UN SDSN Global Climate Hub: Modelling Net Zero Pathways

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Contents

Executive Summary

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.

During its first year, the GCH initiated a holistic approach to climate, economic, and energy modelling to deliver a first set of results. The process described in this report consists of a thorough review and assessment of potent Integrated Assessment Models (IAMs) and the delineation of a first set of sustainable pathways on the EU energy sector, the deployment, and effects of renewable energy transition in Southeast Asia and the development of sustainable pathways for land-use and food systems in Greece. In addition, the researchers of the GCH are examining interlinkages and complementarities across diverse IAMs which will yield horizontal and vertical synergies and elaborate on the potential pathways to net zero for 2050.

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.

Enhancing the capacity and utilization of renewable energy sources is the first step towards achieving net zero for Southeast Asia. With governments pledging to support cleaner energy systems and considerable technological cost reductions, renewable energy is predicted to account for a growing portion of Southeast Asia's energy mix. Hydropower, solar, wind, and bioenergy are Southeast Asia's four main renewable energy sources. The strategy to switch from coal to natural gas must be modified. More storage and connections will be required, which will take time, in order to be able to incorporate more of Southeast Asia's plentiful variable renewable electricity into the grid. Southeast Asia should concentrate on creating dispatchable renewable energy sources, such wood pellets, which can replace coal as a baseload power source in the interim period.

As the Greece case study shows, 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.

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.

1. Introduction

As the global community grapples with the profound challenges posed by climate change, the imperative to transition to a sustainable and decarbonized future has never been more pressing. Achieving net-zero emissions by 2050 has become a rallying cry for governments, businesses, and individuals alike, reflecting a shared commitment to safeguarding our planet for current and future generations. According to the IPCC AR6 Report (IPCC, 2023) "Challenges from delayed adaptation and mitigation actions include the risk of cost escalation, lock-in of infrastructure, stranded assets, and reduced feasibility and effectiveness of adaptation and mitigation options" (p.60). Maintaining the current course is simply not an option if we want to achieve net zero emissions by 2050 and wish to promote sustainable pathways for humanity. The report underscores that keeping approximately the same level of annual CO2 levels for the coming decade at the 2019 levels would imply the exhaustion the remaining carbon budget for 1.5°C and depleting more than a third for 2°C. According to data for Europe from Copernicus (Copernicus, 2022), 2022 was the second warmest year on record in Europe, at 0.9°C above average, and the summer of 2022 was the warmest on record, recording 1.4°C above average, and 0.3–0.4°C above the previous warmest summer, which was in 2021.

Against this backdrop, national governments, international institutions, and global production networks need to design and implement bold initiatives to be compatible with the paradigm shift to net zero emissions by mid-century. The multifaceted and complex issues stemming from climate change, geopolitical tensions, and unexpected events (showcased aptly by the COVID-19 pandemic) warrant for the joint efforts of stakeholders across this societal spectrum. At the epicenter of this colossal effort lies the decarbonization of global economic activity through the phasing out of fossil fuels. In addition to abating GHG emissions, decoupling economic growth from fossil fuels' use is a lever to promote energy security as documented in the recent energy crisis. The energy sector, which accounts for approximately one fifth of global GHG emissions recorded a new record high of 37 billion tonnes (Gt) in 2022, 1% above their pre-pandemic level, however total emissions are expected to peak before 2030 (IEA, 2023). While some regions and sectors have made progress in reducing the impact of fossil fuels on GHG emissions, the overall trend still highlights the pressing need to accelerate the transition to cleaner and more sustainable energy sources to combat climate change effectively. Particularly in the EU, emissions in 2021 were cut by 30 per cent compared with 1990 levels. Nonetheless, reaching the 2030 target of a 55% drop it would require making further emissions cuts equal to approximately the annual output of 332 gas-powered stations[1].

Meeting net zero targets warrants unprecedented advances in renewable energy capacity, energy efficiency through electrification and new technologies, abrupt halting of deforestation and promotion of afforestation, rapid deployment of carbon capture technologies, and acute behavioral change regarding to food consumption, transportation, and energy use. To this end, systems of innovation at the national and the international level ae of utmost importance for the development, commercialization, and dissemination of green technologies for climate mitigation and adaptation. Their success is contingent on the functioning and interlinkages across multiple institutions including research centers and academia, private enterprises, the public sector, financial institutions, and civil society. Fostering innovation systems and steering society towards net zero transition also requires ambitious and politically costly policies whose positive effects manifest in the long run. However, it is imperative that the transition does not stifle economic growth, especially for developing countries and that it leaves no person or community behind in the process. Hence, in this context, scientific methods provide the necessary data and measurements and combine diverse inputs and methodologies to undertake holistic evaluations of the transition pathways. It is precisely this science-driven and human-centric approach to transition that the Global Climate Hub champions.

Responding to the challenges posed by climate change and the need for immediate decisive and collaborative action to meet the SDGs and net zero in this century, the United Nations launched the UN SDSN Global Climate Hub (GCH) in July 2022. The GCH is operating as an SDSN Thematic Network leveraging the expertise and skills of individuals and members of

[1] https://newclimate.org/what-we-do/projects/european-climate-neutrality-observatory-ecno

the SDSN Network[2]. Its mission is to provide science-based recommendations for developing sustainable socio-economic pathways for the medium- and long-term horizon using extensive data, knowledge, techniques, and technologies provided by experts across different scientific fields. It combines a global approach with the design and implementation of country-specific action plans to be adopted by policymakers and reinforced by all pillars of the quadruple helix (public sector, private sector, academia & research institutions, and civil society). The overarching objective of the GCH is to design sustainable solution pathways based on scientific knowledge coupled with the socioeconomic narratives that underpin these transitions and to provide policy recommendations, which will consider economic efficiency, environmental sustainability, and justice epitomized in the "leave no person behind" dogma. Having said that, the Hub will build on the development of metrics and assessment of local and national SDG achievement carried out by the UN SDSN network, to formulate science modeling that employs a holistic multi-module approach, allowing for the evaluation of variable complexities and scales.

The aim of this report is to present the work of the Global Climate Hub on net zero pathways, mirroring the work undertaken in some of its distinct units. Having established the benchmark in the current state of environmental indicators and environmental policies (operating and designed), the GCH is currently collating and evaluating scientific methods embedded in modelling systems in order to integrate strands of research into coherent environmental, energy and socioeconomic pathways. Section 2 briefly summarizes the review of Integrated Assessment Models (IAMs) which

[2] The Hosting Institutions of the SDSN Global Climate Hub (SDSN-GCH) are the Athens University of Economics and Business (AUEB) and the "Athena" Research and Innovation Center in Information, Communication and Knowledge Technologies (ATHENA RC), both of which are part of the Alliance of Excellence for Research and Innovation on Aephoria (AE4RIA), an initiative for collaboration between research institutions, innovation accelerators, and science-technology-policy interface networks focused on sustainable development. The Academy of Athens and the Technical University of Denmark are two of the most important co-founding institutions of the GCH. The chair of the SDSN-GCH is Prof. Phoebe Koundouri, who also is the founder and director of AE4RIA.

form the multi-dimension scientific arsenal in the pathways' development, while section 3 outlines a first set of results stemming from energy and land-use models. More specifically, section 3.1 addresses the issue of decarbonization of the EU energy system as envisioned in the Fit-for-55 and RePowerEU initiatives through the projections of the BALMOREL model. Section 3.2 describes the pivotal role of renewable energy for bolstering ecosystems services in Southeast Asia and section 3.3 summarizes the key tenets of sustainable and-use and food system pathways for Greece using the FABLE Calculator. Finally, section 4 describes the potential for system integration under the auspices of the GCH and highlights the areas for future work in promoting net zero pathways.

