simulation. Also, for each sector, the CNPP's expected fuel mixes (phasing out fossil fuels and replacing them by cleaner ones) were simulated.
Food-land system, Agricultural production-based and energy-based systems	The Greek CAP, aligned with the broader EU CAP framework, clearly acknowledges the need to boost agricultural productivity, promote sustainable diets (reducing meat) within the constraints of limited land, and enhance energy efficiency in agriculture. However, while these objectives are articulated as strategic goals, the policy largely outlines broad priorities and financial support mechanisms rather than prescribing specific, technical interventions or detailed action plans (Kyriakopoulos et al., 2023; Doukas et al., 2024). The CNPP focuses primarily on generic agroecological practices and cyclical economy considerations to decarbonize the agricultural sector. To model such a trajectory, considering land-use, GHG emissions and costs, we developed a high crop and livestock productivity scenario within FABLE Calculator, corresponding to the CNPP (and CAP) requirements by 2050. High productivity growth shifts historical (2000-2010) growth rates by reversing negative values, multiplying by a factor of 2 if they were below 1%, and by 0.7 if they exceeded 1% (Mosnier et al., 2020). In the case of Greece, the average productivity growth during the first decade of the century had negative values.
Shipping sector	The CNPP assumes energy use efficiencies' improvements and cleaner energy mixes; however, there are no specific interventions. So, for Greek ports (LEAP) and for the Greek fleet (MaritimeGCH) a moderate transition scenario to cleaner fuels was simulated, assuming oil-type fuels phasing out, being replaced by transition gas-type fuels initially, while green fuels (MeOH, NH_3 and H_2) ultimately becoming more prevalent in the future. Additionally, for the fleet, per ship type, a combination of emission-reduction technologies was simulated in this scenario, including engine power optimization, route optimizer technology, port-call technology, more efficient propulsion systems, on-board carbon-capture, and hull-cleaning & maintenance technologies. These strategies reflect both the CNPP and the IMO's and EU ETS regulation targets and obligations (Rodanakis, 2014; Pavlidis, 2024).
Water consumption	The European Union's Water Framework Directive (WFD) 2000/60/EC establishes a comprehensive framework for water policy, aiming to protect and enhance the quality of water resources across Member-States. While the WFD sets overarching objectives for achieving 'good status' of all water bodies, it does not prescribe specific water consumption reduction targets for individual sectors (European Commission, 2023). In all Member-States, the implementation of the WFD is carried out through River Basin Management Plans (RBMPs), assessing the status of water bodies and outline Programmes of Measures (PoMs) to address identified issues. While the RBMPs focus on protecting and managing water resources, they do not set explicit sector-specific water consumption reduction targets or measures. Instead, they emphasize the need to improve water efficiency and sustainable use across various sectors (YPEKA, 2014; Karavitis & Oikonomou, 2024). In this scenario, we assumed a central measure to improve water use efficiency by reducing urban water losses (LC) by half.

Food-Land system

The BAU scenario leads to increased production-based agricultural emissions by 2050, as expected. In contrast, the CNPP scenario shifts productivity levers for crop and livestock, dropping GHG emissions by 2050 by 50% (3MtCO2e) compared to the BAU scenario (Figure 2a,2b). This represents a 29% reduction from 2020 levels and a dramatic 73.4% decline from Greece's agricultural emissions in 2050. This reduction is primarily achieved through the livestock-related emissions dropping to 2.47MtCO2e in 2050, and land use changes leading to increased emission withdrawals of 3.28MtCO2e in 2050. This improvement in land use efficiency stems from the assumed shift to more sustainable diets managing the demand-side, and the higher and more efficient agricultural productivity, which enables greater yields without requiring additional inputs or extensive land expansion, as evidenced by declining pastureland areas (Figure 2e,2f). Additionally, emissions from crop production show notable improvements in the CNPP scenario, with a marked divergence from the BAU projections becoming apparent after 2035. Enhanced agricultural productivity is beneficial both in terms of climate change mitigation (GHG emissions), and of domestic agriculture’s competitiveness. This is particularly relevant following the 2023 extreme weather events and 2023-27 CAP implementation, with Devot et al. (2023) highlighting how climate change-intensified weather events impact EU agricultural production and costs.

Under the CNPP scenario, total costs are projected to decrease from 828million€ in 2025 to less than 630million€ by 2050. This reduction is largely attributed to declining pesticide expenses, which constitute the majority of total costs. Most notably, producers’ pesticide expenditures decrease by 27.5% between 2025-2050 in the high productivity scenario, amounting to just 40% of the costs projected in the BAU. While fertilizer costs show a more modest decline of 14.8% over the same 25-year period, the contrast with the BAU’s upward trend still results in significant cost savings of nearly 40%. This demonstrates how improved productivity can strengthen competitiveness while adapting to climate challenges.

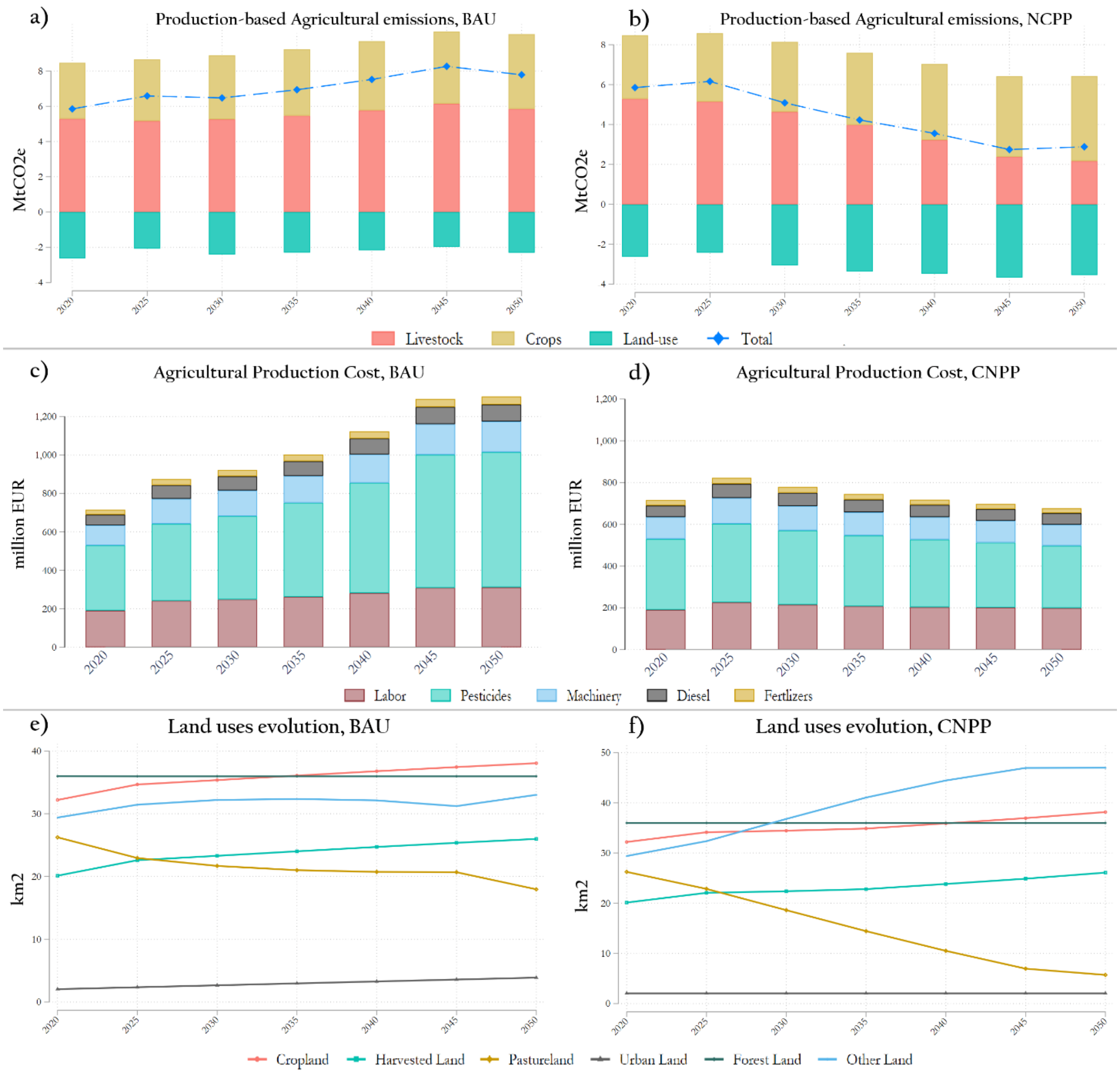

Figure 2. Production-based agricultural GHG emissions, for the BAU (a), and the CNPP scenario (b). Production costs for the BAU (c), and the CNPP scenario (d). Land use changes for the BAU (e), and the CNPP scenario (f).

The pronounced increase in agricultural productivity and the shift to healthier diets, associated with reduced red meat consumption, leads to the marked drop in pastureland in the CNPP scenario (Figure 2e,2f). The total area for pastureland drops by 29% in the 2020-2030 period, whereas mid-century levels are 78% lower compared to the starting figure in 2020. The respective decreases for the BAU scenario are 17.3% and 31.2% respectively. Given the lack of national commitment for a quantitative afforestation target and the marginal reduction in cropland, this leads to a significant surge in the area described as "Other" Land in the FABLE Calculator (Figure 2e,2f).

Cross-sectoral Energy-Emissions Analysis

The energy-emission simulation of all sectors was performed for the BAU scenario, assuming a 'do-nothing' case, continuing current accounts' trends and assumptions, and the CNPP scenario, which is in essence the Greek NECP. The parameters that are changing according to the specific NECP recommendations, include the fuel mix shares serving the demand (increasing the share of cleaner fuels), and improvements in energy efficiencies per sector and use.

The results project a significant reduction in energy consumption and emissions under the CNPP scenario, in contrast to the BAU (Figure 3a,3b). An overall reduction in energy demand of 23% is observed, with the most drastic reductions achieved in industry (58%), passengers and freight transportation including international aviation and maritime (34% each). Improvements in energy efficiency is mainly driving these trends. The decreasing trend of the residential energy consumption over time is primarily driven by the country's shrinking population (AL). The services sector, including public buildings, hotels, hospitals, exhibits a 28% increase of energy consumption, following increased future needs for services. Agriculture's energy consumption increases by 15%, following the increased productivity requirements simulated in the FABLE Calculator. Overall, the level of energy consumption is estimated to remain significantly high in 2050, under both scenarios.

