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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 by 2050. We follow a systems-nexus approach that encompasses the FABLE Calculator, the Low Emissions Analysis Platform (LEAP), and the tools WaterReqGCH, LandReqCalcGCH and BiofuelGCH. The results indicate that most individual/sector 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 governance assumptions that often overlook sectoral interdependencies and infrastructure constraints, hindering progress towards a unified and more holistic sustainable transition.

Keywords: Climate Neutrality; Energy-emissions modelling; LEAP; FABLE Calculator; 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) (1). 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 (NECP), 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 (2,3). 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 (4,5). 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 (6). However, in reality, the scientific community exposes crucial weaknesses of policies in addressing more holistic and sustainable progress. Merfort et al. (7) explore the negative effects of fragmented land-energy policies. Fujimori et al. (8) 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. (9) 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 (10).

A key element in assessing different future climate-neutrality scenarios, evaluate and guide relevant policies, is the use of sound scientific tools, so that multiple relevant systems are assessed (11). 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 (12), the deep decarbonization models (DDMs), which are bottom-up, engineering-economic models that minimize the costs of achieving net-zero emissions (13), or custom combinations based on case-specific needs and concepts (14). Several studies couple different models, representing mainly the water-energy-food-land systems, as the core ones to climate-neutrality (15). For instance, Doelman et al. (16) explored water-land-food-climate trade-offs by combining the MAgPIE and IMAGE models. Yue et al. (17) 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. (18) 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 are usually more focused on a specific system, e.g. energy, or land. Capros et al. (19) used the PRIMES energy model to explore pathways towards climate-neutrality in the EU energy-system by 2050 and 2070. Duffy et al. (20) 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. This also reflects an inherent limitation of such integrated models, which is their weak representation of national-scale case studies. Usually, the scenarios refer to global scale assumptions that do not capture the national context. Overall, to the best of our knowledge, there is no study following a holistic approach to evaluate existing national policies across a wide range of sectors in Greece.

Thus, we aim to fill this gap by developing a scenario assuming the joint implementation of the main national policies aiming at climate-neutrality in Greece. We consider a combination of simulation models for food-land, water, and cross-sectoral energy systems (including residential, industrial, agriculture, transportation, and services sectors). Agricultural and energy policy frameworks are assessed jointly while discussing potential implications for natural resources, such as land and water, 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 (21). 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 (22). The NECP 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 (23), or macroeconomic impacts (24), 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 (25). While there are no substantial land use changes in Greece, the land degradation is a pressing issue for agriculture and food production (26). 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 (27,28). The NECP does not have specific recommendations for agriculture though. The Common Agricultural Policy (CAP) is an overarching plan covering such concerns, aiming at 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.

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) (29); 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 (30,31). 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 (32,33). 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 (34). 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 (35). Most studies explore the effects on specific sectors or regions of Greece (36), with limited research on a cross-sectoral basis, like in this paper.

For the aforementioned sectors we considered one main policy that reflects the National Climate Neutrality Commitments (NCNC), and we compare it with a Business As Usual (BAU) scenario:

- NCNC scenario = NECP + CAP + RBMPs,
- BAU scenario = ‘Current accounts’ or do-nothing scenario.

Our rationale is that we aim to focus on the main policies that are currently implemented in each sector. Other policies that are not considered in this study concern mostly economic measures. Such policies include, among others, the EU Taxonomy, the Climate Delegated Act, the EU Circular Economy Act, Industrial Policy, and ETS for energy and agriculture. In this research, we do not look at economic policies, since the focus is on the “water-energy-food-emissions modelling nexus”, showcasing the combination of such models. Nonetheless, it is in our future plans to augment our methodology with a Computable General Equilibrium (CGE) model that will allow us to explicitly consider and evaluate the main economic policies for each sector as well.

Each sector of the economy also faces unique challenges. The residential sector, which 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 with 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 (37). Moreover, the 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 (38). 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 (39). 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 to countries that are not traditionally used to such holistic governance (40,41). 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 (42) for the potential evolution of food and land-use systems; the Low Emissions Analysis Platform (LEAP) (43) for the simulation of the energy consumption and the associated GHG emissions of multiple pollutants; the WaterReqGCH accounting tool (44) 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.

