Decarbonization Pathways in the Energy and Land-use Sectors for the EU

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1. Introduction

In this report, we delve into the intricate tapestry of results derived from two integrated assessment models (IAMs), which serve as powerful tools for policymakers, researchers, and stakeholders alike. Within the realm of integrated assessment modeling, the exploration of energy and land-use dynamics holds particular significance. Energy production and consumption as well as land-use patterns have profound implications for GHG emissions, biodiversity, ecosystem services, and food system functioning. By synthesizing data from disparate fields such as climate science, economics, and ecology, IAMs offer a holistic perspective on the consequences of various energy and land-use decisions, illuminating pathways towards sustainable development and environmental stewardship.

We elaborate on decarbonization pathways for the pan-European energy sector using the BALMOREL model and sustainable land-use and food system pathways for the case of Greece using the FABLE Calculator.

The EU’s mandates under the EU Green Deal, Fit-for-55, and RepowerEU for a decarbonized Europe are feasible through investment into renewable technologies like solar and wind, combined with energy trade-enhancing interconnections between European countries, according to our analysis of sustainable energy pathways for the EU using the BALMOREL model. We also demonstrate that the adoption of a national carbon budget, as opposed to a system carbon budget, increases the capacity and use of renewable energy sources while aiding in the national reduction of emissions without materially raising system costs.

Turning to sustainable land-use and food pathways for Greece, our findings underscore that reforming the land-use system and transforming the agricultural sector is essential to reducing emissions and slowing the loss of biodiversity. By using the FABLE calculator, we discover that as early as 2040, net negative emissions from agriculture result from meeting national obligations outlined in EU consolidated targets and Greek law. In addition, the implementation of policy levers linked to national pledges results in observable advancements in the nation’s biodiversity index, the proliferation of organic farming, the encouragement of nutritious dietary patterns, and increased agricultural output. Adhering to commitments aligned to the agenda 2030 and the EU Green Deal delivers the dual mandate of enhanced productivity and tangible transition to net zero for the Greek agricultural sector.

The UN SDSN Global Climate Hub promotes research harnessing knowledge, talent, and tools from a wide range of scientific fields to deliver socio-economic pathways which have human development in the epicenter. Using sophisticated modelling approaches to estimate the projection of important social, environmental, and economic impacts for the medium- and long-term horizons is a fundamental component of the work being
done in the GCH. Nevertheless, all estimates are placed within the framework of policy and behavioral narratives that are driven by internationally recognized goals (such the SDGs and the Net Zero Transition) and national pledges to attain them.

Policymakers throughout the world will have plenty of motivation to increase their efforts in climate mitigation and adaptation and fulfil their net zero commitments with the help of this initial set of model-based results. Gauging the progress towards net zero and providing empirical evidence of policy and behavioral change using the most up-to-date analytical methods can stimulate a paradigm shift in policy. The GCH will persist in offering refined forecasts via modelling integration approaches and strengthen them with case studies, application cases, and narrative strategies, tackling the intricate problem of socio-economic change in an all-encompassing way.

2. Decarbonization Pathways of the Pan-EU energy system

2.1 Background

Following the establishment of the Paris Agreement at COP21 in 2015, a global goal has been set to decarbonize economic activity and limit global warming. In Europe, this has led to political strategies and specific carbon emission reduction targets. These include environmental strategies, such as the European Green Deal and Fit-for-55 (A European Green Deal, 2023; Fit for 55, 2023), to ensure socially fair and economically efficient decarbonization, as well as political strategies, such as REPowerEU (REPowerEU, 2023), to ensure geopolitical energy independence. While these policies outline goals, provide frameworks, and give tools to reach the policy targets set, the question of how to achieve decarbonization economically most efficiently remains.

EU countries are required to submit National Energy and Climate Plans (NECPs) (National Energy and Climate Plans, 2023) outlining, amongst other dimensions, how each country will address decarbonization. These are, however, not always clear on how the targets should be met, not updated with the latest policy goals, or not all assessed to be of sufficient level of ambition.

Other studies have also investigated the decarbonization of the European energy system, such as Tsiropoulos et al. (2020) comparing multiple studies with varying degrees of decarbonization. However, the tools used are mostly simulation-based models and not optimization models that can better capture some elements, such as potential lock-in effects. Additionally, while 27 countries are member nations of the EU and thus are of primary focus in EU strategies and studies, other nations often left out are also connected to the wider Pan-European energy system, potentially impacting in a significant way.
Lotze et al (2021) also investigate European decarbonization pathways in a Pan-European energy system using the PyPSA model, but do not go into detail on specific countries and policies, as well as existing capacities leading to accurate pathways. This leads us to the main research topic of this study.

The aim of this study is to investigate how we can most effectively reach European decarbonization targets in line with Fit-for-55 and the European Green Deal in a sector-coupled, interconnected pan-European energy system. Fundamental to this question is the element of combining the system-wide perspective of the greater Pan-European energy system with how individual countries integrate into and affect greater system decarbonization. To shed light on this topic, this study seeks to answer how national decarbonization strategies align with Fit-for-55, especially 2030 targets, and the European Green Deal, as well as how the inclusion of Balkan countries, EU, and non-EU, impacts the entire European energy system.

As a part of the study, three of the NECP dimensions are addressed: 1) decarbonization through the use of a carbon budget in accordance with Fit-for-55 and the European Green Deal, 2) energy efficiency through the implementation of heat saving as a technology available for endogenous investment based on renovation potential and construction costs, and 3) renewable technology as an endogenous investment option based on national renewable energy potentials.