2. Integrated Assessment Models (IAMs)

2.1 Introductory Information on Integrated Assessment Models

Integrated Assessment Models (IAMs) are complex computational frameworks used in the fields of environmental science, economics, and policy analysis to assess and evaluate the interrelationships between different factors and systems that influence critical issues, such as climate change, energy policy, and sustainability. These models use a multi-disciplinary approach to integrate data, knowledge, and methodologies, merging *inter alia* climate science, economics, energy systems, to provide a comprehensive and holistic understanding of how different policies and scenarios can impact the environment, society, and the economy in the medium and the long run. IAMs represent the coming together of three different worlds of scientific thinking in relation to energy and climate science: energy system and technological progress models, economic system models, and climate science models.

IAMs play a pivotal role in addressing complex and multifaceted societal challenges, particularly those related to environmental policy and the trajectory to net zero. Integrated assessment models (IAMs) aim to provide policy-relevant insights into global environmental change and sustainable development issues by providing a quantitative description of key processes in the human and earth systems and their interactions. They are utilized in all major publications and reports referring to climate change and climate projections and are gaining ground in the science-based information of policymakers across the globe (Schwanitz, 2013).

This chapter presents a thorough review and classification of selected IAMs for comparing and evaluation sustainable pathways. The main goal of this work is primarily to collate and characterize widely used and potent IAMS in terms of:

i. Coverage
ii. Potential
iii. Accessibility
iv. Inputs-Outputs
v. Synergies & Complementarities

Moreover, this work is conducted with the aim to assess the added value of each IAM individually as well as an integral part of model synergies for the design of sustainable pathways for the Global Climate Hub. Harnessing distinct IAMs is of material importance to the work of the Global Climate Hub and a particular area of focus for the Climate & Energy Systems Modelling Unit and the Land Use and Marine Use Modelling Unit. The objective is to assess the feasibility and performance of different socio-economic and environmental pathways using a science-driven and human-centric approach.

The issue of synergies is particularly challenging and needs to be carefully studied in order to undertake a holistic approach to decarbonization pathways and develop socio-economic narratives associated with the diverse model projections. There are three main types of synergies:

i. Cooperative: The output of one model is used as input in another model.
ii. Complementary: Two or more models need to work together in order to produce an output and you cannot use one without the other, or the output you receive is incomplete without the other.
iii. Independent: Two or more models can create their own distinct and complete output, but due to the coverage of each model (i.e., they both study land use issues), the results of each model can be

joined together, to create a new output that conveys more information than either model did individually.

2.2 Methods

In order to evaluate the relevance, scope, and complementarities of IAMs, we start with a set of classifications. Models are categorized according to the following traits:

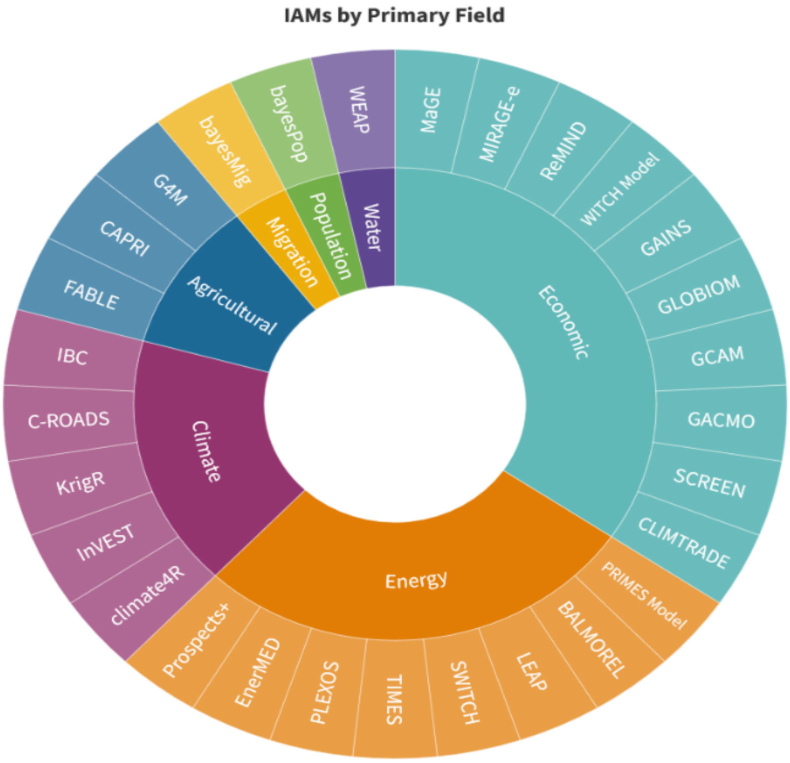
i. Field: Sectors of the Economy and Focal Points (Figure 1). Primary and secondary fields are assigned to cover the multidisciplinary nature of most of the models

ii. Suite: Programming and software requirements

iii. Economic Complexity: general equilibrium versus partial equilibrium models

Having said that, we cast our focus to the main outputs of each model, in order to identify the projections derived from each exercise. In addition, this allows us to identify potential synergies between models through (i) model averaging techniques and (ii) integration whereby outputs from a certain model feed into another model as inputs.

Figure 1. Classification of IAMs by primary field



Source: Authors' Calculations

2.3 IAMs Review

Twenty-nine IAMs were evaluated (see Table 1) in this exercise, however, due to spatial constraints, one model of each of the primary fields will be presented here.

Table 1. List of assessed IAMs

FABLE	PRIMES Model	PLEXOS
bayesMig	GAINS	C-ROADS
bayesPop	CAPRI	GACMO
climate4R	GLOBIOM	IBC
InVEST	G4M	EnerMED

KrigR	BALMOREL	WEAP
MaGE	LEAP	Prospects+
MIRAGE-e	SWITCH	SCREEN
ReMIND	GCAM	CLIMTRADE
WITCH Model	TIMES	

2.3.1 IAMs description

Agricultural primary field:

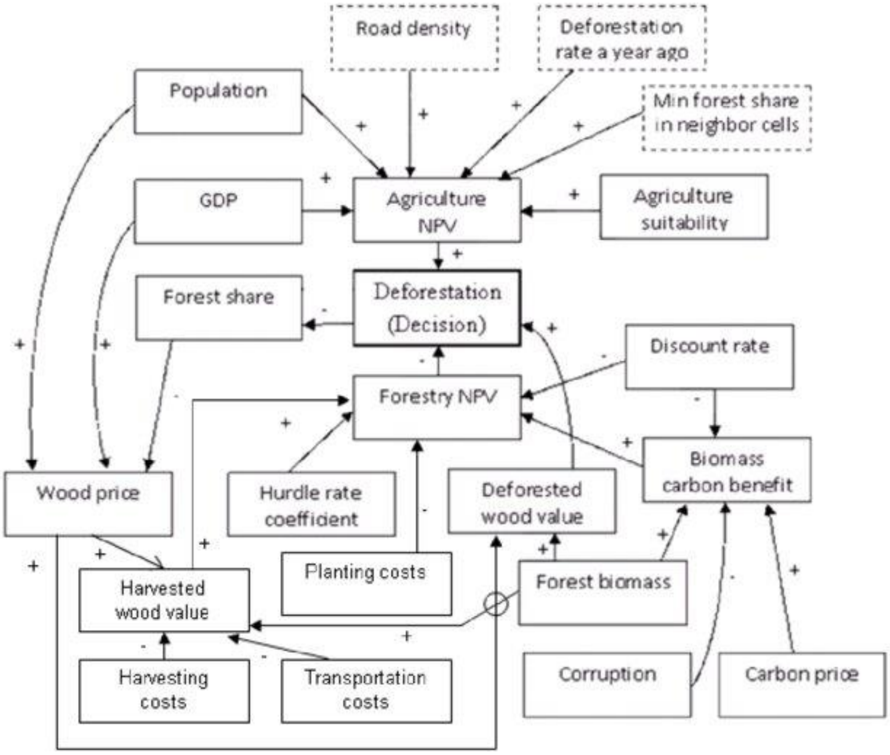
G4M[3] (Global Forest Model) is a climate model comparing the income derived from forests with the income that could be derived from an alternative use of the same land, for example, to grow grain for food or biofuel. G4M demonstrates whether it would be more profitable to grow agricultural crops or biofuels at the location, or whether forestry is the best option for the land. G4M is a versatile model that can be integrated with other models to gain greater clarification of land use potential.