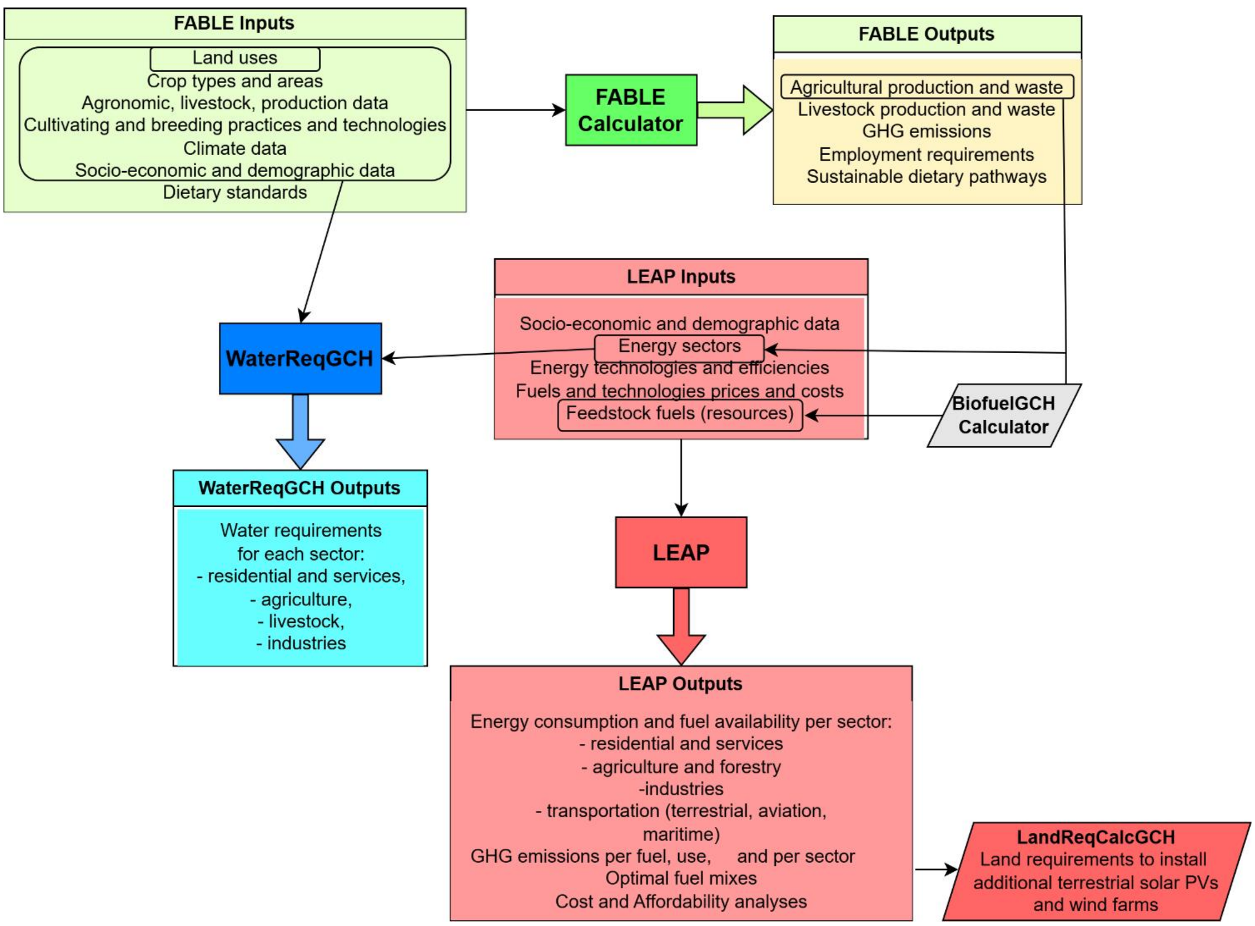

Figure 1. The modelling framework, with the tools, their inputs and outputs, and their connections.

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 (42). 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 potential, 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 (42). 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 (42).

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 (42).

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. It is a software for long-term integrated energy, climate mitigation, and air pollution planning and analysis, developed over the last 40 years by the Stockholm Environment Institute (SEI). It has been developed as a scenario-based modelling tool that explores how emissions may change in the future. 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 within the software, based on the emission coefficients of the IPCC's Fifth Assessment Report (45) per sector, per use and per fuel type for the demand side, and per process for the supply side. In particular, LEAP's "effects" menu provides the option to select different sets of Global Warming Potential (GWP) values corresponding to one of the IPCC Assessment Reports. LEAP includes 20, 100 and 500-year GWP values. These values reflect the relative potential of each effect over each period. Each value is specified in units of tonnes of CO2 equivalent per tonne of pollutant (T CO2e/T). That is, the GWP values measure the warming potential of a tonne of each gas relative to a tonne of CO2.

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

Energy Demand			Data sources
Sectors	**Activity Level (AL)[1]**	**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 (46); ELSTAT (47)
Industry	Value Added of each industry product, or tons of product	Food and tobacco, textiles and leather, wood products, paper pulp and printing, chemicals and chemical products, rubber and plastic, non-metallic minerals, basic metals, machinery, transport equipment, other manufacturing, mining, cement and steel production	IEA (48)
Agricultural energy use	Agricultural products (FABLE Calculator's output)	Energy used for agricultural and livestock products	FABLE Calculator
Transportation (including terrestrial, domestic and international maritime & aviation)	Passengers and freight in passenger/km or tons/km	Cars, light trucks, motorcycles, buses, trains, airplanes, shipping, freight trucks and trains	IEA (48); ELSTAT (47)
Services	Number of public buildings	Tertiary sector services	IEA (48); ELSTAT (47)
Energy Supply (fuels' production processes to cover the demand)			
Primary Resources	Solar, crude oil, coal lignite, hydropower, wind, coal, municipal solid waste, biofuels		EUROSTAT (49); IEA (48); ELSTAT (47)
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 (45)

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 (50). 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 (51,52). The fraction of those

[1] For more information about the recommended and common choices of AL, which we have followed, please refer to LEAP's documentation (Heaps, 2022).

residues is typically available for biofuel use, without affecting food production. So, the biofuel production potential from those specific residues can be calculated (53–55).