To address the research question, the structure of the study is the following: First, in accordance with the European Green Deal, Fit-for-55, and REPowerEU, a carbon budget is implemented at the aggregate European system level, ensuring decarbonization in the energy sectors modeled by Balmorel. The result of this setup creates a baseline pathway to decarbonize power, heating, transport, and the industry sectors. The initial pathway is compared to national commitments regarding emission reductions to see potential misalignments between national and EU-level policy targets, focused on the three National Energy and Climate Plan dimensions. In this respect, we dive deep into selected countries of interest to highlight the nation-level pathways alignment.

Second, a scenario is created in which the carbon budget is implemented at the national rather than the system level, to investigate the impact on system costs, capacity investments, and production pathways. The same countries are highlighted here as previously.

These two scenarios will provide insight into the Pan-European energy system decarbonization including the required production capacities, how national pathways interact with European targets, as well as the impact of national versus system commitments.

2.2 Method

To study European decarbonization, we utilize the open-source and sector-coupled energy system model Balmorel (F. Wiese, 2018). Balmorel is a bottom-up partial
equilibrium energy system optimization with an objective to minimize the total energy system costs. The model extensively covers the power and district heating sector. To fully capture the sector coupling synergizes of the future European system, the model has been extensively developed and expanded to incorporate further heating in the housing sector, heating in the industrial sector, electrified transportation, and hydrogen penetration for both industry and transport. The model covers the full pan-European energy system at a one-node per country level for all mentioned sectors, Figure shows an overview of the spatial level of Balmorel at the country level.

Balmorel is a technology-rich energy system model in which diverse energy sources are turned into energy vectors that can be used to meet demand in various sectors. Simultaneously, the model optimizes both investments and operational dispatching. Furthermore, the model quantifies the optimal cross-border network expansion and trading for both electricity and hydrogen energy vectors between countries.

Considerable emphasis is taken on the modeling of solar and wind technologies which are key technologies for accelerating European decarbonization. In order to incorporate the variability of renewable sources within a simulated country, prospective investments in renewable energy are subdivided into regions known as "resource grades." Grades are assigned in a manner that accounts for distinct technical attributes, including costs, land availability, social acceptance, maximal renewable investments, and Full Load Hours (FLH). Therefore, in Balmorel, variable renewable installations may encounter a technical threshold. Lastly, resource grades are populated with variable time series in the form of capacity factors by utilizing the simulation model CorRES (Koivisto, 2019).

**Figure 1: Balmorel model spatial overview.**
The temporal resolution of Balmorel includes seasons (i.e., 52) and terms (i.e., 168) within a year, representing weeks and hours, allowing for simulating both seasonal and hourly behavior. Due to considerations of tractability and computational efficiency, fewer time steps and seasons are attentively selected. Each year is optimized sequentially, with technology investments carrying over year to year, giving the option of modeling pathways. In this study, we model every five years (myopic approach) using 2050 as the final horizon.

2.3 Data & assumptions

The Balmorel energy system model contains a large amount of data for every country sourced from a variety of datasets or assumptions. In this section, we describe the assumed energy demands and carbon budget, as these are vital data points driving the model results.

Energy demands

At an aggregate level, Figure 2 shows the projected demands for power, heat, and hydrogen for industrial, residential, and mobility applications. A baseline level of electricity consumption of 3137 TWh is assumed, which remains constant across all years. On top of the baseline level, we assume increased electrification of passenger mobility from electric vehicles, busses, and trains, amounting to 941 TWh in 2050. In addition to electricity, a baseline level of consumption is assumed for hot water and space heating (building heating demand) for both district heating-connected users and
individual users, amounting to 3870 TWh. Heat is also consumed by industry for industrial processes. In 2020 we assume a total consumption of 2427 TWh at various temperature levels, decreasing 1778 TWh in 2050 from an increased use of hydrogen in various applications, such as steel production. In 2050, 1713 TWh of direct hydrogen consumption is projected from industrial applications (e.g., iron and steel, cement, chemical industry, refineries) and heavy transportation in buses and freight transport, as estimated by the European Hydrogen Backbone report (Wang, 2021).

Figure 2: Projected consumption of heat, electricity, and hydrogen in TWh.
These projected demands are an exogenous model input and are subject to some level of change by the model. Namely, additional demand for electricity is expected from electrified heating, as well as for hydrogen production from electrolysis. Implemented into the model is also the option of heat renovations to decrease the heat consumption in district heating, and for individual users. Additional information on the contents of the Balmorel open-source energy system model are described in Kountouris et al. (2023).

**Carbon budget**

To ensure decarbonization in line with the Fit-for-55 policy targets, Europe-wide emissions are restricted by a carbon budget. This budget is enforced through the Emissions Trading Scheme (ETS) and ESR mechanisms, which set budgets that are EU-wide and nation-specific, respectively.

The EU ETS covers CO2 emissions from electricity and central heat production and energy-intensive industry sectors (such as steel works and oil refineries). Its next phase will also include aviation within the European Economic Area and maritime transportation. This study only considers emissions from the energy and intensive industry sectors under the “stationary installations” label. Of the modelled countries, this system covers all EU27 as well as Norway, while the United Kingdom and Switzerland use their own ETS system (FOEN, 2023; Legislation.gov.uk, 2020; EUR-Lex, 2023). Approximately 12 % is removed from the stated budgets to account for
aviation in the UK ETS, and removal of part of the non-process related industrial emissions.