As well as demonstrating the pros and cons of different land uses, it can compute optimal forest rotation times to optimize biomass stocking and harvesting rates and can also help to rationalize other important aspects of forest management. Its primary field is land use, while its categories are forestry, economics, population, migration, agricultural, food, water, ecosystems. Its schematic can be seen in Figure 2 that follows.

Synergies: GLOBIOM

[3] https://previous.iiasa.ac.at/web/home/research/researchPrograms/EcosystemsServicesandManagement/G4M.en.html

Figure 2. G4M diagram of the decision on deforestation in a grid cell



Source: Gusti (2015)

<u>Migration - population – water</u> category: BayesPop

BayesPop[4] is an open access R package for probabilistic population projections using outputs from bayesTFR and bayesLife as inputs. Raftery et al. (2012) describes the methodology. Azose (2016) and Ševčíková et al. (2014) give details that are more technical. Its categories are population, fertility, mortality and migration and its primary field includes economics.

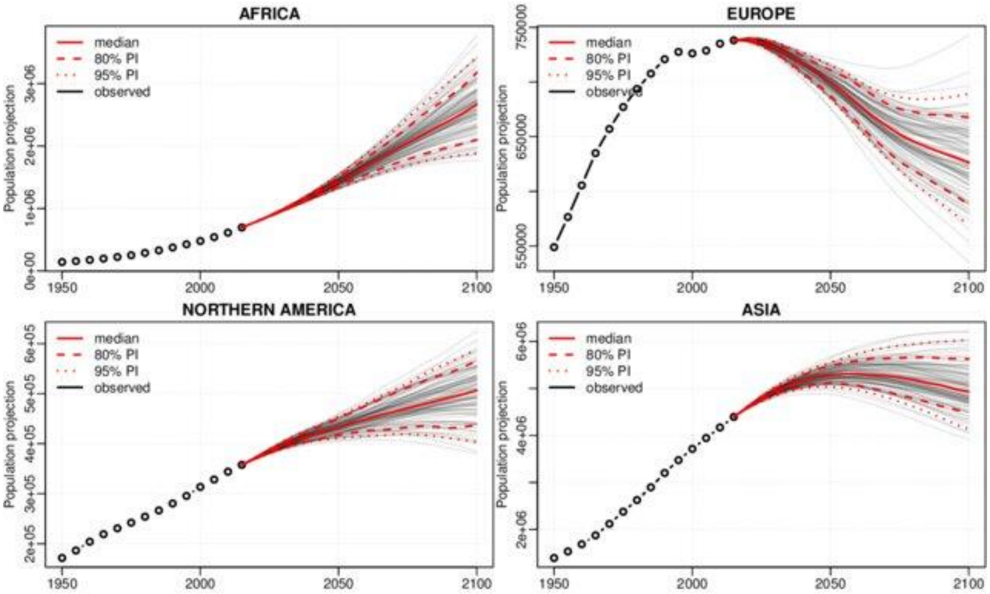
Input: The input components needed to run the simulation include the initial male, female age-specific population counts; Estimates of historical male and female age-specific death rates; Estimates of historical age-specific fertility rates as percentages of TFR; Projection of future sex ratio at birth and others.

Output: The BayesPop model is a probabilistic projection model that provides, as output, a set of sex- and age-specific population trajectories (Figure 3), which can be used to construct posterior distributions of various population quantities of interest.

Synergies: (Cooperative) bayesTFR, bayesLife, MortCast

[4] https://bayespop.csss.washington.edu/

Figure 3. Population trajectories for aggregated regions using BayesPop obtained via the country-based method[5]



<u>Climate</u> category: IBC

IBC[6] (Integrated Benefits Calculator) is an add-on module included in LEAP energy model. It translates emissions scenarios from LEAP into estimates of air pollution-associated health issues (premature mortality), ecosystem impacts (crop yield loss), and climate impacts (global temperature change). IBC examines the numerous benefits in taking measures regarding the long- and shot-lived climate pollutants (SLCPs) and the local air pollutants.

Inputs: utilizes parameterized results from the global atmospheric geochemistry model GEOS-Chem Adjoint, which are combined with emission estimates to calculate population-weighted concentrations of fine particulate matter (PM2.5) and ground-level ozone (O3).

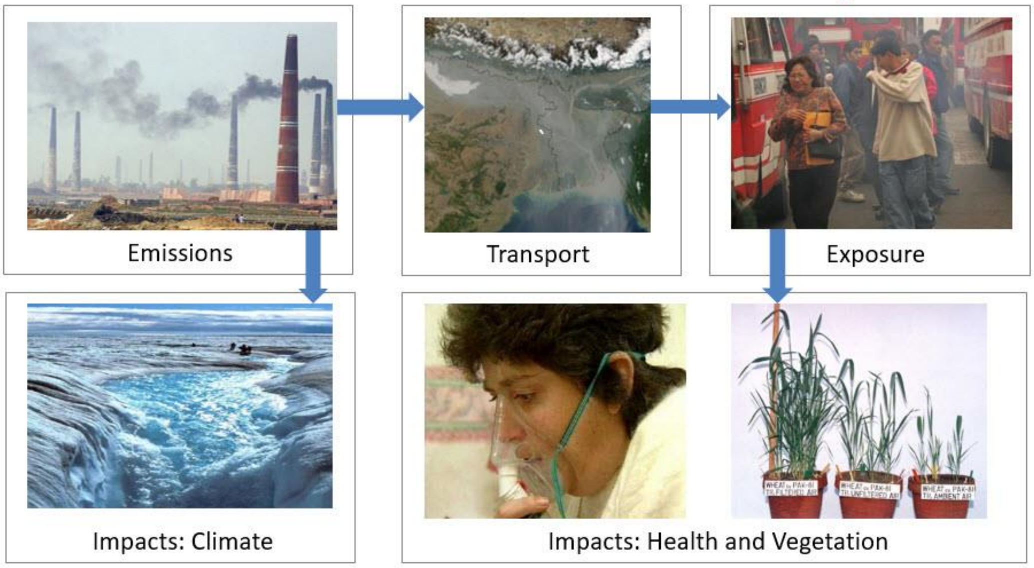
Output: The above concentrations are then used with standard concentration-response functions to estimate premature mortality associated with PM2.5 and ozone exposure and crop yield losses associated with ozone exposure. The results can be viewed by a) geographic source (in-country, natural background, and rest of the world), b) the contribution of emissions

[5] https://www.researchgate.net/publication/311447803_bayesPop_Probabilistic_Population_Projections

[6] https://leap.sei.org/default.asp?action=IBC

of different pollutants to the impact (e.g. the contribution of NOx, black carbon, organic carbon, etc.), c) age group (for premature mortality) or d) crop type (for crop losses, currently rice, wheat, maize and soy). Health impact functions are based on the standard dose-response functions used in the Global Burden of Disease Study[7]. The process from emissions to impacts investigated by LEAP and IBC is seen in Figure 4.
Synergies: LEAP, GEOS-Chem Adjoint

Figure 4. The pathway from emissions to impacts in LEAP-IBC



Source: SEI

<u>Economy</u> category: ReMIND

ReMIND[8] (REgional Model of Investment and Development) is a numerical model that represents the future evolution of the world economies with a special focus on the development of the energy sector and the implications for global climate.