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

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 exports.

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.

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

Equation 3 describes how this model estimates the land requirements (in km^2) that will be needed for additional solar panels and 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.

Water Requirements

Finally, the water requirements of all sectors studied in LEAP are calculated by the WaterReqGCH accounting tool (44). 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 (56–59).

$$W_{sector} = AL_{sector} \cdot CR_{sector} \cdot LC_{sector} \quad (5)$$

The water requirements for industry were estimated (for each one of the 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 (60,44).

Results

All models described run under a common simulation period, from 2020 to 2050, at an annual time-step. As mentioned, the simulation considered two scenarios: i) 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; ii) The National Climate Neutrality Commitments (NCNC). The NCNC assumes that the different policies per sector, which 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 National Climate Neutrality Commitments (NCNC) 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 (NECP), 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 NCNC's expected energy consumption led to the respective energy intensities assumed in this simulation. Also, for each sector, the NECP's expected fuel mixes (phasing out of 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 (38,62). The NECP focuses primarily on generic agroecological practices and cyclical economic 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 NECP (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% (42). In the case of Greece, the average productivity growth during the first decade of the century had negative values.
Land use changes	Although this is not directly related to decarbonization commitments, it is recognized that the requirements on natural resources should be also considered in sustainability assessments. Greece's land use policy is defined by the Presidential Decree 59/2018, which categorizes all national territory into defined zones (residential, urban, agricultural, industrial, recreational, and strict nature protection) thereby channeling urbanization into existing settlements and

	discouraging sprawl in agricultural and natural areas (63). Complementing this, the CAP Strategic Plan 2023–27 seeks to modernize Greek agriculture by promoting innovation, securing farmer incomes, and crucially reducing the sector's environmental footprint through eco-schemes and conditionality that support crop diversification, cover crops, and maintenance of permanent grasslands (64). It also aims to increase forest area, ensuring that agricultural expansion does not come at the expense of woodland health.
Water consumption	Again, this is not directly linked to decarbonization commitments, but as an important natural resource, it is necessary to consider. 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 (65). 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 (66,35). 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 NCNC scenario shifts productivity levers for crop and livestock, dropping GHG emissions by 2050 by 50% (3 MtCO2e) 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 livestock-related emissions dropping to 2.47 MtCO2e in 2050, and land use changes leading to increased emission withdrawals of 3.28 MtCO2e 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 NCNC 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. (67) highlighting how climate change-intensified weather events impact EU agricultural production and costs.

Under the NCNC scenario, total costs are projected to decrease from 828 million € in 2025 to less than 630 million € 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.