Additional budgets for all countries are added from the ESR system, covering emissions from waste, non-ETS transportation and industry, buildings, and agriculture. Only the building sector is considered by Balmorel through the heat consumption of households and commercial buildings not connected to district heating and is by extension the only part that is included in the carbon budget considered endogenously. Historically, this number has been 25% of total non-ETS emissions (Non-ETS emissions by sector, 2023). When applying a country-level budget, the ETS is distributed via the same share of emissions allocated in the ESR system. Countries not included in ETS or ESR are allocated a budget like the EU countries but adjusted for their GDPs.

All budgets are defined until 2030, after which a linear decrease towards 0 is assumed. Table shows the aggregate system budget, while the country-level budgets are included in the appendix.

<table>
<thead>
<tr>
<th>Table 1: Carbon budget in MtCO2</th>
<th>2021</th>
<th>2030</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETS (EU, UK, &amp; Swiss)</td>
<td>1 543</td>
<td>1 163</td>
<td>0</td>
</tr>
<tr>
<td>ESR, buildings</td>
<td>557</td>
<td>449</td>
<td>0</td>
</tr>
<tr>
<td>Additional GDP adjusted¹</td>
<td>288</td>
<td>268</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>2 388</td>
<td>1 880</td>
<td>0</td>
</tr>
</tbody>
</table>

Conventional mobility

As mentioned, BALMOREL only models the transport directly through demand for electricity and hydrogen. This new demand displaces existing fossil demands. Therefore,

¹ For sectors and countries without direct data on allowances, GDP adjustments are made based on existing countries.
we implement fossil- and biofuel-based mobility consumption and emissions in a post-processing step, to address the entire mobility sector.

The passenger car fleet is assumed to be completely electrified by 2050, with a demand transition based on the vehicle fleet stock in each country (Eurostat, 2023) and data from the EU reference scenario 2020 for current demand of fossil and biofuels (European Commission, 2021). The freight transport and bus demand transition are based on assumptions from the European Hydrogen Backbone project (Wang, 2021). Table shows an overview of the mobility demand transition, in which electricity and hydrogen are the only demands directly included in the modelling, while the impact of the remaining is handled exogenously.

Table 2: Final energy consumption in passenger cars and heavy transportation in TWh

<table>
<thead>
<tr>
<th>Fuel</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil fuels</td>
<td>3425</td>
<td>2255</td>
<td>1127</td>
<td>0</td>
</tr>
<tr>
<td>Biofuels</td>
<td>136</td>
<td>329</td>
<td>204</td>
<td>79</td>
</tr>
<tr>
<td>Electric</td>
<td>0</td>
<td>239</td>
<td>517</td>
<td>794</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>0</td>
<td>28</td>
<td>167</td>
<td>337</td>
</tr>
</tbody>
</table>

2.4 Optimal production pathways

In this section, we present pathways for power, heating, and hydrogen production, where decarbonization is controlled by a carbon budget in line with the Fit-for-55 and European Green Deal policy targets at both the system level and national level. Using this we assess the alignment of individual countries to their commitment, as well as the impact of a system budget versus a national budget. The use of a system budget versus a national budget is henceforth labelled by the two scenario names “base” (system budget) and “natlim” (national budget).

Power production

From 2025 to 2050, the total power production of the modelled pan-European power system increases from (3801 / 3719) TWh/year to (7774 / 7787) TWh/year in the two scenarios (base / natlim scenario), as shown in Figure 3. This increase stems from higher electrification in transportation and heating, as well as hydrogen for Power-to-X (PtX) and industry applications. We observe a transition away from fossil fuels to an energy system largely based on variable renewable energy technologies. Coal and lignite
produced a combined (765 / 570) TWh/year of electricity in 2025 followed by a slow, gradual decrease towards a complete phase-out in 2050. Power from nuclear energy sees a decrease from (829 / 835) TWh/year in 2025 to (134 / 134) TWh in 2050, when a large part of the reactor capacity is expected to have expired. Natural gas has a smaller but more constant role in the system. Power from natural gas initially increases slightly from (61 / 76) TWh/year in 2025 to (157 / 147) TWh in 2030, only to decrease sharply after 2035 and phase out completely by 2050. The largest increase in power production is seen from solar PV from (540 / 530) TWh/year in 2025 to (3 609 / 3 620) TWh/year in 2050. Power from wind sees a similar increase from (787 / 879) TWh/year to (3123 / 3127) TWh/year in 2050. The hydropower resource is assumed exhausted and remains at a near-constant level of (723 / 724) TWh/year in 2025 to (718 / 716) TWh/year in 2050. Similarly, municipal waste and biomass remain as small parts of the energy mix from a combined (55 / 66) TWh/year in 2025 to (132 / 131) TWh/year in 2050. In 2050, a small amount of hydrogen for power enters the system, producing (56 / 56) TWh/year in 2050.