The goal of ReMIND is to find the optimal mix of investments in the economy and energy sectors of each model region given a set of population, technology, policy, and climate constraints. It also accounts for regional trade characteristics on goods, energy fuels, and emissions allowances. All greenhouse gas emissions due to human activities are represented in the model. It is an open access, R-package, general equilibrium model.

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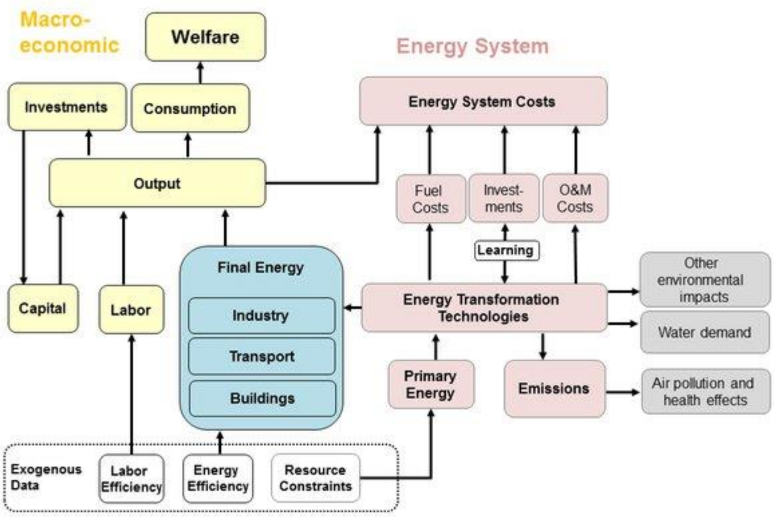
7 https://ehp.niehs.nih.gov/doi/10.1289/ehp.1307049
8 https://www.pik-potsdam.de/en/institute/departments/transformation-pathways/models/remind

It covers twelve world regions, differentiates various energy carriers and technologies, and represents the dynamics of economic growth and international trade. ReMIND uses economic output for investments in the macro-economic capital stock as well as for consumption, trade, and energy system expenditures. It falls into the economic, energy and climate categories, while its fields of functioning also include population and migration. The structure of ReMIND is depicted in Figure 5.
Synergies: Part of the Potsdam Institute for Climate Impact Research (PIK), specifically MAgPIE and MAGICC.

Figure 5. ReMIND structure



Source: Baumstark & al. (2021)

<u>Energy</u> category: PRIMES

PRIMES[9] (Figure 6) is an EU energy system model, which simulates energy consumption and the energy supply system. It is a partial equilibrium modelling system simulating an energy market equilibrium in the European Union and each of its Member States. This includes consistent EU carbon price trajectories. The full PRIMES suite comprises models involving transportation, biomass supply, industry, electricity and heat supply and several others. However, despite the diversity of these fields the focus of all of them is on energy supply and consumption.

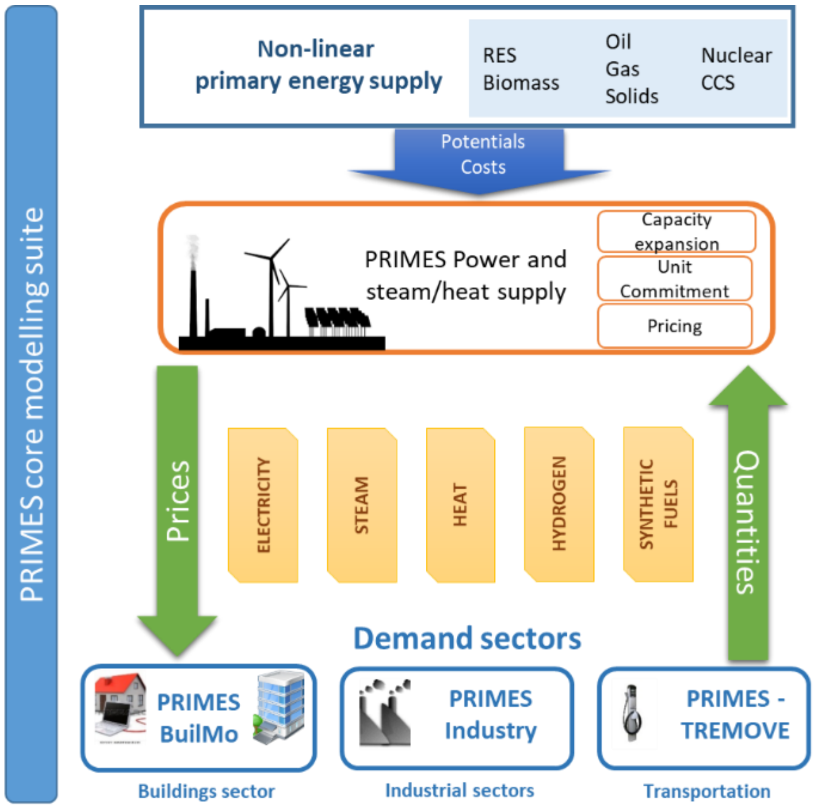
[9] https://e3modelling.com/modelling-tools/primes/

The distinctive feature of PRIMES is the combination of behavioural modelling (using microeconomic foundations) with engineering aspects, covering all energy sectors and markets. The model provides a detailed representation of policy impact assessment instruments related to energy markets and climate, including market drivers, standards, and targets by sector or overall. It handles multiple policy objectives, such as GHG emissions reductions, energy efficiency, and renewable energy targets and provides pan-European simulation of internal markets for electricity and gas.

PRIMES inputs include GDP and economic growth per sector, for many sectors; world prices of fossil fuels; taxes and subsidies; interest rates and risk premia; environmental policies and constraints and several others. The *outputs* include detailed energy balances, in EUROSTAT format; detailed demand projections by sector including end-use services, equipment and energy savings; detailed balance for electricity and steam/heat, including generation by power plants, storage and system operation; production of fuels (conventional and new, including biomass feedstock); emissions of atmospheric pollutants; Policy Assessment Indicators and quite a few others. The outputs depend on the model used and the inputs that provided.

Synergies/ linked models: GEM-E3 and IIASA's GAINS

Figure 6. PRIMES schematic[10]



2.4 Synergies

2.41. The Stockholm Environment Institute (SEI) models' synergies

LEAP and IBC developed by SEI[11] maintain a cooperative synergy, where the outputs from LEAP model are used as input for IBC model.

The calculations of IBC are based on emissions inventories and projections developed in LEAP for a specific country. Users are required to specify extensive emissions inventories and forward-looking scenarios for all major long-lived and short-lived climate pollutants (SLCPs), and local air pollutants such as CO2, CH4, black carbon, organic carbon, PM2.5, non-methane volatile organic compounds (NMVOCs), NOx, SO2 and NH3. A comprehensive set of default emission factors for these pollutants has been evolved by SEI that can be added to existing data sets, which is applicable, for instance, in the case of a country that has already developed a LEAP data set for its analysis of its Nationally Determined Contributions (NDCs). A template LEAP structure for performing these types of analysis, named

[10] https://e3modelling.com/modelling-tools/primes/

[11] https://www.sei.org/

"Asiana" data set, and focused on sectors that are important in terms of generating emissions of important SLCPs, has been also developed by SEI. Furthermore, users can merge their existing data sets with parts of the standard template structure, to create a data set that meets the needs of the subject country.