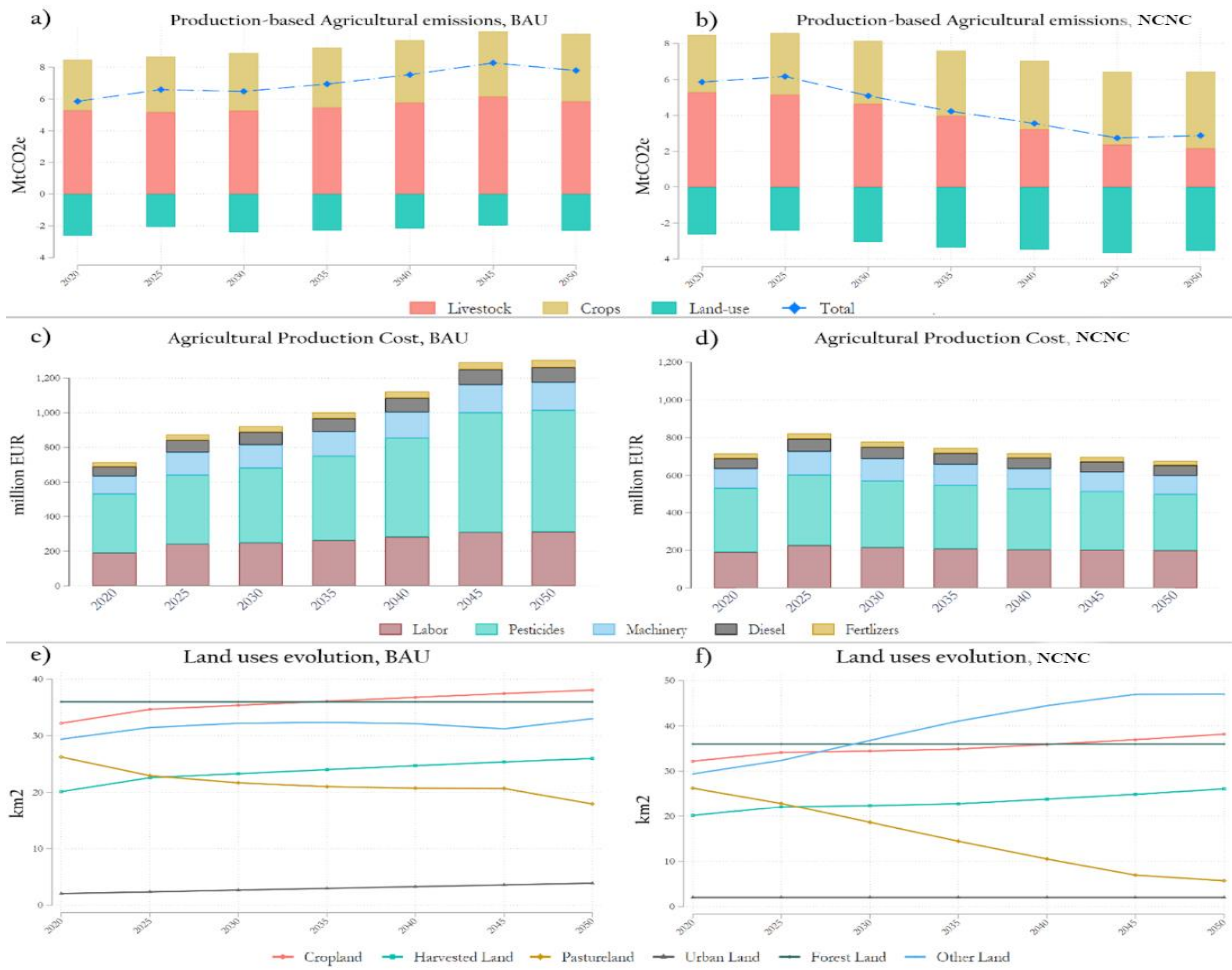

Figure 2. Production-based agricultural GHG emissions, for the BAU (a), and the NCNC (b) scenario. Production costs for the BAU (c), and the NCNC (d) scenario. Land use changes for the BAU (e), and the NCNC (f) scenario.

The two main messages of the national land-use policy frameworks (Table 2) are to discourage urban sprawl in agricultural and natural areas, and increase forest area, ensuring that agricultural expansion does not come at the expense of woodland health. Under the BAU scenario, none of those two goals is being achieved (Figure 2e). While urban land grows only modestly, much of the land-use change is driven by cropland and harvested area, which means agricultural expansion is the dominant driver of sprawl into rural and natural areas (directly at odds with discouraging land-take outside existing settlements). Also, there is no meaningful increase in forest area, but a slightly downward trend. Under the NCNC scenario, only one of these two land-use objectives is met (Figure 2f): Urban land remains essentially flat through 2050, showing that new housing and infrastructure are indeed being held within existing settlements. However, 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 (by 29% in the 2020-2030 period, and 78% in 2050, compared to the 2020 levels; 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. "Other land" increase reflects areas under restoration, set-aside, or low-intensity uses, but these gains do not translate into designated, fully protected forests. So, the aspiration to increase forest area and strengthen woodland health remains unmet under the NCNC scenario.

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 NCNC 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 NCNC 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 are mainly driving these trends. The decreasing trend of 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 in 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.