**Figure 3:** Annual power production in the pan-European energy system in the baseline scenario.
Heat production

In Figure 4 we show the total production of heat for district heating, individual users not connected to district heating, and industrial processes. The heat decarbonization reveals a similar phase-out of coal and lignite by 2045 from (911 / 881) TWh/year in 2025 as seen in the power sector. Natural gas sees a similar reduction pattern from (2216 / 2197) TWh/year in 2025 towards a complete phase-out in 2050, however between 2035 and 2045, the consumption plateaus around 600 TWh/year. Biomass and municipal waste heating take a significant role in total heating at (1033 / 1144) TWh/year in 2025 and remain mostly unchanged through the full pathway. The primary source of decarbonization comes from the increase in electrified heating, mostly from heat pumps, but also to a lesser extent from the expansion of electric boilers and electric arcs in the industry. In 2025, heat from ambient heat and electricity make up (1507 / 1445) TWh/year. By 2050, this quantity increases to (3757 / 3759) TWh/year. In addition to the change in fuel, heat savings also contribute significantly to decarbonization, reducing heat consumption. This is shown in 10 as “HEATSAVINGS”,

Source: Authors’ calculations
amounting to \((822 / 827)\) TWh in 2050, corresponding to 21% of the total heat demand in district heating and non-district heating of residential and commercial buildings.

**Figure 4: Annual heat production in district heating, household and tertiary users not connected to district heating, and industry.**

![Annual heat production graph](image)

Source: Authors’ calculations

**Hydrogen production**

In Figure 5, we show the development in hydrogen production, for industry, transport, and for power production from various sources. The production increases 12-fold from 152 TWh/year in 2025 to a max of 1849 TWh/year in 2050. Natural gas is initially the dominant source of hydrogen but shifting to electrolysis-based hydrogen after 2030, due to the technological decreasing costs. In 2040, almost no conventional fuel-based hydrogen remains. Renewable hydrogen imports via dedicated pipelines play some role in 2040 and 2045, importing 130 TWh/year from Morocco, Tunisia, Algeria, and Ukraine at peak in 2045.
**2.5 Alignment of National Targets**

At the system level, Figure 6 shows the system emissions in the two considered scenarios in both modelled sources from Balmorel and additional mobility emissions added exogenously. The most significant difference between the scenarios is the reduction in emissions from coal and lignite. Other emissions sources, such as natural gas, also exhibit a decrease from year to year, but remain mostly unchanged between scenarios.
From examining the two production pathways of electricity, heat, and hydrogen, it is apparent that the two carbon budget implementations result only in a minor difference on the system-level perspective, but some impact on the use of coal and lignite. From this system level perspective, we shift the focus to a nation-level perspective, examining decarbonization and renewable energy share in 2030.

For the year 2030, we investigate the alignment of emissions from each country to the allocated carbon budget, as well as the national renewable shares to EU targets and national targets.
Decarbonization

Figure 7 shows the national emission budget marked by the red line, the emissions in blue under an EU-wide system budget only, and emissions under national budgets in green. Emissions from transport are added to each country ex-post. All values are indexed to 100, where 100 makes up the allocated national budget. Values larger than 100 indicate a level of emissions that is too high, while lower than 100 indicates fewer emissions compared to the allocated national budget. System pathways for each country (similar to the system level 9-11) are put in the appendix. The budget and national emissions include the non-modelled mobility, amounting to 35% of the national ESR budget.

**Figure 7: Alignment of national emissions in 2030 for the modelled sectors, compared to the allocated carbon budget, indexed to 100**

Source: Authors’ calculations

Overall, the CO2 emissions fall well below the system carbon budget. In the base scenario with imposing only an EU-wide budget, but no national restrictions, Poland
and several of the non-EU Balkan nations are among the countries with the largest budget mismatch. In terms of quantities, Poland shows the largest mismatch at 270 MtonCO2 in 2030, 28% over the allocated budget primarily from a large use of coal and lignite. The Balkan countries have a much lower mismatch, however, large shares of coal in electricity production are again the primary cause of it. The implementation of a nation-level budget reduces the use of coal and lignite on a system-level, but on the nation-level, increase the level of emissions in other countries.

**Renewable share**

Figure 8 shows the renewable energy share within the final energy consumption (FEC) in the modeled sectors, as well as non-electrified mobility, for all countries and the combined pan-European system in 2030. The vertical red line indicates a renewable share of 42.5%, the EU binding target (REPowerEU, 2023). If countries have announced a national renewable target in FEC for 2030 in their NECPs (National Energy and Climate Plans, 2023), these are also included in green.

**Figure 8: Renewable energy share in modelled sectors, national targets when available, and EU target.**

Source: Authors’ calculations
We see that the combined pan-European energy system is able to reach the EU climate commitments for renewable energy by 2030 under both scenarios. Of the countries not reaching the EU target, many contain large shares of nuclear power in their electricity mix, explaining the reduced overall share. These include Slovenia, Slovakia, Czechia, and France. Poland and Serbia, which also don’t meet the EU system target, do however reach their national targets in the natlim scenario with the country-level budgets implemented. The primary reason for this is the lower use of coal and lignite in these countries, which is compensated for by higher shares of renewables.

2.6 A deep-dive into the Balkan nations

As previously mentioned, the results from several non-EU Balkan nations indicate a greater challenge in reaching decarbonization goals in 2030. In this section, we take a deeper look into these countries, and on the earmarked efforts needed to meet targets.

Bosnia & Herzegovina showed a significant share of coal remaining in power production, as seen in Figure 9. The position of Serbia allows for a high degree of connectivity to neighbouring countries. In the long-term this opportunity is utilized in both scenarios, and to achieve more rapid decarbonization, this should be utilized even more, as seen in Figure 16. Like Bosnia & Herzegovina, natural gas consumption for hydrogen production could be phased out in favour of imports of mainly renewable electricity and potentially hydrogen through pipelines. Montenegro sees a slight decrease in power production from lignite, but more significantly sees a reduction in natural gas usage for heat and hydrogen, as seen in Figure 11. In the heating sector, decarbonization happens through increase in the degree of electrification utilising heat pumps and the use of biomass. Hydrogen production is in both scenarios handled nationally without relying on trade but transitioning quicker to electrolysis-based hydrogen.