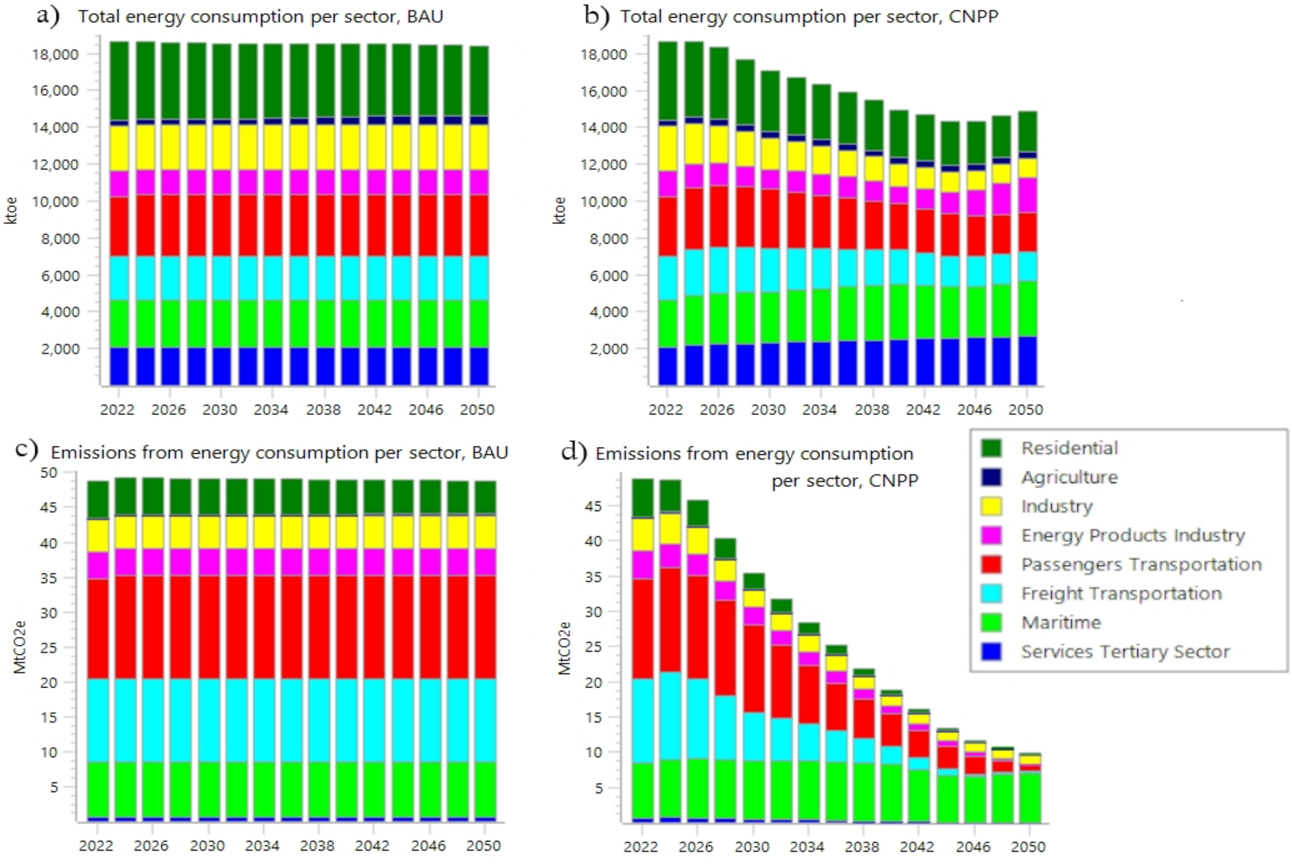

Figure 3: Total energy consumption per sector, under the BAU (a) and the CNPP scenario (b), with the respective GHG emissions (100-Year GWP), under the BAU (c) and the CNPP scenarios (d).

With respect to the supply side (energy generation), Figures 4a and 4b illustrate the total energy generated per feedstock fuel type, which is then used to cover the consumption. As expected, there is a substantial decline in oil refining products under CNPP, almost by 3 times in 2050. Conversely, electricity production is expected to rise significantly, by 6.5Mtoe in 2050. New contributions to energy production include hydrogen and synthetic fuels, reaching in total 1.1Mtoe and 571ktoe, respectively. The shift in energy production types, highlighted by the reduced reliance on conventional petroleum products and fossil-based electricity, contributes to further GHG emission reductions. Emissions are projected to decrease from 26MtCO_2eq in 2022 to 5.2MtCO_2eq by 2050. These changes are attributed to the evolving energy mix and technologies introduced under the CNPP scenario.

Both energy consumption and fuels supply results were also validated, cross-checking with data from CNPP's assumptions, EUROSTAT (2022), and the IEA (2023a).

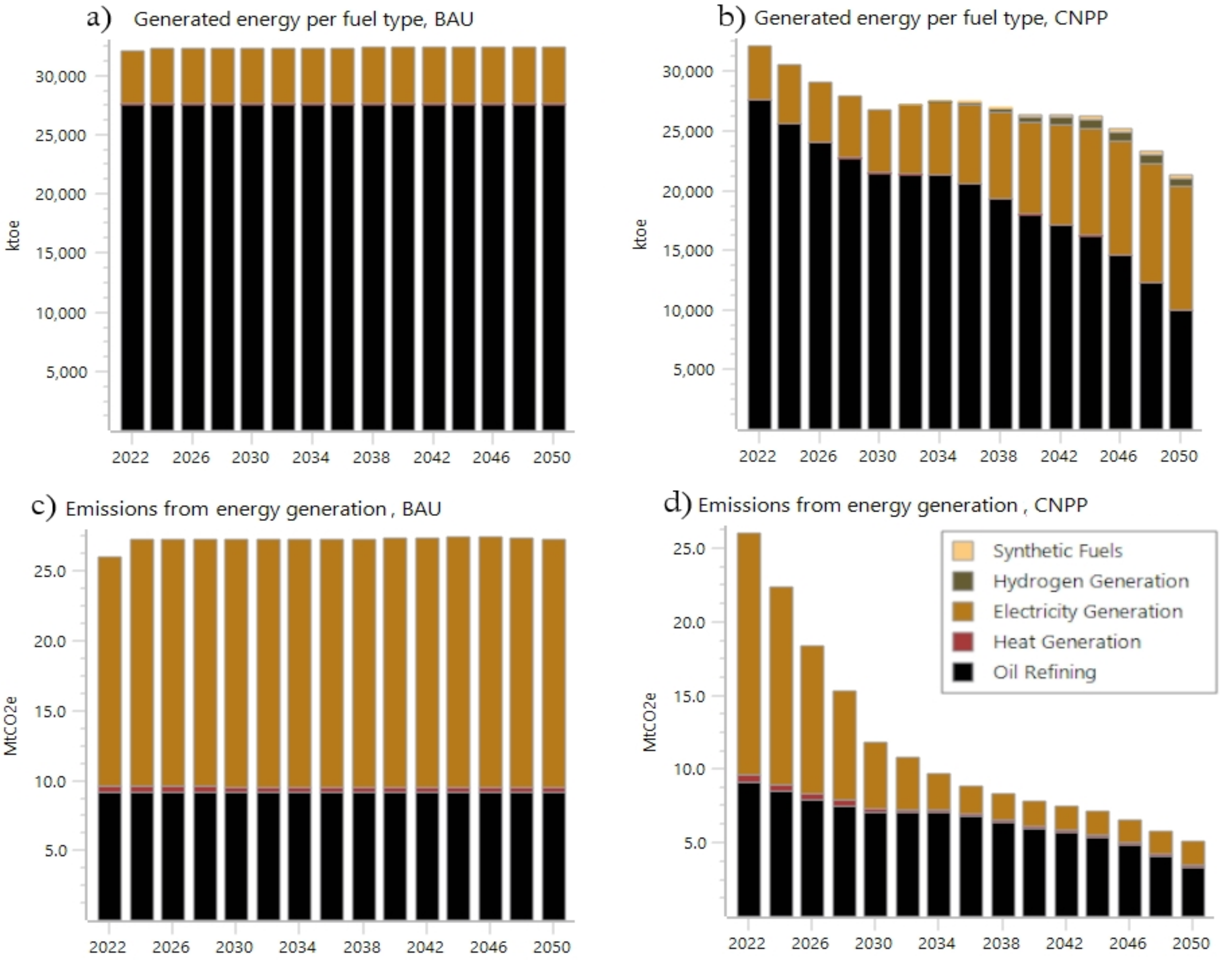

Figure 4: The generated energy from the different feedstock fuels for the BAU (a), and the CNPP scenario (b), with the respective GHG emissions (100-Year GWP) from these energy generation processes, for the BAU (c), and the CNPP scenario (d).

The NECP-projected energy sources, particularly for electricity, indicate a complete phase-out of lignite for electricity production; a 77% reduction in natural gas use, and substantial increases in clean energies (renewables, hydrogen, synthetic fuels, and oil products). These have been also simulated in detail. Indicatively for the significant changes that are projected, we mentioned that wind and solar power deployment are about to increase by 540% by 2050, while the hydroelectric power output is projected to rise by 120%.

The implementation of the NECP would lead to a dramatic reduction of GHG emissions by 2050 compared to the BAU scenario, decreasing by 91.7% (Figures 3c,3d, Figures 4c,4d). These emissions are calculated using the 100-year Global Warming Potential (GWP) of direct GHG emissions and are predominantly composed of Carbon Dioxide (CO_2), with smaller contributions from Methane (CH_4), Nitrous Oxide (N_2O), and Carbon Monoxide (CO). By 2050, the CNPP scenario achieves near-complete decarbonization, whereas the BAU has a slightly increasing trend. At this stage, it is worth commenting again on the key difference between the FABLE Calculator's production-based agricultural GHG emissions and LEAP's energy-based agricultural GHG emissions: FABLE Calculator estimates agricultural GHG emissions by simulating food and livestock production processes, including land use changes, agronomic practices, and non-energy-related processes (such as enteric fermentation, manure management, and fertilizer application), capturing thus a broader range of emissions associated with agricultural production. Hence the term "production-based emissions" for FABLE Calculator. Complementarily, the LEAP model calculates the emissions based solely on the energy use in production processes (per unit of final products). Hence the term "energy-based emissions" for LEAP.