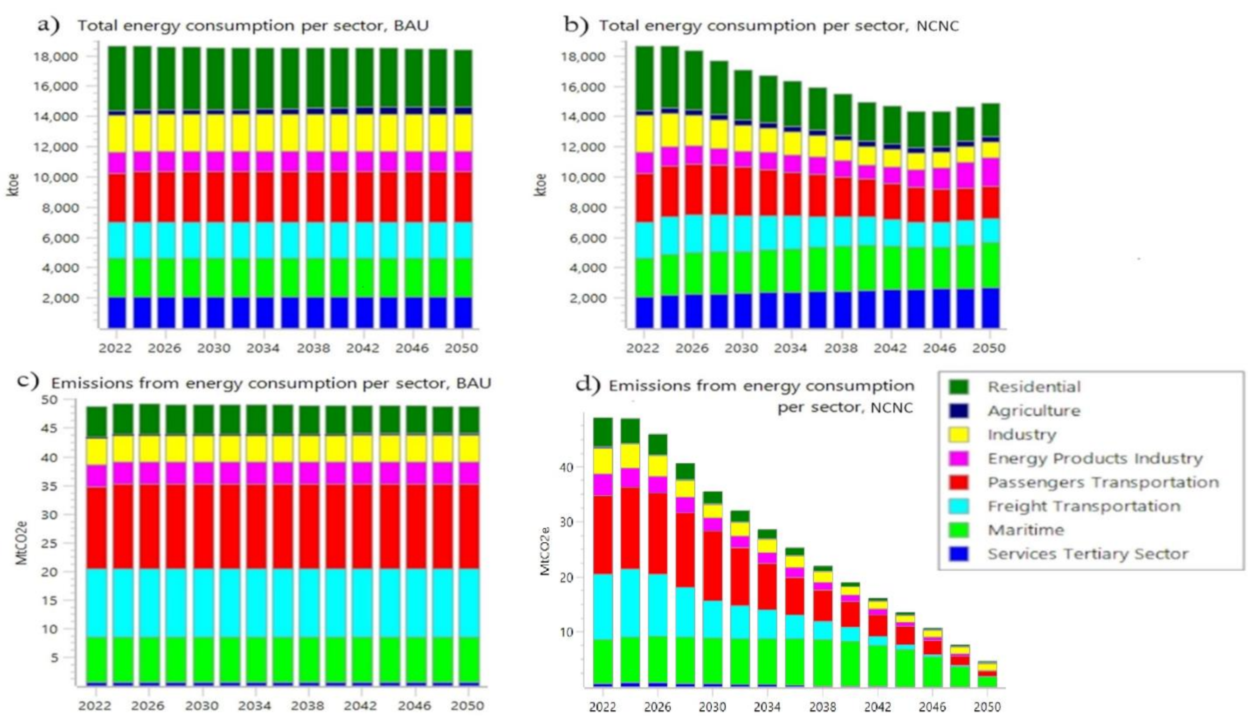

Figure 3: Total energy consumption per sector, under the BAU (a) and the NCNC scenario (b), with the respective GHG emissions (100-Year GWP), under the BAU (c) and the NCNC scenarios (d).

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 NCNC, almost by 3 times in 2050. Conversely, electricity production is expected to rise significantly, by 6.5 Mtoe in 2050. New contributions to energy production include hydrogen and synthetic fuels, reaching in total 1.1 Mtoe and 571 ktoe, 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 26 $MtCO_2e$ in 2022 to 5.2 $MtCO_2e$ by 2050. These changes are attributed to the evolving energy mix and technologies introduced under the NCNC scenario.

Note that both energy consumption and fuels supply results were also validated, cross-checking with data from NCNC's assumptions, EUROSTAT (49), and the IEA (48).