Figure Both scenarios show a long-term potential for a power system based on renewables with net-exports. To further mitigate emissions in intermediate years, coal use should be reduced in favour of higher imports from other countries. Use of natural gas in hydrogen production should also be avoided in favour of imports from surrounding countries.

The position of Serbia allows for a high degree of connectivity to neighbouring countries. In the long-term this opportunity is utilized in both scenarios, and to achieve more rapid decarbonization, this should be utilized even more, as seen in Figure 16. Like Bosnia & Herzegovina, natural gas consumption for hydrogen production could be phased out in favour of imports of mainly renewable electricity and potentially hydrogen through pipelines. Montenegro sees a slight decrease in power production from lignite, but more significantly sees a reduction in natural gas usage for heat and hydrogen, as seen in

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2 Negative numbers represent electricity exported to neighboring countries, while positive represent imports.
In the heating sector, decarbonization happens through increase in the degree of electrification utilising heat pumps and the use of biomass. Hydrogen production is in both scenarios handled nationally without relying on trade but transitioning quicker to electrolysis-based hydrogen.

**Figure 9: Power production pathway for Bosnia & Herzegovina in TWh.**
Source: Authors’ calculations

**Figure 10: Power production pathway for Serbia in TWh.**

Source: Authors’ calculations

**Figure 11: Heat and hydrogen production pathways for Montenegro in TWh.**
In North Macedonia, the national budget is reached by decreasing coal consumption and increasing solar production. As a result, trade also increases both in imports and exports, as shown in Figure 12. In general, the showcased countries here indicate that implementing stricter decarbonization requirements lead to a reduction in fossil fuel used in favour of more trade and renewable energy production.

Figure 12: Power production pathway for North Macedonia in TWh.
The results show little difference in pathways at the aggregate system level between a system-level and country-level carbon budget. Both tools are feasible methods of reaching decarbonization, and while some countries emit more from the stricter constraints put on other countries, cumulative emissions over the time horizon decrease. Additionally, as shown in Figure, the costs incurred across the two scenarios are close to identical. The difference comes from a reduction in fuel costs by reduced consumption of coal and lignite, replaced by mostly wind and biomass in the early years 2025 and 2030, and more solar in 2040 and 2045 (Figure 13). The cost reduction is balanced out by an increased CAPEX and fixed OPEX from the necessary new investments.

**Figure 13: Annualized total cost in MEUR**
Due to the low difference, country-level emission restrictions in line with the Fit-for-55 and even the stricter RepowerEU targets could arguably be worth the additional costs to reduce local pollution.

3. Decarbonizing Land use and Food Systems – Evidence for Greece using FABLE

3.1 Climate Change and Agro-food Systems

Climate change is already affecting food and agricultural systems exacerbating food insecurity, debasing ecosystem services and catalysing biodiversity loss. Food systems driven by agricultural and trade practices on the supply side and by economic activity, population dynamics and human behaviour on the demand side are of material importance in the transition to net zero. Land-use and land-use change for agricultural and socio-economic purposes affects biodiversity and contributes significantly to Greenhouse Gas (henceforth GHG) emissions across the globe. In 2019, agriculture was accountable for 13.1% of global emissions, more than industry (11.6%) and second only
to energy (19.1%), with land-use and land-use change representing almost half of the sector’s output (Boehm, 2022). Ambitious policies to transform the agri-food sector are imperative at the country and international level if humanity aims to meet global targets for food security, biodiversity conservation, water use, and GHG emissions. These policies are expected to have the maximum impact only if they are delineated towards fostering synergies across distinct sectors and communities to allow for positive externalities and minimize trade-offs over short and long-time horizons. Reaching net zero by 2050 and putting a halt to biodiversity collapse warrants a paradigm shift in the agricultural sector, away from the focus of just expanding production and towards mitigating adverse environmental effects through healthy diets and green environmental practices (Willett & al, 2019).

The FABLE Consortium is a global collaborative of researchers who develop national pathways that are consistent with global sustainability objectives, including the Sustainable Development Goals (SDGs) and the Paris Climate Agreement targets. Calculations and development of sustainable pathways are carried out using the FABLE Calculator, an Excel tool that relies on the FAOSTAT (2020) database for input data on 88 raw and processed indicators on the agricultural sector, the economy and population (Mosnier, 2020). For every 5-year time step over the period 2000-2050, the Calculator computes the levels of agricultural activity, land use change, food consumption, trade, greenhouse gas (GHG) emissions, water use, and biodiversity conservation according to selected scenarios. Users can shape mid-century pathways by combining scenarios in 22 categories covering socio-economic variables, environmental and economic policies, behavioural aspects, trade, and climate change. The resulting options of more than 1.5 billion potential mid-century pathways allow for an evaluation and comparisons based on the pathways’ feasibility efficiency and adherence to societal needs tailored to country attributes.