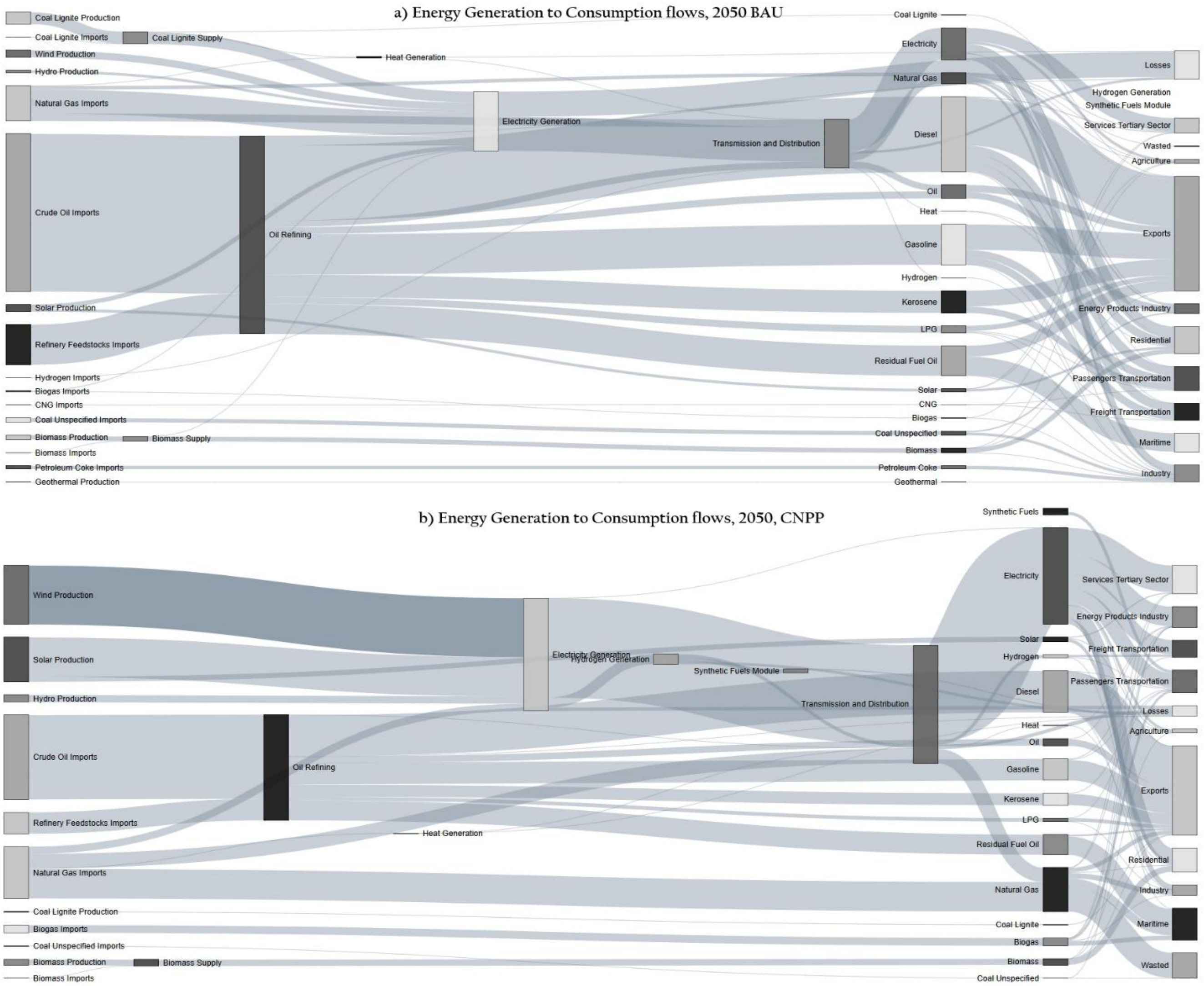

Figure 5: Sankey diagrams for the energy generation and consumption flows, for the BAU (a) and the NCPP scenario (b).

In general, regarding the total GHG emissions, the primary driver of the reductions in the total emissions (both from energy consumption and energy generation) is the significant decrease in fossil fuel use across the residential, industrial, and transportation sectors, one of the core recommendations of the NECP. Additionally, the adoption of renewable energy sources in electricity production – coupled with the introduction of hydrogen and synthetic fuels, particularly in the transportation sector – further contributes to these reductions. Figures 5a and 5b show the flows of feedstock fuels into energy transformation processes to produce fuels that cover different energy demand uses, indicatively for 2050. The transition to cleaner fuels is obvious, as mentioned. Both Sankey diagrams indicate that the energy production-transformation-consumption balance is "confirmed" throughout the simulation period.

Biofuel production potential

As mentioned, the agricultural output results of the FABLE Calculator are analyzed through the BiofuelGCH Calculator, to account for the residues available for biofuel production (without affecting food production), and estimate this potential. This refers to the amount of bioethanol (produced from corn, sugarbeets, and wheat residuals), and the amount of biodiesel (produced from sunflower and olive residuals). So, it does not take into account the wooden and pellet potential production, which is however the major use of biomass for residential heating and cooking.

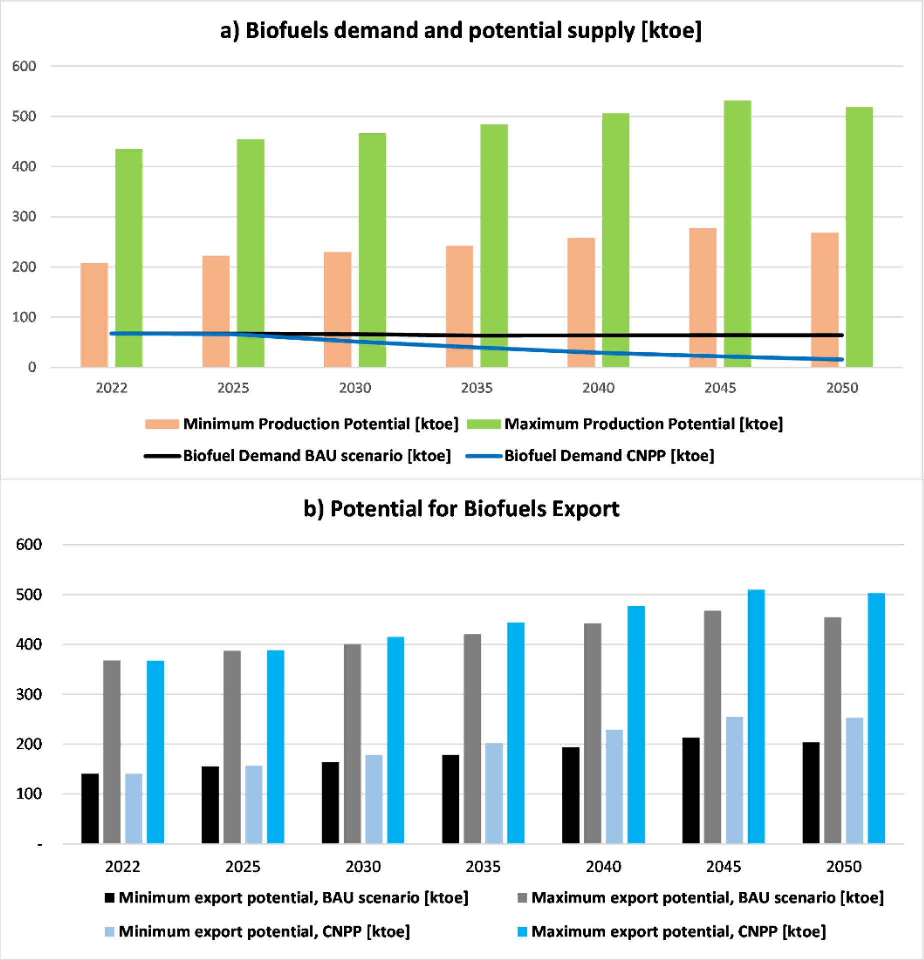

Figure 6: a) The resulted biofuel production potential (min-max), and the demand for biofuels use (for the BAU and the CNPP scenarios), excluding wood and pellet products. b) The excess production potential that can be exported (min-max) for the BAU and the CNPP scenarios.

The results indicate that there is a significant potential to produce biofuels domestically, ranging from 208-435ktoe in 2022 to 268-519ktoe in 2050. This production can fully cover the biofuel demand from uses such as agriculture, energy production and transformation processes (Figure 6a), and the excess amount can be used for exports (Figure 6b).

Land requirements

The implementation of the CNPP, as simulated in LEAP, requires in total 35051MW of solar energy, and 24780MW of wind power in 2050. This corresponds to an additional capacity of 28051MW and 16280MW respectively, compared to the current (2025) solar and wind power. Moreover, the CNPP projects that 52.46% of the wind power will be onshore, while the rest should be offshore. So, this results in 8541MW.

The LandReqGCH model, based on these figures, uses typical values from the literature to convert these additional required capacities in solar and wind power into land requirements (km^2) for the installation of additional solar panels and wind farms (onshore). These values from the literature are used as land conversion coefficients (km^2/MW), taking into account the types of land uses, and the types of projects, and considering a range of options, according to Denholm et al. (2009) and Ong et al. (2013).

So, for solar panels that would range from 670km^2 (min) to 846km^2 (average) and to 1022km^2 (max). The onshore wind farms would require from 19km^2 (min) to 25km^2 (average) and to 35km^2 (max).

The LandReqGCH model also provides estimates of the expected costs for the installation of these projects, considering their typical costs (EWEA, 2010; Tamesol, 2023).

Regarding the solar panels, the cost would range (min-average-max) from 1005million€ to 1269million€ and to 1533million€. The respective costs for the wind farms would range from 18.8 million€ to 25.3million€ and to 35million€.