IBC makes a complex and highly computing-intensive modelling methodology accessible to planners in the developing world. It parameterizes the calculations of GEOS-Chem Adjoint that takes a few days to perform per country, and hereinafter, the calculations in LEAP are run in a few seconds. LEAP is furthermore used for all data management and results visualization, making it readily usable by developing country planners.

Up to 2018, LEAP-IBC worked for a selected set of national-scale applications, designed to operate for 71 countries for PM2.5, and 20 countries for Ozone-related impacts. An expansion of coverage to 150 countries in 2018 was planned. Moreover, an IBC tool with city scale application, providing greater information on the impacts of indoor air pollution, including gender-based disaggregation of impacts has been also scheduled.

2.4.2. Compass Toolbox from New Climate Institute

New Climate Institute[12] has developed the "COMPASS" toolbox within the framework of the Climate action Outcomes and Mitigation Policy Assessment. The toolbox involves New Climate Institute produced climate scenario modelling tools, for understanding and assessing the impacts of climate action and policies for climate change mitigation. The models are excel based analytical tools to expedite the comparison of different scenarios, policies, and outcomes and to investigate potential opportunities and obstacles in raising climate ambition. All these tools can be utilized independently, or with soft links to other COMPASS tools and/or third-party models.

The following IAMs are harnessed under a cooperative synergy scheme model:

[12] https://newclimate.org

i. PROSPECTS+ and CAAT (Climate Action Aggregation Tool) for tracking and projecting GHG emission scenarios at sectoral and economy-wide levels.
ii. SCAN (SDG Climate Action Nexus tool), EIM-ES (Economic Impact Model for Electricity Supply), AIRPOLIM-ES (Air Pollution Impact Model for Electricity Supply), TRACE (Transport sector climate action co-benefit evaluation tool), SCREEN (Sustainable development and climate action green recovery screening tool) and CLIMTRADE (Economic impacts of climate regulation in trade tool) for understanding the impacts of climate action on sustainable development objectives.
iii. EV policy impact assessment tool and RE policy impact assessment tool, both supporting policy impact projections drawing on technology S-curve modelling logic.

2.5 Discussion and Conclusions

IAMs should be considered as complementary models and not competing. Exhibiting a vast range of sectoral expertise, different IAMs can be utilized for different predictions, yielding precise results. The possibility of adaptation to local or sectoral level (downscaling) of an Integrated Assessment Model would further assist the predictions regarding a specific country or area.
Integrated Assessment Models (IAMs) offer great possibilities of scientific predictions. IAMs offer a holistic systems approach incorporating economy, energy, climate, and biodiversity sectors. However, the complementarity and synergies between the IAMs should be further investigated. Finally, IAMs can facilitate the evaluation of Sustainable Pathways within the framework of the Global Climate Hub.

3. Decarbonization Pathways

3.1 Decarbonization Pathways of the Pan-EU energy system

3.1.1 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.

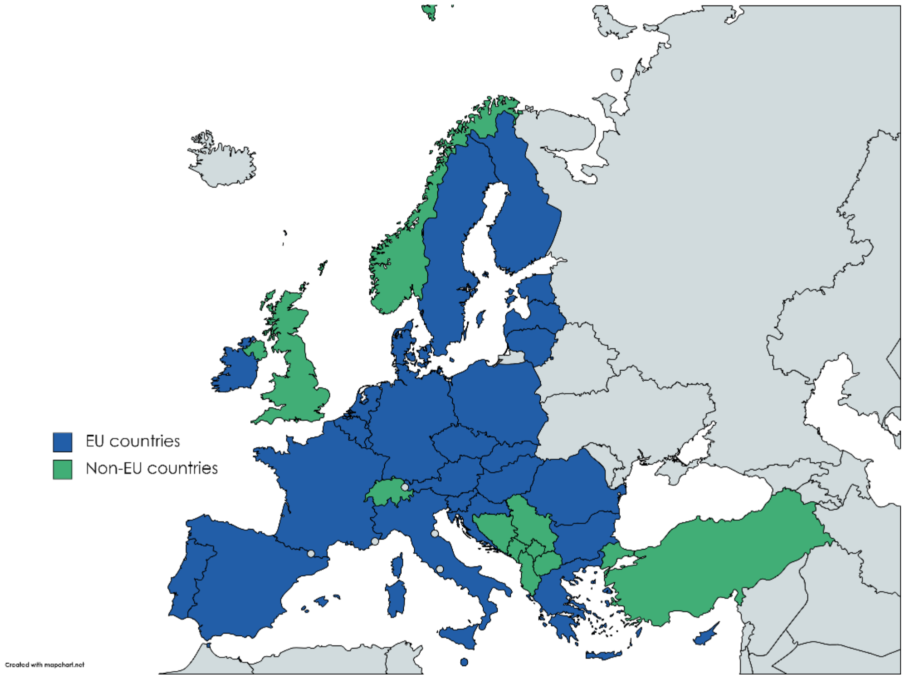
3.1.2 Method

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 7: Balmorel model spatial overview.



Source: Authors' calculations

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.

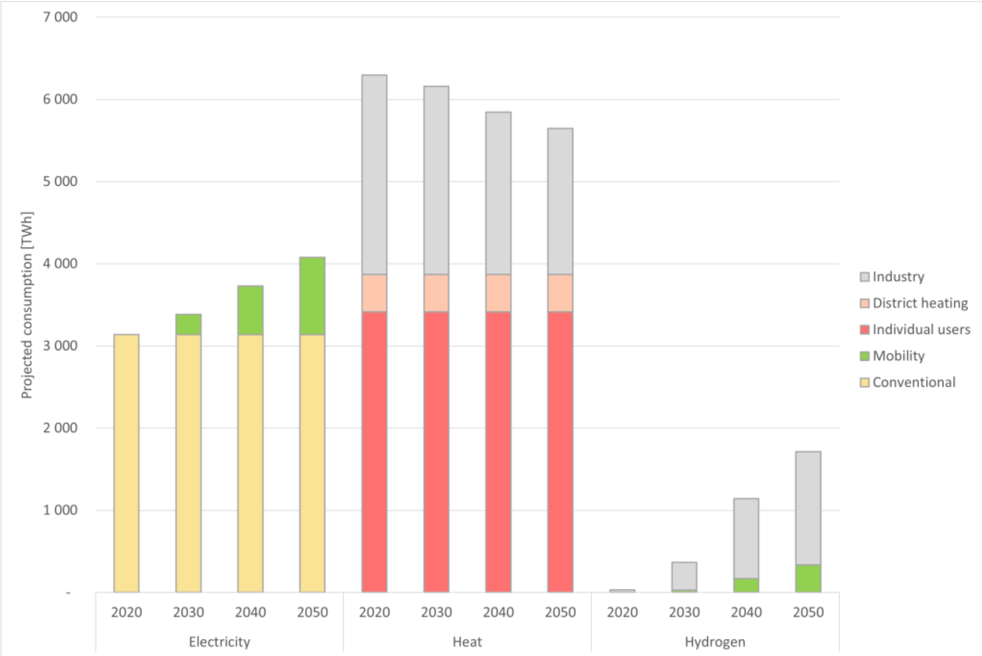
3.1.3 Data & assumptions

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 8 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 8: Projected consumption of heat, electricity, and hydrogen in TWh.



Source: Authors' calculations

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 CO_2 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 2: Carbon budget in MtCO2

	2021	2030	2050
ETS (EU, UK, & Swiss)	1 543	1 163	0
ESR, buildings	557	449	0
Additional GDP adjusted[13]	288	268	0
Total	2 388	1 880	0

Conventional mobility

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

[13] For sectors and countries without direct data on allowances, GDP adjustments are made based on existing countries.