3.2 Assumptions for Greece

The Greek team under the auspices of the AE4RIA network submitted the sustainable pathways for Greece for the first time in 2023. The Greek team, leveraging the knowledge stock and expertise of the Global Climate Hub collated and evaluated all quantifiable national commitments based on national and EU documents, pieces of legislation and official declarations (see Table A1 in the Appendix for a detailed outline). Having said that, regarding the issues where no concrete numerical targets were specified, the team used the most updated data to investigate the trends and make calculated assumptions regarding the targets at hand. After documenting national and EU commitments enshrined in official documents, the iterative process continues with the team updating the FAO data with national sources and beginning the consultation with national stakeholders and scientific experts. The national and global targets set the stage for the second part of the exercise, which consists of translating into distinct pathways for 2050. These pathways are integrated in the FABLE calculator thus shaping the trajectories under the three scenarios, described below:
i. **Current Trends**

The Current Trends Pathway projects key elements of the food, land-use, energy, and biodiversity systems conditional on no significant policy and behavioural changes in Greece for the 2020-2030 period. The continuation of business as usual implies high urbanization and an uptick in economic activity, no change in dietary consumption for the general population, a 50% surge in key exports and increased reliance on food imports. Moreover, we assume no substantial shift in biofuel demand, no afforestation target, and no change in post-harvest losses. This Pathway is embedded in a global GHG concentration trajectory that would lead to a radiative forcing level of 6 W/m² (RCP 6.0), or a global mean warming increase likely 2-3°C above pre-industrial levels.

ii. **National Commitments**

The National Commitments Pathway is underpinned by specific numerical and qualitative targets based on Greece’s NECP, the Development Plan for the Greek Economy (Pissarides, 2020) and the commitments accruing from EU participation. The pathway entails medium to high speed of economic growth, shift to a healthy diet (as described by the Lancet Committee), and reduced imports. Having said that, exports are expected to double by 2050 reflecting the country’s aspiration for outward-oriented economic growth and productivity is expected to surge both for crops and for livestock production. This Pathway is embedded in a global GHG concentration trajectory that would lead to a lower radiative forcing level (RCP 4.5) and assumes expansion of protected areas and an increase in the deployment of organic practices in agricultural land.

iii. **Global Sustainability**

Global sustainability targets were benchmarked from international agreements such as the Sustainable Development Goals, Paris Agreement, United Nations Forest Goals, and Global Biodiversity Targets. Aligning national targets to global goals includes assuming lower speed of economic growth compared to national commitments, albeit with the assumptions for higher crop and livestock productivity remaining stable. In addition, afforestation is aligned with the Bonn challenge and ruminant density does not grow as assumed in the national commitments’ pathway. The global sustainability pathway is underpinned by a global GHG concentration trajectory leading to a lower radiative forcing level of 2.6 W/m² by 2100 (RCP 2.6), in line with limiting warming to 2°C.

3.3 Results using the FABLE Calculator

The pathways characterizing current trends and national commitments are calculated through the choice of options for 22 distinct scenarios following the data outlined in table A1. The FABLE calculator projects the trajectories for a battery of variables covering food consumption, GHG emissions, trade in agricultural products, agricultural
jobs, land use, and biodiversity. The results comparing national commitments and current trends pathways highlight the importance of adhering to national (and EU) commitments for ameliorating emissions from agriculture and promoting biodiversity preservation. It is noteworthy that the national commitment pathway imposes the high degree scenario in economic activity compared to medium for current trends, hence the promising results reflect improvements in productivity and efficiency to a large extent.

Regarding GHG emissions fulfilling (all) national commitments results in Greece achieving net zero agricultural emissions by 2040, contrary to the business-as-usual pathway, which maintains GHG emissions above 1 Mt of CO2 equivalents beyond the 2050 horizon (Figure 14). More specifically, total emissions including land use and land use change remain above 1 Mt through the 30-year period until 2050 if the country maintains its current trend. By contrast, there is a sharp drop under the national commitments scenario whereby total agricultural emissions are 0.83 Mt as early as 2030 and turn net negative after 2040. The purported surge in livestock and crop productivity is pivotal in reducing agricultural emissions from the two sources and, at the same time, are in line with the utmost economic priority of productivity increase for the coming decades. Adhering to the commitments set by the NECP and reflected in Greece’s EU participation results in livestock emissions standing at 1.24 Mt in 2050, approximately half the value of the same variable under the current trends scenario. Moreover, the effect is underpinned on the demand side by behavioural change as shifting to a healthy diet (following the Lancet Committee) is part of the pathway of national commitments. The acute reduction in calories per capita coming from red meat and pork is reflected in the precipitating drop in pastureland (Figure 15) and the corresponding reduction in livestock emissions from 3.2 to 1.3 Mt CO2 equivalent units over the 2020-2050 timespan, marking an impressive 62.5% cumulative decrease. The succinct difference in emissions from agriculture emerges despite the small additional contribution of land use under the national commitments’ scenario. Although this scenario contains the commitment for the expansion of protected areas and the enhanced stringency regarding the land available for agricultural use, there are no significant gains to be modelled with the Calculator from afforestation or ceasing deforestation. The reason is the lack of a comprehensive strategy for afforestation which includes quantitative targets, as Greece is not a signatory of the Bonn Declaration. Hence, there is no distinction between the two pathways that can be translated into reliable projections using the tool. Failing to identify a bold commitment for forest areas does not unlock the potential for further emissions reduction through land-use and land-use change and should be considered a policy priority for the near future.