Shipping sector

The port activities covered by the LEAP model indicate that a mix of cleaner fuels must be supplied to ships, phasing out the predominant oil-type fuels that are currently used. An additional consideration is the composition and response of the Greek fleet travelling domestically and internationally. The MaritimeGCH model simulates and optimizes the fleet's maritime operations, considering a composition of container, tanker, bulk cargo, general cargo, and other vessels, including passengers. The model provides the optimal composition of the fleet each year for the planning period, considering the age and lifetime per vessel type, and ensuring that the demand in shipping services will be met, along with all the other techno-economic constraints mentioned in the previous section. Also, the model allows ships to select their CII grading, and exceed the ETS emissions threshold (cap) in line with the real-world case, while accounting for emissions allowances, that must be purchased under the ETS (Figure 7).

Currently, the Greek fleet is estimated to emit 99.68MtCO2e, which is well above the European regulatory threshold of 97.9MtCO2e. in alignment with the EU maritime policy and IMO's targets, the simulated CNPP involves:

a) the combination of the following emission-reduction technologies:

- Optimizing engine power: tuning engines for efficiency, potentially using advanced fuel injection systems, and optimizing speed for reduced fuel consumption and emissions.
- Route Optimizer technology to reduce emissions: real-time weather and sea conditions to determine the most fuel-efficient and emissions-saving routes.
- Port-call technology for optimal entrance to a port: streamlining vessel arrival times to ports, reducing idle time, fuel consumption, and emissions during waiting periods.
- Propulsion system: more efficient systems, such as wind-assisted propulsion, air lubrication systems, or alternative fuel propulsion systems.
- Hull cleaning and maintenance: technologies to clean the ship aiming at reduced traction, and subsequently emissions.
- On board carbon capture: Technologies to capture and concentrate the carbon dioxide from emitting flue gas.

For each one of these technologies, a reduction factor in emissions was considered, with implementation costs assigned to operating expenses of each vessel though its lifetime.

b) a moderate fuel-transition projection, assuming that oil fuels will gradually phase out (Oil and Refined Petroleum products), being replaced by the transition fuels (LNG and LPG), while by 2050 they will be replaced by clean fuels such as MeOH, NH3 and H2.

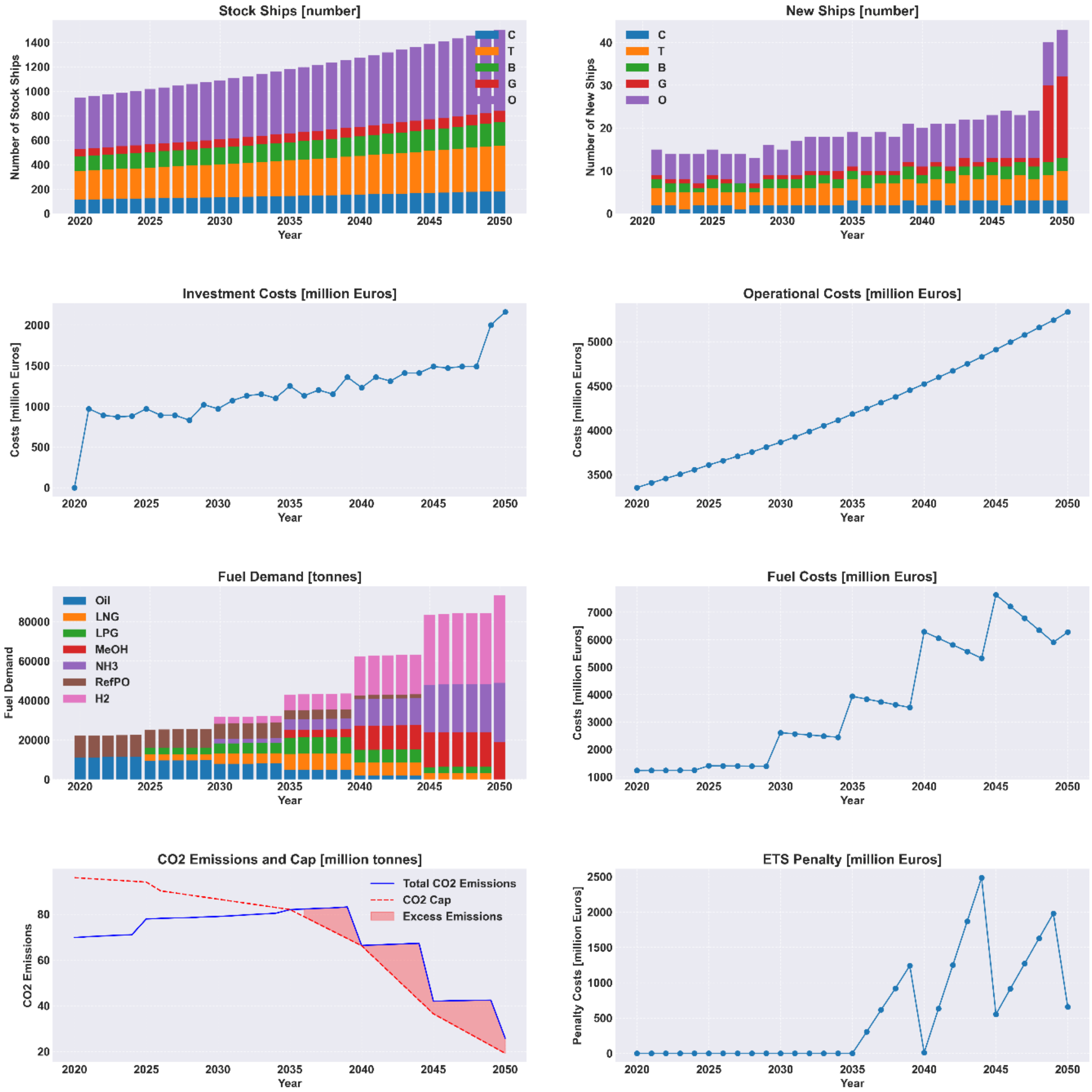

Figure 7: Results of the application to the Greek fleet for the base case scenario assuming the combined technology scenario and the transition to cleaner fuels, including: the fleet composition (stock and new ships); investment and operational costs; fuel demand and the associated costs; the CO2 emissions compared to the ETS threshold, and the associated penalty.

The results show the fleet evolution, investment, and operational metrics until 2050. As assumed, there is a steady growth in the shipping demand services, driving a respective increase in the number of vessels for its coverage (exceeding 1,400 vessels by 2050). There is a notable increase in container (C) ships and a significant uptick in 'other' (O – mainly passenger) ships towards 2050. The investment costs remain relatively stable from 2020 to 2045 (fluctuating between €1,000million and €1,500million until 2045), followed by a marked increase approaching 2050, following the need for new vessels (nearly

€2,000million). The fuel demand distribution shows a declining reliance on oil as cleaner fuels gain prominence, indicating a strategic shift towards sustainability. Oil fuels give their place gradually to LNG and LPG in the mid-term, and NH3, MeOH and H2 in the long-term. With the combination of efficiency measures and technologies implemented, emissions are well below the threshold (cap) set by the ETS and gradually increase as further shipping demand is met with fossil fuels. The results indicate an inflection point in the mid-2030s as cleaner fuels displace fossil fuels and emissions monotonically begin to drop. This increases fuel costs significantly, as much as triple the cost compared to 2020. Simultaneously, due to emissions trajectories not keeping up with the emissions cap reductions, ETS penalties take effect in the late 2030s and do not disappear by 2050. By 2050, emissions reach 25Mtpa, 6MT above the cap, but trending in the right direction. This indicates in the base case scenario, with significant bunkering capabilities going online within the next 10-15 years for cleaner fuels, emissions will significantly decrease by 2050 but increase in the short-term, in conjunction with fuel costs, doubly hurting the shipowners' bottom line when the ETS cap is exceeded. It is only due to the fuel-efficiency technologies being implemented right away that shipowners do not face significant ETS penalties until the latter half of the simulation.

Based on this finding, it can be concluded that without further action in terms of subsidies, technology advancement or commitments the full decarbonization of the maritime industry by 2050 simply is not possible. We would like to caveat these results by stating that the emissions factors do not consider upstream emissions reduction in clean fuels. Fuels made from lower or negative emissions intensity via direct air capture, biomass and renewable energy can lower the lifecycle emissions factors to 0, but this analysis evaluates fuel-combustion related emissions. advancement or commitments the full decarbonization of the maritime industry by 2050 simply is not possible. Ship-owners need to act proactively by investing in mature, cost-efficient fuel-saving technologies, which can substantially lower ETS costs. An intensified development of bunkering infrastructure for alternative fuels is necessary to facilitate fuel switching without significant supply bottlenecks. A coordinated regulatory framework combining ETS revenues, FuelEU Maritime requirements, and AFIR-based port investments is necessary for the transition to green shipping to take place smoothly. Decarbonization led by the market is not enough—policy intervention, fiscal incentive, and infrastructure development, all aimed at preventing unwarranted compliance costs and business displacement for Greek shipping, are required.

Water Requirements

The WaterReqGCH model was applied for all sectors and years of the studied period, providing also estimates for monthly distributions, accounting thus for seasonality in water requirements. The water sector faces the higher uncertainties, as the consumption is affected by various socio-economic, infrastructure, and hydro-climatological factors that are inherently uncertain. Moreover, there are no specific demand management measures per sector, according to the Greek RBMPs.

Urban water use, encompassing residential and service sectors, represents the 7–8% of total consumption. This comparatively modest share is indicative of more efficient urban water management, for a lower population-driven demand relative to agricultural needs. Urban water consumption decreases from an average of 725.19hm^3 in 2020 to 630.31hm^3 in 2050, driven by Greece's reducing population. The CNPP scenario assumed a reduction in water network losses, so they reach 20% in total. This measure would further reduce the urban water requirements to 578hm³ in 2050, which is within the estimated range area plotted in Figure 8.

Agriculture is the dominant consumer of water resources, consistently accounting for 88–89% of the total consumption over the period 2020-2050. This is indicative of the sector's reliance on irrigation and water-intensive practices, which reflect Greece's Mediterranean climate and the importance of agriculture in its economy. Agricultural water consumption follows a slight increase after 2025 and reaches an average consumption of 8041.12hm³ by 2050, with only minor fluctuations. The CNPP scenario for agriculture, as defined within the FABLE Calculator, assumes that the number of livestock population and the amount of irrigated areas will remain stable, aiming to higher productivity outputs while using the same input resources. Based on this assumption, the livestock and irrigation water requirements will not vary outside of the plotted uncertainty range for agriculture, as shown in Figure 8. Another key factor here is the assumption that the demand remains stable, driving this relatively stable behaviour, which is largely uncertain, though.