Table 3: Final energy consumption in passenger cars and heavy transportation in TWh

Fuel	2020	2030	2040	2050
Fossil fuels	3 425	2 255	1 127	0
Biofuels	136	329	204	79
Electric	0	239	517	794
Hydrogen	0	28	167	337

3.1.2 Optimal production pathways

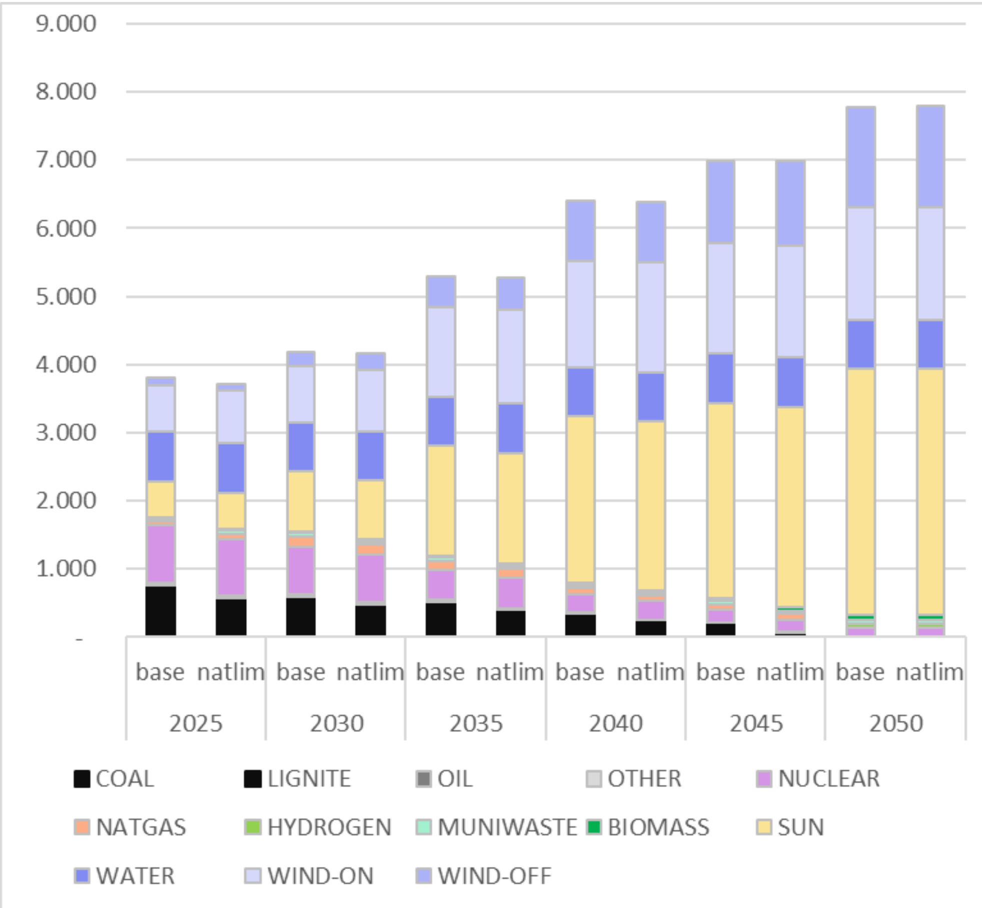
In this section, we present pathways for power, heating, and hydrogen production, where decarbonization is controlled by a carbon budget in line with the Fit-for-55 and European Green Deal policy targets at both the system level and national level. Using this we assess the alignment of individual countries 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 9. 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 9: Annual power production in the pan-European energy system in the baseline scenario.



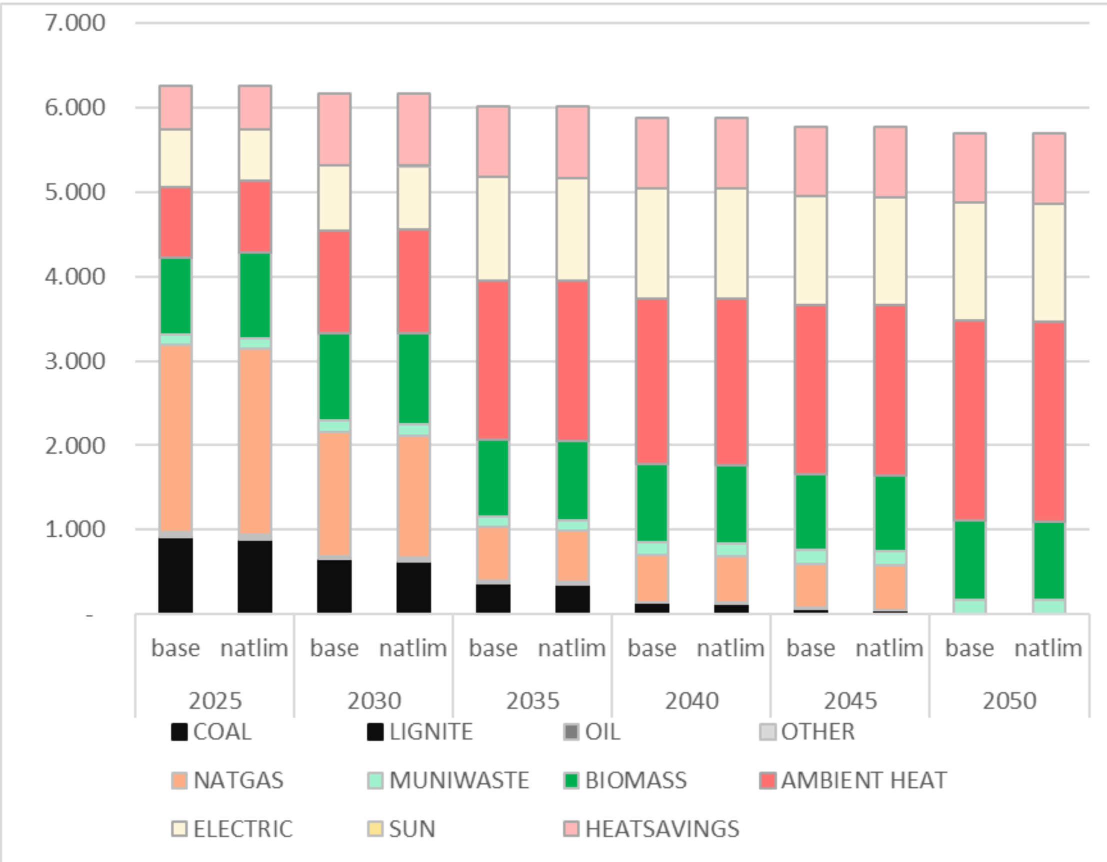
Source: Authors' calculations

Heat production

In

Figure 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", 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 10: Annual heat production in district heating, household and tertiary users not connected to district heating, and industry.