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3 The module on Water use is still under modification, hence no relevant results are produced in the current version of the Calculator (Update 43).
Figure 14: Agricultural Emissions Projections for Greece

Source: FAO and Authors' Calculations

Figure 15: Evolution of Pastureland for Greece

Source: FAO and Authors' Calculations
The gains in biodiversity are also non-negligible as the share of land where natural processes predominate surges from 65.9% in 2020 to 69.2% in 2050 under the national commitments’ pathway, compared to a drop to 64.2% if current trends are maintained (Figure 16). The results could be even more encouraging and supportive to biodiversity preservation, however, apart from the lack of an afforestation/deforestation quantitative target, the Greek authorities have not established a comprehensive framework governing the expansion of agricultural areas. Hence, the assumption in this context is the same across both pathway selections. Enhancing regulatory stringency, coupled with quantitative targets where possible would yield more nuanced projections and would enable the measurement of gains for biodiversity in a data-driven manner.

**Figure 16: Land where Natural Processes predominate**

As envisioned in the NECP for Greece, national commitments result in an increase in land with agro-ecological farming practices which manifests after 2040 and results in 1.62 million hectares in 2050 compared to 1.58 million under current trends (Figure 17). It must be noted that, given the vast drop in pastureland, there is a rebound increase in cropland under national commitments. Hence the share of land with agro-ecological practices as a share of total cropland is lower in comparison to the current trends scenario, however this result needs to be viewed in context.

Finally, production value in agriculture is reduced substantially across both pathways, reflecting the structural change of the Greek economy. Moreover, the implied paradigm
shift in demand regarding to healthy dietary norms drastically reduces livestock production. Under the national commitments’ scenario, the post-harvest losses are gradually minimized, and overall economic activity is tilted to the upward side, which explains the less pronounced fall in production value (Figure 18).

**Figure 17: Agro-ecological Farming Practices**

![Agro-ecological Farming Practices](image1)

**Figure 18: Production from Crops and Livestock**

![Production from Crops and Livestock](image2)
The results from the FABLE Calculator underline the sharp differences in trajectories towards 2050 under different pathways. To reap the benefits of transformation in food and land-use systems and drastically abate GHG emissions from agriculture, countries need to establish clear commitments (ideally enshrined in national or international legal documents) and commit to achieving quantitative targets. In the case of Greece, this translates in negative net emissions from agriculture by 2040 and substantial gains in biodiversity without draining economic activity. Earmarking policies towards green innovation to foster productivity and addressing the synergies and trade-offs between the agro-economy and biodiversity must be at the epicentre of the country’s net zero strategy for 2050.

4. Conclusion

The use of cutting-edge energy and land-use assessment models presents a promising avenue for devising sustainable pathways in the face of climate change and environmental degradation. These models offer a comprehensive understanding of the intricate interactions between energy systems and land use, allowing policymakers and stakeholders to make informed decisions that balance energy demands with environmental conservation objectives.

Examining sustainable energy pathways for the EU using the BALMOREL model, we find that the EU mandates under the EU Green Deal, Fit-for-55, and RepowerEU for a decarbonized Europe are feasible through investment into renewable technologies like solar and wind, combined with energy trade-enhancing interconnections between European countries. Through investment into renewable technologies like solar and wind together with interconnections between countries fostering trade, it is possible to achieve a fully decarbonized power sector in 2050, but also achieve the 2030 targets. The power sector can further enable sustainable heating, industrial processes, and transport through electrification and the extended use of hydrogen. In the building sector, renovation of buildings can also play a significant role in reducing the need for heating by about 21%. In the current policy horizon towards 2030, the choice of carbon budget implementation methods can impact individual countries’ ability to meet targets. While the overall system can meet the allocated budget, some countries, especially some of the non-EU Balkan countries such as Serbia and Bosnia & Herzegovina, are not able to phase out existing non-renewable infrastructure implementing only Europe-wide system budget.

Transformation in the land-use and agricultural sectors is a decisive factor for abating emissions and curtailing biodiversity loss as indicated by the case study of Greece. Using the FABLE calculator, we find that fulfilling national commitments enshrined in Greek law and EU consolidated targets leads to net negative emissions from agriculture as early as 2040. Moreover, the policy levers associated with national commitments yield tangible improvements in the country’s biodiversity index, the spread of organic farming,
the promotion of healthy diets and enhanced agricultural productivity. The findings underscore the importance of shaping different trajectories towards 2050 through the implementation of publicly announced national commitments. The emission mitigating effects stemming from both the demand and supply side marks the necessity to delineate national policy towards the promotion and adoption of green technology as well as public awareness on the effects of dietary patterns on the sustainability of the agricultural and food systems.

This first set of model-based results provide ample fodder to policymakers across the globe to step-up their climate mitigation and adaptation efforts and adhere to their net zero pledges. The GCH will continue to provide nuanced projections through modeling integration techniques and embolden them with case studies, use cases, and storytelling methods, addressing the complex issue of socio-economic transition in a holistic fashion. The adoption of sustainable pathways derived from the BALMOREL and FABLE models holds the potential to drive transformative change across various sectors of society. By promoting renewable energy sources through significant investment, enhancing carbon sequestration through sustainable land management practices, advocating for a shift to healthy dietary patterns and fostering biodiversity conservation, these pathways offer a roadmap towards a more resilient and equitable future.