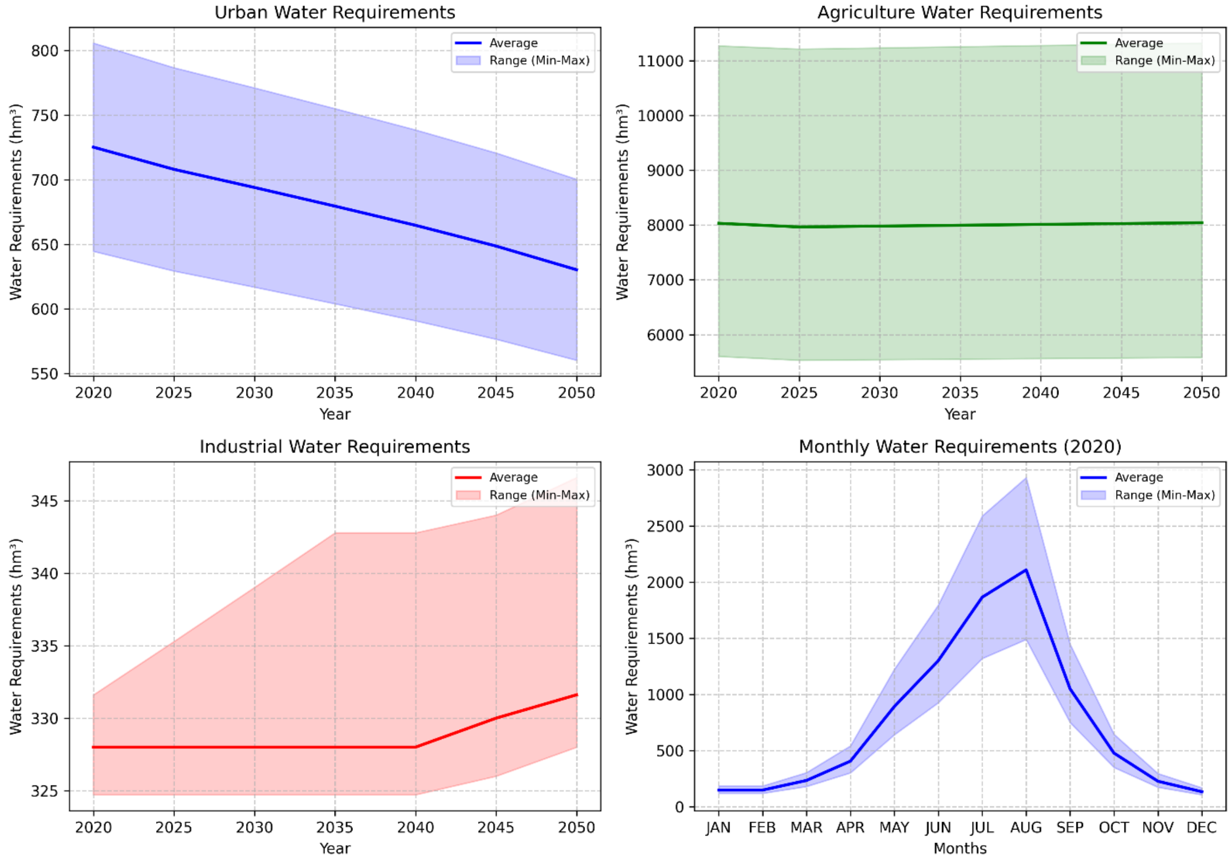

Figure 8: Urban (residential and services), agricultural (irrigation and livestock), and industrial water requirements. The monthly water requirements plot shows the monthly allocation of the total consumption.

Industrial use remains the smallest contributor at 3–4%, aligning with Greece's economic structure, where industrial activity is less dominant compared to agriculture and services. Its water consumption remains relatively stable, with slight increases from 328hm³ in 2020 to 331.61hm³ in 2050. The ranges of minimum-maximum values are larger for agriculture, and reflect various data and computational uncertainties. The CNPP does not assume any specific measures per industry types' water use.

The monthly distribution of the total water requirements is shown indicatively for 2020, and follows the same pattern until 2050. It reveals a sharp increase during the prolonged Greek summer period (May–October), reflecting peak irrigation needs and heightened urban water use during the tourist season, and due to increased temperatures. For instance, the average monthly water requirement in July (1866.6hm^3) is more than eight times higher than in December (134.55hm^3). This pronounced seasonality underscores the pressure on water resources during the dry season and the importance of adequate storage and distribution infrastructure (Alamanos, 2021).

Challenges to progress towards ambitious climate-neutrality targets

So far, Greece's progress towards achieving climate neutrality has been notably limited, with slow decarbonization across major sectors despite EU mandates and global commitments, despite its overly ambitious targets (IEA, 2023). As mentioned in the study area description, the country continues to rely heavily on fossil fuels, and investments in renewable energy and energy efficiency remain insufficient compared to the NECP's goals. In spite of the 2024 EU ETS inclusion of maritime transport, shipping – one of the economic pillars of Greece – remains lacking a national climate strategy. Our analysis suggests that even profound fuel switches and emission-reducing technologies might not be enough to completely decarbonize the Greek fleet without further policy support and financial incentives. The danger of omitting maritime decarbonization from national energy planning is increased ETS expenses and operating discontinuity for shipowners. The overall slow progress so far makes the achievement of the NECP targets quite challenging, as documented by the European Environment Agency (EEA) and echoed in recent analyses (e.g., IEA reports and the NECP review by the European Commission) (IEA, 2023a, 2023b).

The agricultural sector in Greece is also underperforming in terms of sustainability and resource efficiency. The Greek CAP plan emphasizes to improved competitiveness by promoting innovation and new technologies, fostering young entrepreneurship, as the sector consists mainly of aging and declining population (CAP Strategic Plan, 2022). In parallel, it sets ambitious targets on reducing the environmental footprint of agriculture and apply innovative technologies. However, the sector suffers from outdated farming practices and limited modernization opportunities, weak managerial control and accountability mechanisms (Despoudi, 2021; Kleanthis et al., 2022; Kyriakopoulos et al., 2023). This results in low productivity and inefficient energy use, as highlighted in studies such as Shan et al. (2015) and Kourgialas (2021), as well as in a recent living lab in Greece's major agricultural region (Alamanos et al., 2022).

Under the WFD, Member-States must update and report their RBMPs with the respective programmes of measures every six years. Greece delayed two and a half years to review, adopt or report its RBMPs, along with other Member-States. The European Commission referred Greece to the Court of Justice of the European Union (European Commission, 2024a). This inaction is reflected also in the actual progress, with the latest cycles of the RBMPs revealing a slight degradation of water bodies, along with a big body of research warning about ecological and water management issues, with agriculture being the main pressure (Shan et al., 2015; Kourgialas, 2021; Karasoy, 2024). Demand management is at a very primitive stage, where the general perception still sees large-scale engineering works increasing the (limited supply) as synonymous to the country's development, and is skeptical to more integrated, efficiency-oriented strategies (Alamanos et al., 2022; Kyriakopoulos & Sebos, 2023).

Overall, there are efforts towards climate-neutrality, which face however significant challenges.

Scattered policies with uncertain and unintended consequences

The examined policies (NECP, CAP, RBMPs) face challenges due to differing planning horizons, target years, and implementation responsibilities. This fragmented approach can lead to scattered efforts and potential inefficiencies in achieving Greece's sustainability goals.

In particular, the current NECP sets targets for 2030 and 2050, while CAP operates on a seven-year cycle (with the current one running from 2023 to 2027), and the RBMPs are updated every six years to manage water resources at the river basin level, and their third and final cycle ends in 2027. This misalignment in timelines and objectives can result in uncoordinated strategies, where policies may not effectively complement each other.

Our findings indicate potentially unintended consequences among these policies, under the simulated CNPP scenario. For example, the achievement of the NECP's objectives requires an increase of wind and solar power deployment by 540% by 2050. This translates to an additional land requirement (on average) of 871km^2 for solar panels and onshore wind farms, costing on average 1295million€. Capacity and economic feasibility concerns can naturally occur though. For instance, it is worth mentioning as a measure of comparison, that in figure 2f, the forest land is around 36km^2. So, there are more land use changes that are not considered in any policy, and are directly conflicting with agriculture, forestry, biodiversity, smallholders and farmers ownerships and interests, with the expansion of green energy and the respective expectations on decarbonization.

The NECP has only in theory the potential to curb emissions from agriculture, residential, industrial, transportation, services, and energy production sectors. Again, that would require its proper implementation, which in turn requires certain behavioural changes (e.g. adoption of technologies to improve energy efficiency and mixes of cleaner fuels). Even if this is achieved, it is worth noting that the NECP does not achieve a complete decarbonization in 2050, there are still emissions, but significantly lower.

For the case of agriculture, the NECP does not explicitly indicate technological and fuel mix changes to be considered. Our modelled CNPP scenario in the FABLE Calculator is actually more ambitious than the NECP itself, because we took into account broader goals and national commitments. For instance, the European food policy aims for higher productivity and resilience, along with the decarbonization goals, while in the Greek CAP these are represented more vaguely. Our model presented a scenario showing that a combination of these goals – since they are inherently interconnected (higher productivity, same land, lower emissions) is actually possible, and at a lower cost. However, it also led to a slight (15%) increase in energy use, while it cannot directly account for the potential increases in water use. The FABLE Calculator did not have solid restrictions on their potential expansion. So, there might be more feasibility constraints to achieve this target. In reality, the high productivity CNPP scenario can be water-intensive, even if the irrigated areas do not expand. Therefore, it is expected that agricultural water requirements might increase. This is also reinforced by the expected drier climate, which increases crop evapotranspiration, demanding more irrigation (Nastos et al., 2015; Deveci & Konukcu, 2024). The dominance of agriculture in water consumption emphasizes the need for targeted interventions in this sector, which are side-mentioned by the RBMPs (Karavitis & Oikonomou, 2024).