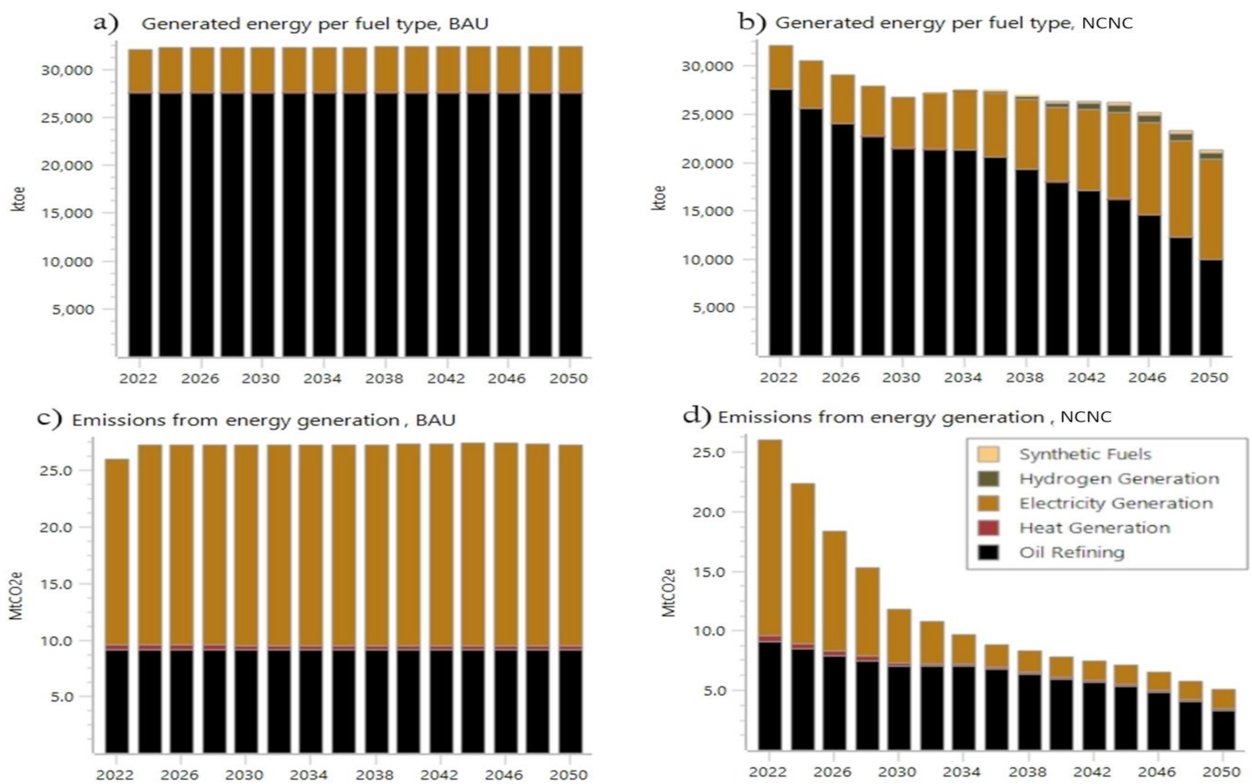

Figure 4: The generated energy from the different feedstock fuels for the BAU (a), and the NCNC scenario (b), with the respective GHG emissions (100-Year GWP) from these energy generation processes, for the BAU (c), and the NCNC scenario (d).

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 and synthetic fuels). 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 NCNC 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.

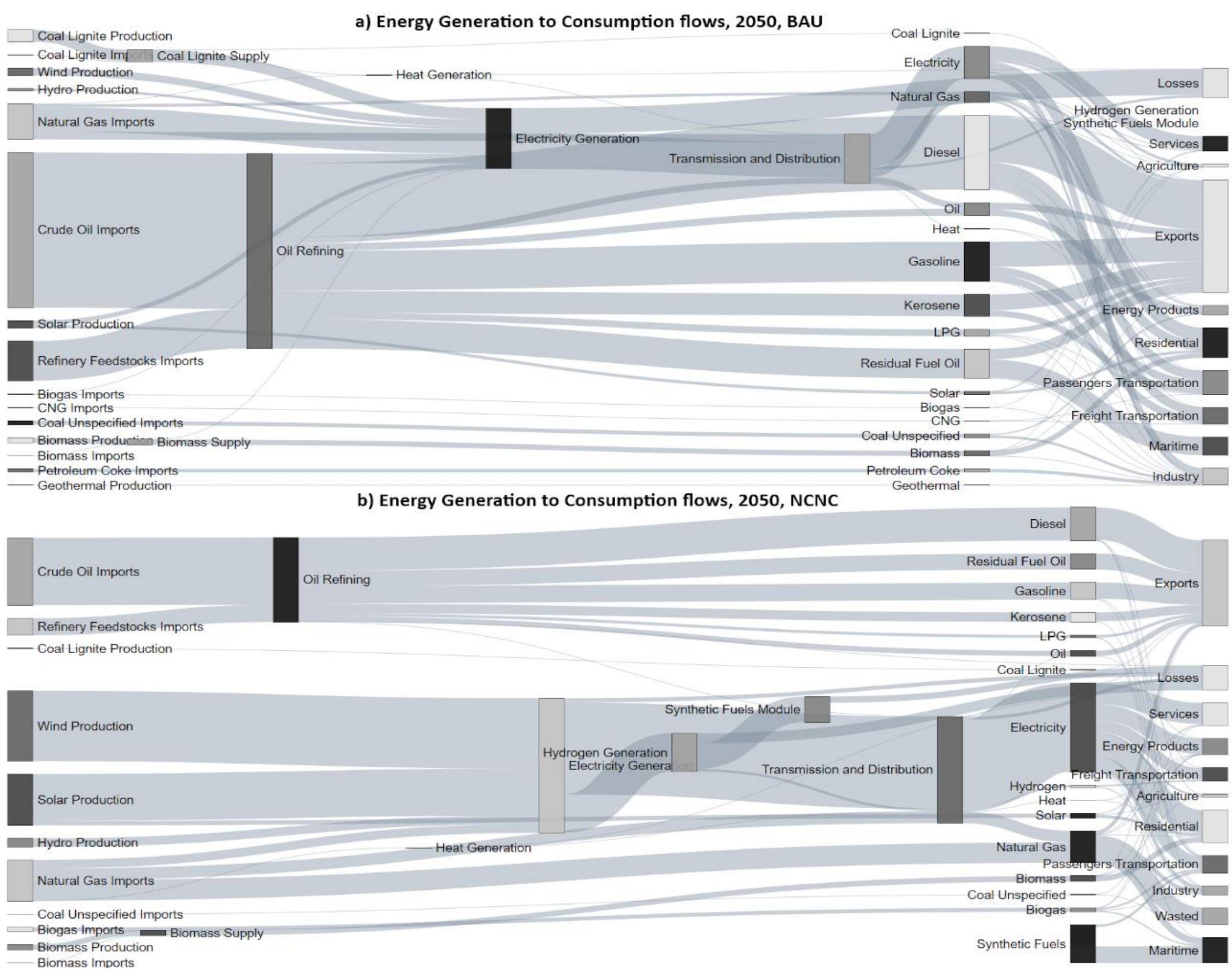

Figure 5: Sankey diagrams for the energy generation and consumption flows, for the BAU (a) and the NCNC scenario (b).

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.