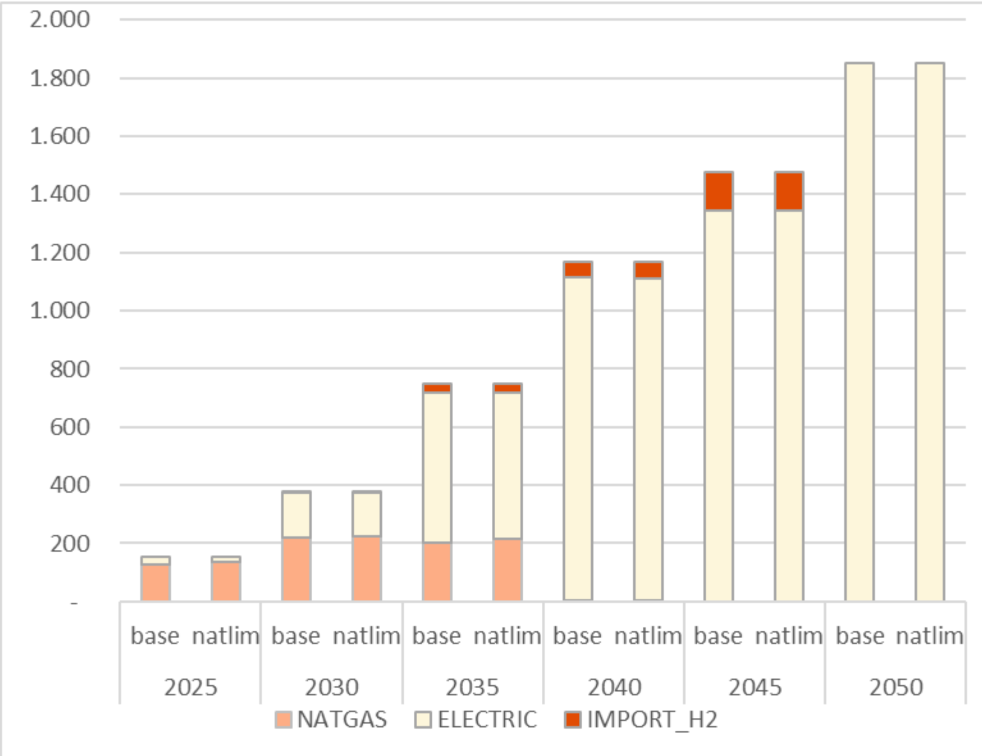


Source: Authors' calculations

Hydrogen production

In Figure 11, 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.

Figure11: Annual hydrogen production the pan-European energy system.

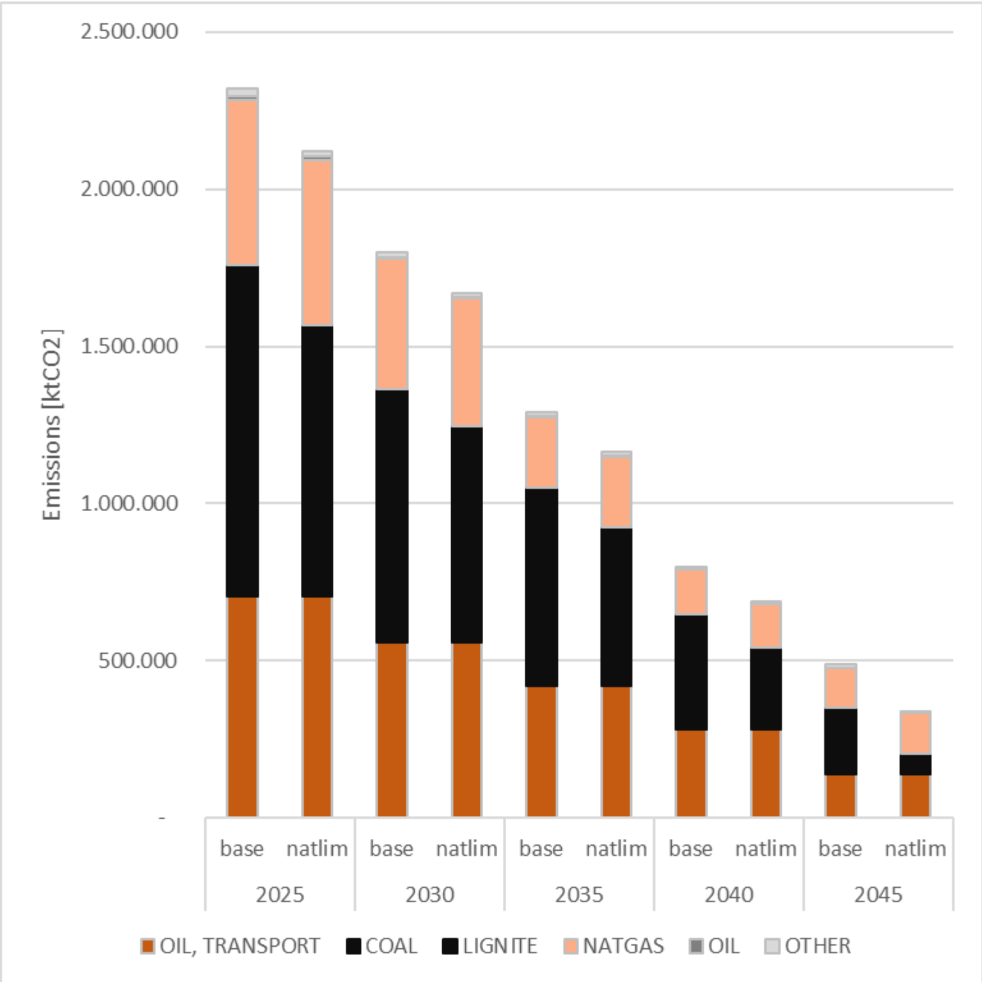


Source: Authors' calculations

3.1.4 Alignment of National Targets

At the system level, Figure 12 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.

Figure 12: Emissions from modelled sectors as well as additional mobility in ktCO2



Source: Authors' calculations

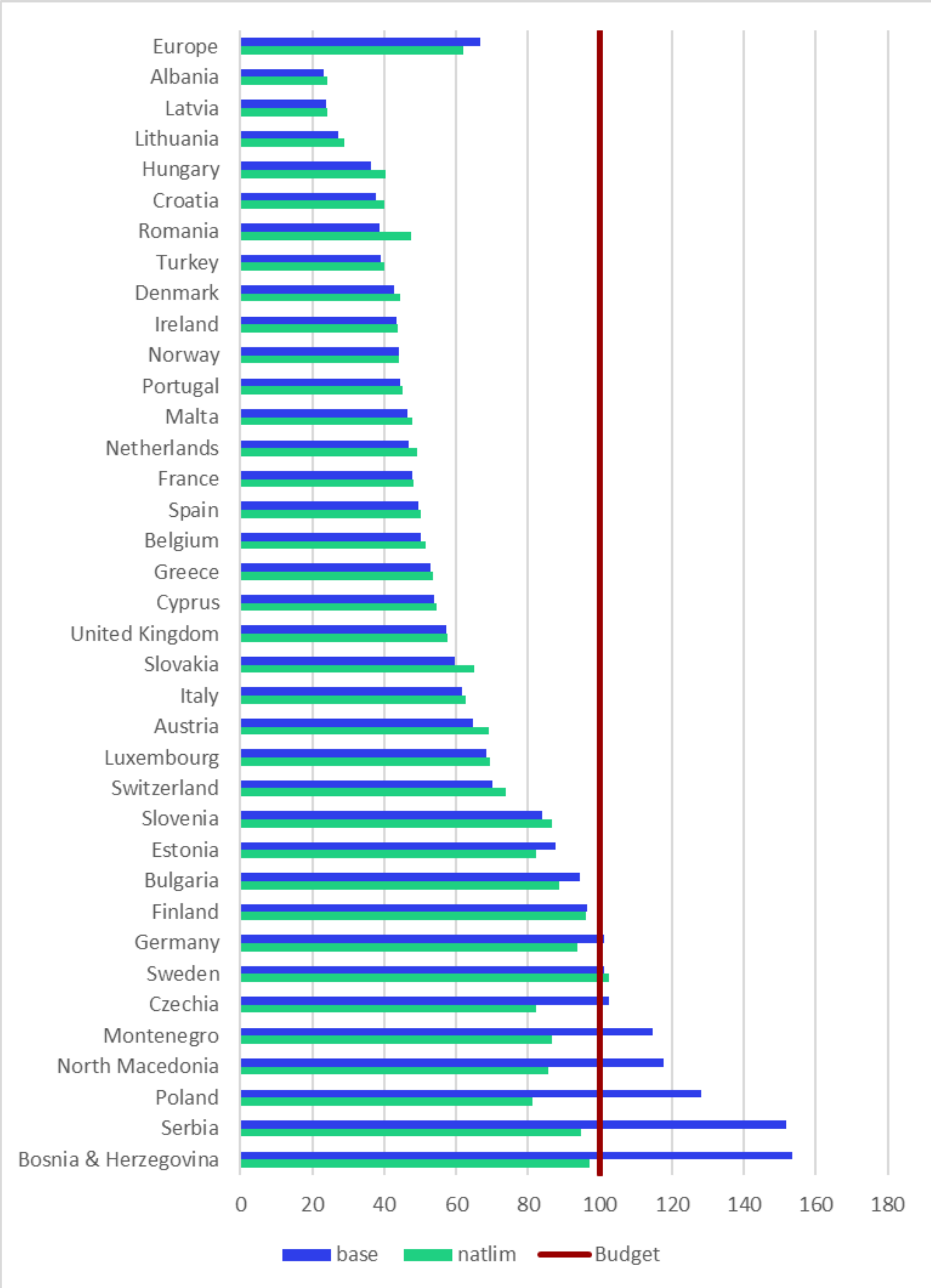
From examining the two production pathways of electricity, heat, and hydrogen, it is apparent that the two carbon budget implementations result only in a minor difference on the system-level perspective, but some impact on the use of coal and lignite. From this system level perspective, we shift the 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 13 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 13: Alignment of national emissions in 2030 for the modelled sectors, compared to the allocated carbon budget, indexed to 100