Biofuel production remains another overlooked area. Our findings indicate that Greece has the capacity to potentially fully cover the biofuel demand from certain uses and even be exported (while currently Greece imports biofuels). Also, with respect to biofuels, currently no policy considers their role in shipping decarbonization, although their role has increased significantly with the IMO's FuelEU Maritime regulation that suggests their adoption and sets strict emissions controls.

Furthermore, the implementation of these policies often falls under the jurisdiction of different ministries and regional authorities, such as the Ministry of Environment and Energy overseeing the NECP, the Ministry of Rural Development and Food managing the CAP, and all 13 Greek Regional Authorities being responsible for the implementation of their respective RBMPs. Also, shipping sector's efforts towards climate-neutrality will be challenging, requiring the coordination of policies between the Ministry of Environment and Energy, which oversees fuel supply at ports, and the Ministry of Transportation, responsible for fleet management, along with divergent interests among private stakeholders. Also, the translation of European policies into national context can be challenging in practice, although the recently introduced Alternative Fuels Infrastructure Regulation (AFIR) (EU 2023/1804) and Renewable Energy Directive (RED III) (EU 2023/2413) require the consideration of how decarbonization actions should be addressed within each Member-State's policy. For instance, the European Commission's 'Fit for 55' package proposes ambitious climate policies, including the modelled EU ETS to shipping, yet gaps remain in ensuring cross-sectoral policy coherence, notably between shipping and energy-related decarbonization approaches. These fragmented governance structures can create siloed communication channels, hindering effective collaboration and integrated policy execution. Recognizing these challenges, the European Commission has provided support to enhance collaboration among Greek governing bodies and public entities through an interministerial coordination manual (European Commission, 2016).

Concluding remarks

This research presented an integrated modelling approach, to assess the Greek CNPP, as closely as possible to the current real-world policy landscape, referring to the main systems (food, land, energy, emissions, and water). The simulated CNPP scenario is a theoretical case, assuming that policies like CAP, the NECP, and the RBMPs will be fully implemented.

Unavoidably, this work does not come without limitations. First, the assumption of the CNPP scenario as a hypothetical case, which however, served as a useful cross-sectoral analysis to inform about trade-offs, gaps, and areas for improvement. Second, we simulated Greece as a whole, without providing a more refined spatial representation, considering the different regions of the country. This was due to data limitations and inconsistencies across all the studied systems in different regions, as well as the increased computational demand when combining different models that consider inputs that are mostly subject to different scales, units and time-steps. However, we believe that for the purpose of this national plans' assessment, the results provide a satisfactory picture of the studied nexus and policy in Greece. Third, the focus on food, land, energy, emissions, and water system does not mean that these are the only relevant ones. They are simply the main relevant ones to the existing CNPPs, and highly interconnected in modelling terms. The social, economic, biodiversity, and waste systems are included in our future research plans.

Besides the limitations, the presented combination of tools for the assessment of different planned efforts towards climate-neutrality, provide critical insights into nexus systems and potential trade-offs, which is crucial for addressing complex sustainability challenges. Such assessments allow also the exploration of the impact of real policies. Although specific sectoral plans have the potential to achieve multiple co-benefits, the absence of a unified framework can lead to insufficiencies and missed opportunities for synergies and unintended conflicts among objectives. A key point in transitioning to unified and more integrated approaches is the realization that climate adaptation cannot be seen merely as an emissions reduction effort. It requires a broader sustainability context, wider than just decarbonization, involving the improvement of all interconnected sectors. This position is in line with a recent Comment in Nature (Arezki et al., 2024) arguing that the European policy itself has to evolve first, to accommodate global changes that happened since the design of ambitious targets. This research further highlights that national policies can be also play a pivotal role in triggering such policy evolutions, considering multiple sectors under more unified and coordinated frameworks. Greece could benefit from the European Commission's guidance and establish an inter-ministerial coordination mechanism, creating a dedicated body to align the implementation of NECP, CAP, and RBMPs, their planning horizons, developing thus more coherent long-term strategies that would consider multiple trade-offs. Finally, integrated modelling approaches can serve as central tools in these efforts. Therefore, the development of robust national integrated modelling systems of fine resolution is also recommended. The creation of a unified platform for simulating complex systems, monitoring policy interactions, and tracking progress across all related policies can facilitate better decision-making, resource allocation, and long-term sustainability planning.

Next Steps

The next steps of the presented modelling approach refer to:

- Development of a LEAP model version that will be significantly more time-efficient, data-handling efficient, with increased accuracy, and easily expandable & replicable, to ensure a fast simulation of the other European countries.
- Comparison of the two model versions to benchmark them, and build a strong case for a robust and time-efficient modelling approach for Europe.
- Consider the potential use of economic inputs in LEAP, to have this information in a single model – Complementary with the General Computable Equilibrium model that will be developed.
- Replicate the approach for all European countries, ideally by spring.
- Get access to more FABLE Calculators, for more European countries, and/or find ways to work on the land-agriculture system of countries with no available Calculators.
- Present a novel methodology to develop the "SDSN success pathway" by 2050. The developed methodology will be directly transferable from the individual national level (of each country) to the continental scale, and consider a flexible, explicable narrative and tangible trade-offs among the models presented here.

References

Abeliotis, K., Costarelli, V., & Anagnostopoulos, K. (2016). The Effect of Different Types of Diet on Greenhouse Gas Emissions in Greece. *International Journal on Food System Dynamics*, *Vol 7*, 36-49 Pages. https://doi.org/10.18461/IJFSD.V7I1.714

Abram, S., Atkins, E., Dietzel, A., Jenkins, K., Kiamba, L., Kirshner, J., Kreienkamp, J., Parkhill, K., Pegram, T., & Santos Ayllón, L. M. (2022). Just Transition: A whole-systems approach to decarbonisation. *Climate Policy*, *22*(8), 1033–1049. https://doi.org/10.1080/14693062.2022.2108365

Alamanos, A. (2021). Water resources planning under climate and economic changes in Skiathos island, Aegean. *Journal of Water Supply: Research and Technology-Aqua*, *70*(7), 1085–1093. https://doi.org/10.2166/aqua.2021.061

Alamanos, A., Nisiforou, O., Garcia, J.A., Papadaki, L. & Koundouri, P. (2024). *Integrated fleet optimization under techno-economic shipping and environmental constraints: the MaritimeGCH model.* DOI: 10.13140/RG.2.2.35892.87680. Available at: https://github.com/Alamanos11/MaritimeGCH

Alamanos, A. (2025). *The online free web app of the MaritimeGCH model*. https://share.streamlit.io

Alamanos, A., & Koundouri, P. (2024). *Estimating the water requirements per sector in Europe.* https://www.researchgate.net/profile/Angelos-Alamanos/publication/386245556_Estimating_the_water_requirements_per_sector_in_Europe/links/6749d5873d17281c7deacbd1/Estimating-the-water-requirements-per-sector-in-Europe.pdf?__cf_chl_tk=fHpUHdaHJiBdO64MqGFr6VdICQGVzayXeMIMNj0xgg8-1738254361-1.0.1.1-gml.ztb2RIAZtV8FEt_VNzJfQjcHuYhn1AAaEIVwPNk

Alamanos, A., Koundouri, P., Papadaki, L., & Pliakou, T. (2022). A System Innovation Approach for Science-Stakeholder Interface: Theory and Application to Water-Land-Food-Energy Nexus. *Frontiers in Water*, *3*. https://doi.org/10.3389/frwa.2021.744773

Alamanos, A., Sfyris, S., Fafoutis, C., & Mylopoulos, N. (2019). Urban water demand assessment for sustainable water resources management, under climate change and socioeconomic changes. *Water Supply*, *20*(2), 679–687. https://doi.org/10.2166/ws.2019.199

Alexandropoulou, V., Koundouri, P., Papadaki, L., & Kontaxaki, K. (2021). New Challenges and Opportunities for Sustainable Ports: The Deep Demonstration in Maritime Hubs Project. In P. Koundouri (Ed.), *The Ocean of Tomorrow: The Transition to Sustainability – Volume 2* (pp. 173–197). Springer International Publishing. https://doi.org/10.1007/978-3-030-56847-4_11

Angeli, A., Karkani, E., Alamanos, A., Xenarios, S., & Mylopoulos, N. (2020, March 23). *Hydrological, socioeconomic, engineering and water quality modeling aspects for evaluating water security: Experience from Greek rural watersheds.* https://doi.org/10.5194/egusphere-egu2020-22101

Arezki, R., Landau, J.-P., & van der Ploeg, R. (2024). Why the EU must reset its Green Deal—Or be left behind. *Nature*, *636*(8041), 42–44. https://doi.org/10.1038/d41586-024-03918-w

Blackburn, C., Harding, A., & Moreno-Cruz, J. (2017). Toward Deep-Decarbonization: An Energy-Service System Framework. *Current Sustainable/Renewable Energy Reports*, *4*(4), 181–190. https://doi.org/10.1007/s40518-017-0088-y

CAP Strategic Plan. (2022). *Greece – CAP Strategic Plan*. https://agriculture.ec.europa.eu/cap-my-country/cap-strategic-plans/greece_en#annual-performance-reports

Capros, P., Zazias, G., Evangelopoulou, S., Kannavou, M., Fotiou, T., Siskos, P., De Vita, A., & Sakellaris, K. (2019). Energy-system modelling of the EU strategy towards climate-neutrality. *Energy Policy*, *134*, 110960. https://doi.org/10.1016/j.enpol.2019.110960

Chen, H., Feng, L., & Sun, X. (2024). Beyond central-local relations: The introduction of a new perspective on China's environmental governance model. *Humanities and Social Sciences Communications*, *11*(1), 1–12. https://doi.org/10.1057/s41599-024-03082-6

Clarksons. (2024). *Maritime & Shipping Research Services*. https://www.clarksons.com/research

Den Elzen, M. G. J., Dafnomilis, I., Forsell, N., Fragkos, P., Fragkiadakis, K., Höhne, N., Kuramochi, T., Nascimento, L., Roelfsema, M., Van Soest, H., & Sperling, F. (2022). Updated nationally determined contributions collectively raise ambition levels but need strengthening further to keep Paris goals within reach. *Mitigation and Adaptation Strategies for Global Change*, *27*(5), 33. https://doi.org/10.1007/s11027-022-10008-7