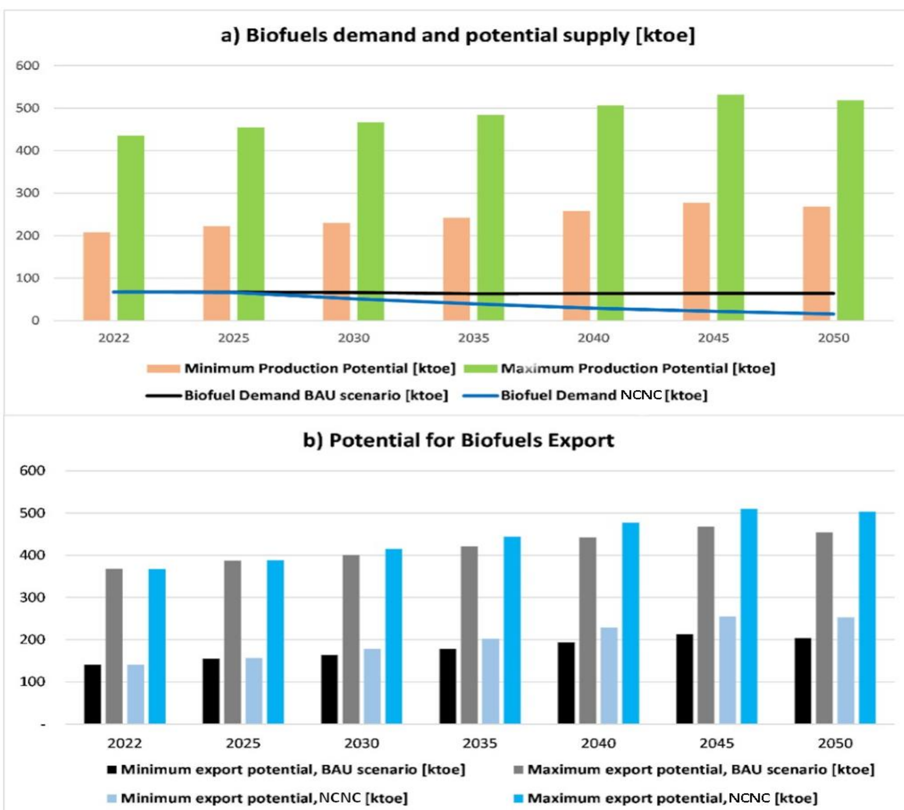

Figure 6: a) The resulted biofuel production potential (min-max), and the demand for biofuels use (for the BAU and the NCNC scenarios), excluding wood and pellet products; b) The excess production potential that can be exported (min-max) for the BAU and the NCNC scenarios.

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

Land requirements

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

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. (68) and Ong et al. (69).

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). These magnitudes, even at their high end, are under 1100 km^2 or about 0.8% of Greece's total land area, but it is non-negligible when overlaid on a landscape already under competing demands. Specifically, in Figures 2e and 2f we observe rapid growth in "Other land" (mosaic, low-intensity uses) and continued pressure on cropland and pasture, under both the BAU and NCNC scenarios. Installing solar parks and wind farms will most likely encroach on these less-intensive zones or marginal agricultural lands, rather than pristine forests. If this required renewables infrastructure ends up replacing set-aside fields or semi-natural grasslands, it may conflict with the objective to preserve permanent grasslands and pastures, which will challenge traditional grazing economies and even biodiversity.

The LandReqGCH model also provides estimates of the expected costs for the installation of these projects, considering their typical costs (70,71). Regarding the solar panels, the cost would range (min-average-max) from 1005 million € to 1269 million € and to 1533 million €. The respective costs for wind farms would range from 18.8 million € to 25.3 million € and to 35 million €.

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 highest 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 725.19hm³ in 2020 to 630.31hm³ in 2050, driven by Greece's declining population. The NCNC 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 7.

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 NCNC 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 7. Another key factor here is the assumption that demand remains stable, driving this relatively stable behaviour, which is largely uncertain though.