References


**Appendix**

Table A1: Greece National Targets for the Food & Land-use Sectors

<table>
<thead>
<tr>
<th>Policy area</th>
<th>Policy ambition</th>
<th>FABLE team’s proposed quantitative national targets</th>
<th>Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food</td>
<td>Undernourishment</td>
<td>0% undernourished share of population</td>
<td>By 2030, double the agricultural productivity and incomes of small-</td>
</tr>
<tr>
<td>Food</td>
<td>Overweight / obesity</td>
<td>Food</td>
<td>Diet-related disease</td>
</tr>
<tr>
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<td>----------------------</td>
<td>------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td>Priority reduction of childhood obesity from 25% (2017) to at least 10% (EU average) by 2030</td>
<td></td>
<td>Improvement of the nutritional composition of food products in line with The National Action Plan for Public Health 2021-25 and line with SDG 3.4, under joint initiative by the UN and WHO as part of the 9 voluntary targets adopted by Member States during the World Health Assembly in May 2013. Supported by the EU for member states.</td>
</tr>
<tr>
<td>Climate mitigation</td>
<td>Total GHG emissions reduction</td>
<td>Agriculture GHG emissions reduction</td>
<td>Greece aims to reduce total greenhouse gas emissions by 55% by 2030 and by 80% by 2040 compared to 1990 before achieving zero-net emissions by 2050. Total GHG emissions in Greece are expected to decrease to 60.6 MtCO2e in 2030.</td>
</tr>
</tbody>
</table>
onwards, net emissions followed the trend set by total emissions in the country.

<table>
<thead>
<tr>
<th>Climate mitigation</th>
<th>Reduce or halt deforestation</th>
<th>In line with the EU Green Deal to stop deforestation, and SDG 15.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiversity</td>
<td>Reduce or halt loss of natural ecosystems</td>
<td>The aim of the biodiversity strategy is to halt the loss of biodiversity and the degradation of ecosystem services in Greece by 2026, and restore them, as far as it is feasible, while communicating the value of biodiversity as our national capital, and stepping up the Greek contribution towards averting global biodiversity loss.</td>
</tr>
<tr>
<td></td>
<td>Promote afforestation</td>
<td>Alignment with the objectives of the National Reforestation Plan aim to: strengthen the resilience of forests against natural disasters, protect biodiversity, limit the country’s carbon footprint and mitigate the effects of the climate crisis, create new jobs, improve the living conditions in urban and peri-urban areas, embed ecological culture and environmental awareness.</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Expand protected areas or 'Other effective area-based conservation measures' (OECMs)</td>
<td>Protected areas represent 30% of land and water by 2030</td>
</tr>
<tr>
<td></td>
<td>Expand cropland area under agroecological practices</td>
<td>The Law 5037/2023 will guide the implementation of the EU Biodiversity Strategy in Greece following article 174 under Targets for Nature Conservation: by 2030, at least 30% of the land area and sea of the country are covered by protected areas. Protected areas should fully cover Key Biodiversity Areas.</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Reduce or halt use of agrochemicals and other agricultural practices that harm biodiversity</td>
<td>The European Commission has set the target of 25% of the EU’s agricultural area under organic farming by 2030</td>
</tr>
</tbody>
</table>

Reduction by 50% of the use of chemical pesticides and more hazardous pesticides and more hazardous pesticides by 2030 compared to the annual average the 2015-2018 period

The Farm to Fork and Biodiversity Strategies set two key targets for pesticides:

Target 1: to reduce by 50% the use and risk of chemical pesticides by 2030.

This target will be measured based on the quantities of active substances contained in the pesticides which are placed on the
<table>
<thead>
<tr>
<th>Category</th>
<th>Target Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fertilizer use</td>
<td>Limit N use</td>
<td>Reduce the use of N fertilizer by 20% by 2030 compared to 2015</td>
</tr>
<tr>
<td>Fertilizer use</td>
<td>Limit P use</td>
<td>Reduce the use of P fertilizer by 20% by 2030 compared to 2015</td>
</tr>
<tr>
<td>Water</td>
<td>Limit water use</td>
<td>Reduce water consumption in agriculture by 10-20% by 2030 compared to 2020 levels</td>
</tr>
<tr>
<td>Water</td>
<td>Other water related targets</td>
<td>Sustainable water use is highlighted in the National Recovery and Resilience Plan (NRRP) and the new EU CAP. Greece has reported a reduction in water consumption in agriculture by 8.3% during the 2010-20 period.</td>
</tr>
<tr>
<td>Economy</td>
<td>Farmers’ income</td>
<td>10-15% increase by 2030 compared to 2020</td>
</tr>
<tr>
<td>Economy</td>
<td>Agricultural exports</td>
<td>The new CAP aims to support agricultural income and create supportive market and non-market mechanisms. According to our data analysis, 2020 marked a ~30% increase in farmer income compared to 2010. In 2017, the average gross farm income was EUR 17,817. Agriculture represents 4.1% of Greece’s Gross Value Added (GVA) and 14% of total employment.</td>
</tr>
</tbody>
</table>

Target 2 - 50% reduction in the use of more hazardous pesticides

As part of the Farm to Fork strategy, the European Commission aims to see a reduction in nutrient losses of at least 50% by 2030. This is expected to lead to a reduction in fertilizer use of at least 20%.
continued to grow (from €3.7 billion to €5.3 billion).

<table>
<thead>
<tr>
<th>Economy</th>
<th>Timber exports</th>
<th>According to our data analysis, wood &amp; wood products exports averaged ~ 200 mil 2012-16 and dropped to ~60 mil 2017-2020.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Economy</td>
<td>Employment in agricultural sector</td>
<td>According to the Pissarides report, the goal is to increase agricultural productivity and change the age participation in agricultural employment. According to our data analysis, agricultural employment, in 2017, was 14% of total employment making a gradual decline over the last 30 years.</td>
</tr>
</tbody>
</table>

3x wood & wood product exports by 2030 compared to 2020