Denholm, P., Hand, M., Jackson, M., & Ong, S. (2009). *Land-Use Requirements of Modern Wind Power Plants in the United States*. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy09osti/45834.pdf

Despoudi, S. (2021). Challenges in reducing food losses at producers' level: The case of Greek agricultural supply chain producers. *Industrial Marketing Management*, *93*, 520–532. https://doi.org/10.1016/j.indmarman.2020.09.022

Deveci, H., & Konukcu, F. (2024). Modeling the Effect of Climate Change on Evapotranspiration in the Thrace Region. *Atmosphere*, *15*(10), Article 10. https://doi.org/10.3390/atmos15101188

Devot, A., Royer, L., Arvis, B., Deryng, D., Caron Giauffret, E., Giraud, L., Ayral, V., & Rouillard, J. (2023). *Research for AGRI Committee – The impact of extreme climate events on agriculture production in the EU*. European Parliament, Policy Department for Structural and Cohesion Policies, Brussels. https://www.europarl.europa.eu/RegData/etudes/STUD/2023/733115/IPOL_STU(2023)733115_EN.pdf

Doelman, J. C., Beier, F. D., Stehfest, E., Bodirsky, B. L., Beusen, A. H. W., Humpenöder, F., Mishra, A., Popp, A., Van Vuuren, D. P., De Vos, L., Weindl, I., Van Zeist, W.-J., & Kram, T. (2022). Quantifying synergies and trade-offs in the global water-land-food-climate nexus using a multi-model scenario approach. *Environmental Research Letters*, *17*(4), 045004. https://doi.org/10.1088/1748-9326/ac5766

Doukas, Y. E., Vardopoulos, I., & Petides, P. (2024). Challenging the Status Quo: A Critical Analysis of the Common Agricultural Policy's Shift Toward Sustainability. In A. Ribeiro Hoffmann, P. Sandrin, & Y. E. Doukas (Eds.), *Climate Change in Regional Perspective: European Union and Latin American Initiatives, Challenges, and Solutions* (pp. 115–134). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-49329-4_8

Duffy, C., Prudhomme, R., Duffy, B., Gibbons, J., O'Donoghue, C., Ryan, M., & Styles, D. (2022). GOBLIN version 1.0: A land balance model to identify national agriculture and land use pathways to climate neutrality via backcasting. *Geoscientific Model Development*, *15*(5), 2239–2264. https://doi.org/10.5194/gmd-15-2239-2022

Elbehri, A., Segerstedt, A., & Liu, P. (2013). *Biofuels and the sustainability challenge: A global assessment of sustainability issues, trends and policies for biofurls and related feedstocks*. Food and Agriculture Organization of the United Nations, Trade and Markets Division.

ELSTAT. (2024). *Main Page ELSTAT - the Hellenic Statistical Authority*. https://www.statistics.gr/en/home/

European Commission. (2016). *Interministerial coordination in Greece*. https://reform-support.ec.europa.eu/what-we-do/public-administration-and-governance/interministerial-coordination-greece_en

European Commission. (2023). *Water Framework Directive—European Commission*. https://environment.ec.europa.eu/topics/water/water-framework-directive_en

European Commission. (2024a). *Commission decides to refer GREECE to the Court of Justice*. https://ec.europa.eu/commission/presscorner/detail/en/ip_24_1235

European Commission. (2024b). *Decarbonising maritime transport – FuelEU Maritime—European Commission*. https://transport.ec.europa.eu/transport-modes/maritime/decarbonising-maritime-transport-fueleu-maritime_en

EUROSTAT. (2022). *Greece Energy Snapshot*. https://energy.ec.europa.eu/system/files/2022-10/EL_2022_Energy_Snapshot.pdf

EWEA. (2010). *Chapter 2: European Market Overview*. https://www.wind-energy-the-facts.org/the-current-status-of-the-eu-wind-energy-market.html

Fadiga, A., Ferreira, L. M. D. F., & Bigotte, J. F. (2024). Decarbonising maritime ports: A systematic review of the literature and insights for new research opportunities. *Journal of Cleaner Production*, *452*, 142209. https://doi.org/10.1016/j.jclepro.2024.142209

FAO. (2010). *Bioenergy and Food Security: The BEFS Analytical Framework*. FAO.

Felder, F. A., & Kumar, P. (2021). A review of existing deep decarbonization models and their potential in policymaking. *Renewable and Sustainable Energy Reviews*, *152*, 111655. https://doi.org/10.1016/j.rser.2021.111655

Fujimori, S., Krey, V., van Vuuren, D., Oshiro, K., Sugiyama, M., Chunark, P., Limmeechokchai, B., Mittal, S., Nishiura, O., Park, C., Rajbhandari, S., Silva Herran, D., Tu, T. T., Zhao, S., Ochi, Y., Shukla, P. R., Masui, T., Nguyen, P. V. H., Cabardos, A.-M., & Riahi, K. (2021). A framework for national scenarios with varying emission reductions. *Nature Climate Change*, *11*(6), 472–480. https://doi.org/10.1038/s41558-021-01048-z

Garcia, J. A., & Alamanos, A. (2023). A Multi-Objective Optimization Framework for Water Resources Allocation Considering Stakeholder Input. *ECWS-7 2023*, 32. https://doi.org/10.3390/ECWS-7-14227

Giannitsis, T., & KastelliI, I. (2014). Industrial policy in times of crisis: The case of Greece. In *Structural Change, Competitiveness and Industrial Policy*. Routledge.

Greek Ministry of Energy and Environment. (2024). *National Energy and Climate Plan (NECP)*. Greek Ministry of Energy and Environment. https://ypen.gov.gr/energeia/esek/

Halkos, G. E., & Tzeremes, N. G. (2012). Analyzing the Greek renewable energy sector: A Data Envelopment Analysis approach. *Renewable and Sustainable Energy Reviews*, *16*(5), 2884–2893. https://doi.org/10.1016/j.rser.2012.02.003

Heaps, C. G. (2022). *LEAP: The Low Emissions Analysis Platform* (Version 2024.1.1.15) [Computer software]. Stockholm Environment Institute. https://leap.sei.org

IEA. (2023a). *Energy Policy Review: Greece 2023*. https://www.iea.org/reports/greece-2023

IEA. (2023b). *Greece 2023 – Analysis*. https://www.iea.org/reports/greece-2023

IEA. (2023). *Greece must build on its successes in reducing fossil fuel dependence, IEA report says—News*. https://www.iea.org/news/greece-must-build-on-its-successes-in-reducing-fossil-fuel-dependence-iea-report-says

IEA Bioenergy. (2011). *Biorefineries: Adding value to the sustainable utilisation of biomass*. IEA.

IPCC. (2014). *Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Draft conclusions proposed by the Chair.* https://unfccc.int/documents/8496?gad_source=1&gclid=Cj0KCQiAi_G5BhDXARIsAN5SX7qZkQc1UmZZswcJBJbVJ8oMBbQwb7LCsAc2BeLvTy4wit5eIgCllREaAm5EEALw_wcB

Karamesouti, M., Detsis, V., Kounalaki, A., Vasiliou, P., Salvati, L., & Kosmas, C. (2015). Land-use and land degradation processes affecting soil resources: Evidence from a traditional Mediterranean cropland (Greece). *CATENA*, *132*, 45–55. https://doi.org/10.1016/j.catena.2015.04.010

Karasoy, A. (2024). Is agricultural production detrimental to Greece's ecological sustainability? Evidence from the dynamic ARDL simulations and bootstrap causality analysis. *Natural Resources Forum*, *48*(3), 925–940. https://doi.org/10.1111/1477-8947.12358

Karavitis, C. A., & Oikonomou, P. D. (2024). Water Resources Management and Policy in Greece: Challenges and Options. In R. Darques, G. Sidiropoulos, & K. Kalabokidis (Eds.), *The Geography of Greece: Managing Crises and Building Resilience* (pp. 113–128). Springer International Publishing. https://doi.org/10.1007/978-3-031-29819-6_7

Kattelmann, F., Siegle, J., Cunha Montenegro, R., Sehn, V., Blesl, M., & Fahl, U. (2021). How to Reach the New Green Deal Targets: Analysing the Necessary Burden Sharing within the EU Using a Multi-Model Approach. *Energies*, *14*(23), 7971. https://doi.org/10.3390/en14237971

Keppo, I., Butnar, I., Bauer, N., Caspani, M., Edelenbosch, O., Emmerling, J., Fragkos, P., Guivarch, C., Harmsen, M., Lefèvre, J., Le Gallic, T., Leimbach, M., McDowall, W., Mercure, J.-F., Schaeffer, R., Trutnevyte, E., & Wagner, F. (2021). Exploring the possibility space: Taking stock of the diverse capabilities and gaps in integrated assessment models. *Environmental Research Letters*, *16*(5), 053006. https://doi.org/10.1088/1748-9326/abe5d8

Keramitsoglou, K. M., & Tsagarakis, K. P. (2011). Raising effective awareness for domestic water saving: Evidence from an environmental educational programme in Greece. *Water Policy*, *13*(6), 828–844. https://doi.org/10.2166/wp.2011.103

Khilchevskyi, V., & Karamushka, V. (2020). Global Water Resources: Distribution and Demand. In W. Leal Filho, A. M. Azul, L. Brandli, A. Lange Salvia, & T. Wall (Eds.), *Clean Water and Sanitation* (pp. 1–11). Springer International Publishing. https://doi.org/10.1007/978-3-319-70061-8_101-1

Kılkış, Ş., Krajačić, G., Duić, N., Rosen, M. A., & Al-Nimr, M. A. (2020). Advances in integration of energy, water and environment systems towards climate neutrality for sustainable development. *Energy Conversion and Management*, *225*, 113410. https://doi.org/10.1016/j.enconman.2020.113410

Kleanthis, N., Stavrakas, V., Schibline, A., Ceglarz, A., Süsser, D., Michas, S., & Flamos, A. (2022). *"Pathways to climate neutrality in Europe with a spotlight in Greece: Challenges, uncertainties, solutions" – Workshop Synthesis Report – TEESlab*. https://teeslab.unipi.gr/pathways-to-climate-neutrality-in-europe-with-a-spotlight-in-greece-challenges-uncertainties-solutions-workshop-synthesis-report/

Kolokytha, E. K. (1998). Economic aspects of water supply policy in Greek cities. *Protection and Restoration of the Environment IV: Proceedings of an International Conference*. https://ikee.lib.auth.gr/record/227397?ln=en

Kolokytha, E. K., Mylopoulos, Y. A., & Mentes, A. K. (2002). Evaluating demand management aspects of urban water policy—A field survey in the city of Thessaloniki, Greece. *Urban Water*, *4*(4), 391–400. https://doi.org/10.1016/S1462-0758(02)00024-9

Koundouri, P., Alamanos, A., Plataniotis, A., Stavridis, C., Perifanos, K., & Devves, S. (2024). Assessing the sustainability of the European Green Deal and its interlin kages with the SDGs. *Npj Climate Action*, *3*(1), 23. https://doi.org/10.1038/s44168-024-00104-6

Koundouri, P., Chatzigiannakou, M. A., Dellis, K., Ioannou, A., & Landis, C. (2023). *Fable scenathon 2023 pathways for food and land use systems in Greece*. Paris: Sustainable Development Solutions Network (SDSN).