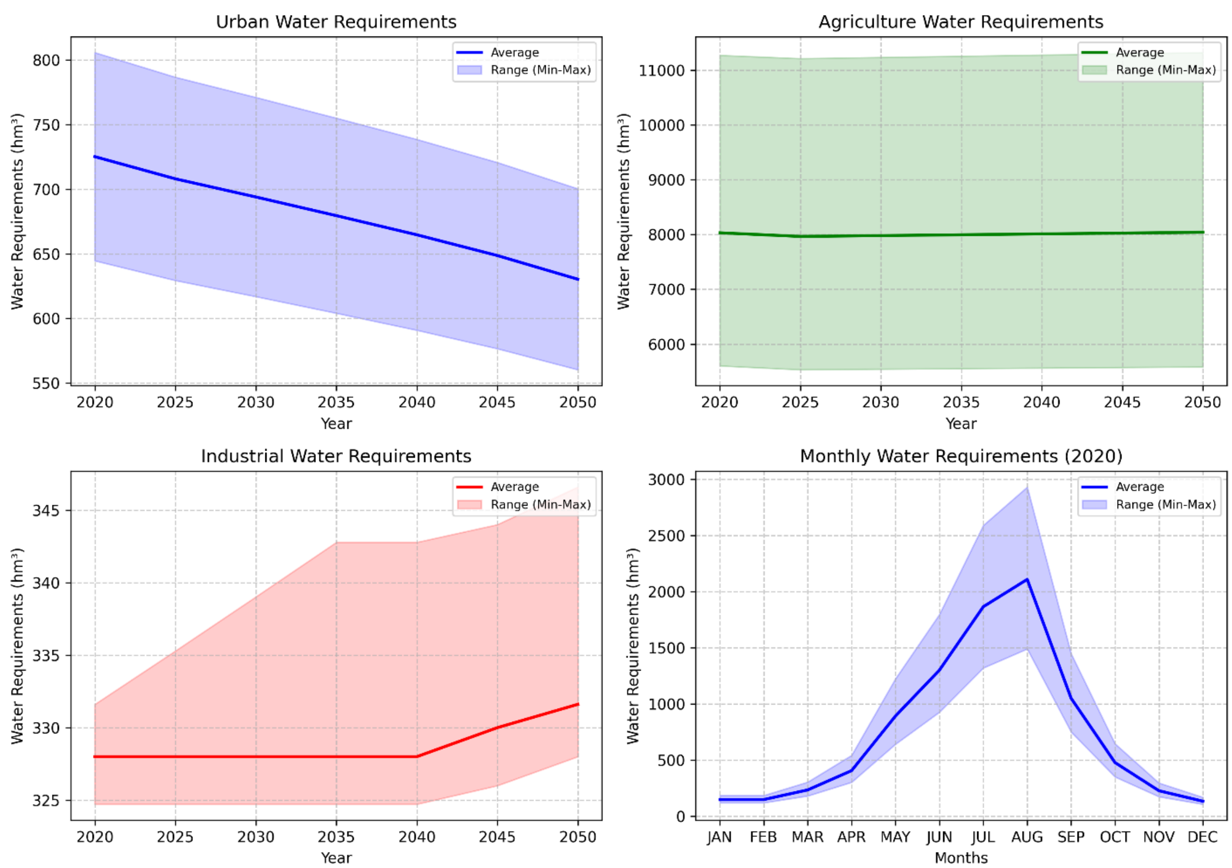

Figure 7: Urban (residential and services) (a), agricultural (irrigation and livestock) (b), and industrial water requirements (c). The monthly water requirements plot (d) shows the monthly allocation of the total consumption.

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 NCNC 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 (1866.6hm³) is more than eight times higher than in December (134.55hm³). This pronounced seasonality underscores the pressure on water resources during the dry season and the importance of adequate storage and distribution infrastructure (29).

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, and despite its overly ambitious targets (72). As mentioned, 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. 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) (72,73).

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 (64). 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 (38,74,75). This results in low productivity and inefficient energy use, as highlighted in studies such as Shan et al. (36) and Kourgialas (33), as well as in a recent living lab in Greece's major agricultural region (76).

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 (77). 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 (36,33,78). 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 (76,79).

Scattered policies with uncertain and unintended consequences

The examined policies (NECP, CAP, Land-use, 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 NCNC 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 1295 million €. 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, a recommendation would be to prioritize brownfield and rooftop photovoltaics, agrivoltaics, and expansion primarily into low-value and degraded lands, reducing new land take. Otherwise, if planners ignore these, there will probably occur direct conflicts with agriculture, forestry, biodiversity, smallholders and farmers' ownerships and interests, with the expansion of green energy and the respective expectations on decarbonization. Without deliberate co-siting strategies and explicit renewable-land-use rules, the green energy transition could unintentionally undermine the very land-use efficiency and conservation goals it must support.

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 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 NCNC 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 NCNC 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 (80,81). The dominance of agriculture in water consumption emphasizes the need for targeted interventions in this sector, which are side-mentioned by the RBMPs (35).

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 become net exporter (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 (a major driver of the Greek economy) 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. 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 (82).

Concluding remarks

This research presented an integrated modelling approach to assess the Greek NCNC, as closely as possible to the current real-world policy landscape, referring to the main systems (food, land, energy, emissions, and water). The simulated NCNC 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 NCNC 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 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 ones relevant to the existing NCNCs, and highly interconnected in modelling terms.

Nonetheless, augmenting our current nexus-systems approach with social, economic, biodiversity, and waste systems is included in our future research plans. To this direction, we plan to develop a CGE model that will be interconnected with all individual models presented in this paper. This will allow us to evaluate, besides the main policies considered for each sector so far, additional policies that concern, among others, economic externalities (e.g. health effects, co-benefits from waste management), the economic and social distribution of costs and benefits, and explicit impacts on employment. This approach will yield further insights on the direct and indirect (economic) costs and (environmental) benefits of alternative decarbonization pathways.

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 (83) 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 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.

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