Kourgialas, N. N. (2021). A critical review of water resources in Greece: The key role of agricultural adaptation to climate-water effects. *Science of The Total Environment*, *775*, 145857. https://doi.org/10.1016/j.scitotenv.2021.145857

Kouridis, C., & Vlachokostas, C. (2022). Towards decarbonizing road transport: Environmental and social benefit of vehicle fleet electrification in urban areas of Greece. *Renewable and Sustainable Energy Reviews*, *153*, 111775. https://doi.org/10.1016/j.rser.2021.111775

Koutsandreas, D., Spiliotis, E., Doukas, H., & Psarras, J. (2021). What Is the Macroeconomic Impact of Higher Decarbonization Speeds? The Case of Greece. *Energies*, *14*(8), Article 8. https://doi.org/10.3390/en14082235

Kyriakopoulos, G. L., & Sebos, I. (2023). Enhancing Climate Neutrality and Resilience through Coordinated Climate Action: Review of the Synergies between Mitigation and Adaptation Actions. *Climate*, *11*(5), Article 5. https://doi.org/10.3390/cli11050105

Kyriakopoulos, G. L., Sebos, I., Triantafyllou, E., Stamopoulos, D., & Dimas, P. (2023). Benefits and Synergies in Addressing Climate Change via the Implementation of the Common Agricultural Policy in Greece. *Applied Sciences*, *13*(4), 2216. https://doi.org/10.3390/app13042216

Li, Y., & Zhang, R. (2023). A Review of Water-Energy-Food Nexus Development in a Just Energy Transition. *Energies*, *16*(17), Article 17. https://doi.org/10.3390/en16176253

MarineTraffic. (2024). *Global Ship Tracking Intelligence: AIS MARINE TRAFFIC*. https://www.marinetraffic.com/en/ais/home/centerx:-12.0/centery:25.0/zoom:4#google_vignette

Martin, N., Talens-Peiró, L., Villalba-Méndez, G., Nebot-Medina, R., & Madrid-López, C. (2023). An energy future beyond climate neutrality: Comprehensive evaluations of transition pathways. *Applied Energy*, *331*, 120366. https://doi.org/10.1016/j.apenergy.2022.120366

Merfort, L., Bauer, N., Humpenöder, F., Klein, D., Strefler, J., Popp, A., Luderer, G., & Kriegler, E. (2023). Bioenergy-induced land-use-change emissions with sectorally fragmented policies. *Nature Climate Change*, *13*(7), 685–692. https://doi.org/10.1038/s41558-023-01697-2

Mosnier, A., Penescu, L., Pérez-Guzmán, K., Steinhauser, J., Thomson, M., Douzal, C., & Poncet, J. (2020). *FABLE Calculator 2020 update*. https://doi.org/10.22022/ESM/12-2020.16934

Naghash, H., Schott, D., & Pruyn, J. (2024). Shifting waves of shipping: A review on global shipping projections and methodologies. *Journal of Shipping and Trade*, *9*(1), 29. https://doi.org/10.1186/s41072-024-00187-8

Nastos, P., Kapsomenakis, J., Kotsopoulos, S., & Poulos, S. (2015). Present and future projected reference evapotranspiration over Thessaly plain, Greece, based on regional climate models' simulations. *Eur. Water*, *51*, 63–72.

Ong, S., Campbell, C., Denholm, P., Margolis, R., & Heath, G. (2013). *Land-Use Requirements for Solar Power Plants in the United States*. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy13osti/56290.pdf

Papadopoulou, C.-A., Papadopoulou, M. P., & Laspidou, C. (2022). Implementing Water-Energy-Land-Food-Climate Nexus Approach to Achieve the Sustainable Development Goals in Greece: Indicators and Policy Recommendations. *Sustainability*, *14*(7), 4100. https://doi.org/10.3390/su14074100

Pavlidis, A. (2024). *Importance of synergy between regulators and the private sector to decarbonize shipping* [Master Thesis, University of Piraeus]. https://dione.lib.unipi.gr/xmlui/handle/unipi/17287

Rodanakis, I. (2014). *An examination of the degree of effective application of ship energy efficiency management plan by the Greek shipping companies through a benchmarking analysis* [Master Thesis, University of Piraeus]. https://dione.lib.unipi.gr/xmlui/handle/unipi/7279

Roelfsema, M., van Soest, H. L., Harmsen, M., van Vuuren, D. P., Bertram, C., den Elzen, M., Höhne, N., Iacobuta, G., Krey, V., Kriegler, E., Luderer, G., Riahi, K., Ueckerdt, F., Després, J., Drouet, L., Emmerling, J., Frank, S., Fricko, O., Gidden, M., … Vishwanathan, S. S. (2020). Taking stock of national climate policies to evaluate implementation of the Paris Agreement. *Nature Communications*, *11*(1), 2096. https://doi.org/10.1038/s41467-020-15414-6

Sfyris, S., Alamanos, A., Fafoutis, C., & Mylopoulos, N. (2019). *Quantifying the impact of different climate conditions and water pricing policies on future water balance in Volos, Greece*.

Shan, Y., Yang, L., Perren, K., & Zhang, Y. (2015). Household Water Consumption: Insight from a Survey in Greece and Poland. *Procedia Engineering*, *119*, 1409–1418. https://doi.org/10.1016/j.proeng.2015.08.1001

Stathi, E., Kastridis, A., & Myronidis, D. (2023). Analysis of Hydrometeorological Characteristics and Water Demand in Semi-Arid Mediterranean Catchments under Water Deficit Conditions. *Climate*, *11*(7), Article 7. https://doi.org/10.3390/cli11070137

Stefanidis, K., Papaioannou, G., Markogianni, V., & Dimitriou, E. (2019). Water Quality and Hydromorphological Variability in Greek Rivers: A Nationwide Assessment with Implications for Management. *Water*, *11*(8), 1680. https://doi.org/10.3390/w11081680

Talebnia, F., Karakashev, D., & Angelidaki, I. (2010). Production of bioethanol from wheat straw: An overview on pretreatment, hydrolysis and fermentation. *Bioresource Technology*, *101*(13), 4744–4753. https://doi.org/10.1016/j.biortech.2009.11.080

Tamesol. (2023). *How much do solar panels do cost in Europe?* https://tamesol.com/solar-pv-panels-cost/

Tsita, K. G., & Pilavachi, P. A. (2017). Decarbonizing the Greek road transport sector using alternative technologies and fuels. *Thermal Science and Engineering Progress*, *1*, 15–24. https://doi.org/10.1016/j.tsep.2017.02.003

Tsoutsos, T., Papadopoulou, E., Katsiri, A., & Papadopoulos, A. M. (2008). Supporting schemes for renewable energy sources and their impact on reducing the emissions of greenhouse gases in Greece. *Renewable and Sustainable Energy Reviews*, *12*(7), 1767–1788. https://doi.org/10.1016/j.rser.2007.04.002

UNCTAD. (2023). *World seaborne trade by types of cargo and by group of economies, annual*. https://unctadstat.unctad.org/datacentre/dataviewer/US.SeaborneTrade

Varela, P. (2025). Greek consumers’ perspectives on sustainable food: A cluster analysis approach. *British Food Journal*, *127*(1), 268–283. https://doi.org/10.1108/BFJ-06-2024-0627

Villamar, D., Soria, R., Rochedo, P., Szklo, A., Imperio, M., Carvajal, P., & Schaeffer, R. (2021). Long-term deep decarbonisation pathways for Ecuador: Insights from an integrated assessment model. *Energy Strategy Reviews*, *35*, 100637. https://doi.org/10.1016/j.esr.2021.100637

Weitz, N., Carlsen, H., Bennich, T., Nilsson, M., & Persson, Å. (2023). Returning to core principles to advance the 2030 Agenda. *Nature Sustainability*, *6*(10), 1145–1148. https://doi.org/10.1038/s41893-023-01212-7

World Bank. (2023). *Urban-Rural Population Growth*. https://data.worldbank.org/indicator/SP.RUR.TOTL.ZG?locations=EU

Yang, L., Lamont, L. D., Liu, S., Guo, C., & Stoner, S. (2023). A Review on Potential Biofuel Yields from Cover Crops. *Fermentation*, *9*(10), 912. https://doi.org/10.3390/fermentation9100912

YPEKA. (2014). *Managemenent plan of the river basins of Thessalia river basin district*. https://wfdver.ypeka.gr/wp-content/uploads/2017/04/files/GR08/GR08_P26b_Perilipsi_En.pdf

Yue, Q., Zhang, F., Wang, Y., Zhang, X., & Guo, P. (2021). Fuzzy multi-objective modelling for managing water-food-energy-climate change-land nexus towards sustainability. *Journal of Hydrology*, *596*, 125704. https://doi.org/10.1016/j.jhydrol.2020.125704

Zheng, J., Hou, X., Duan, H., & Wang, S. (2024). Where we are and where we will go to achieve carbon neutrality: A review of quantitative socioeconomic modeling research. *Fundamental Research*, *4*(6), 1696–1709. https://doi.org/10.1016/j.fmre.2023.12.020