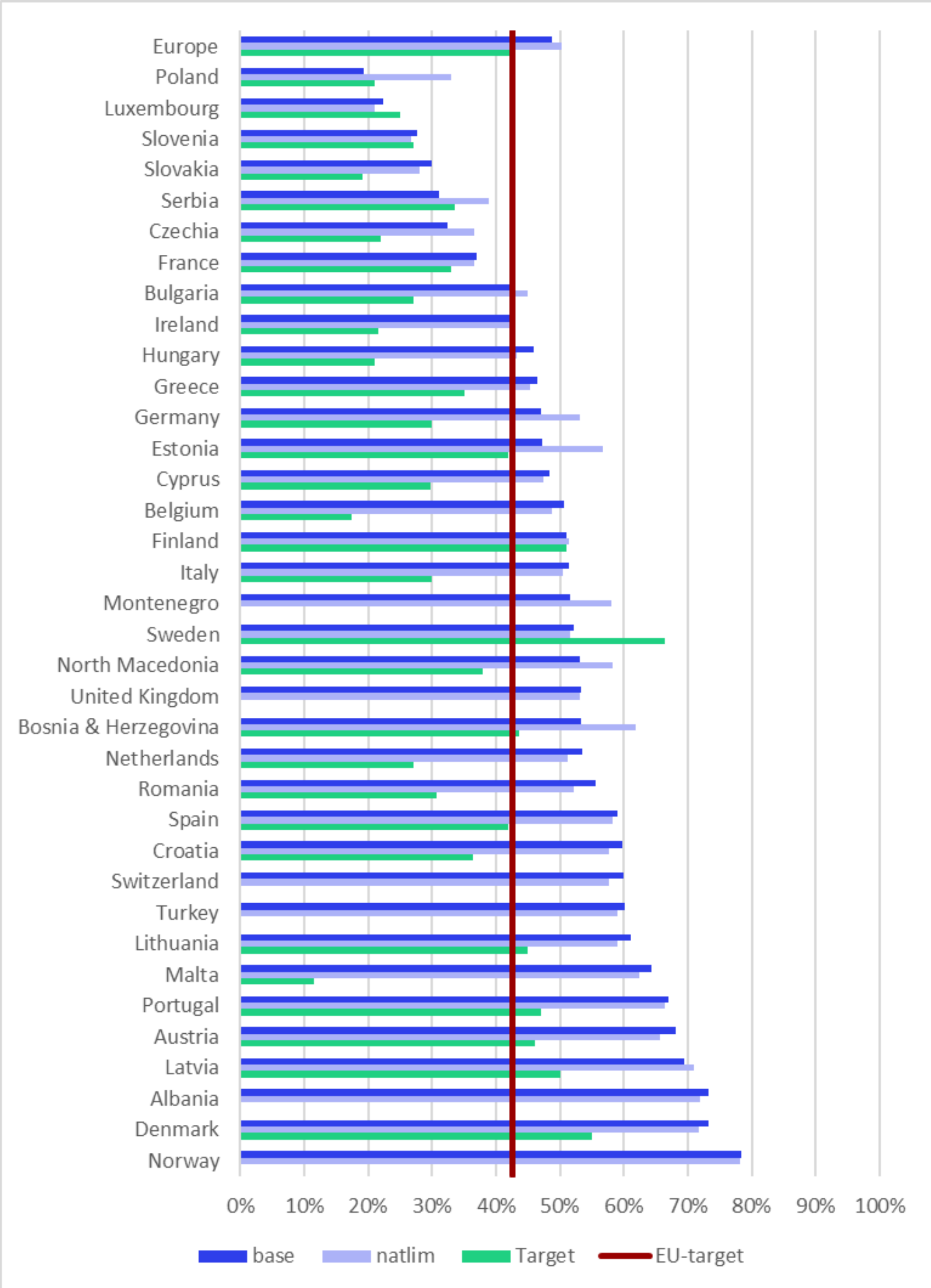
Source: Authors' calculations

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 14 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 14: 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.

3.1.5 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 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 17. 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.

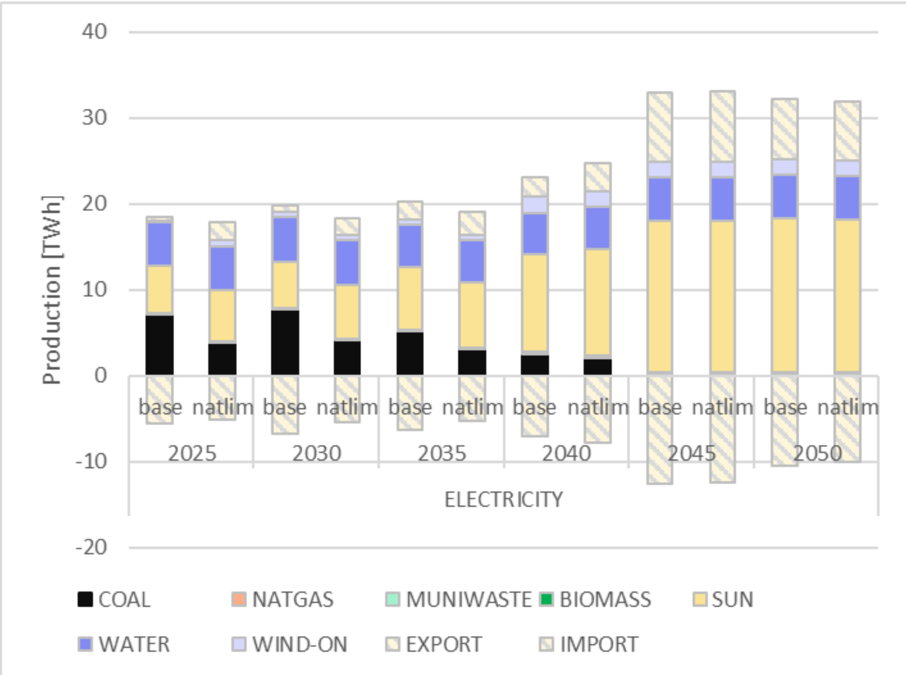
Figure . Both scenarios show a long-term potential for a power system based on renewables with net-exports[14]. To further mitigate emissions in intermediate years, coal use should be reduced in favour of higher imports from other countries. Use of natural gas in hydrogen production should also be avoided 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

[14] Negative numbers represent electricity exported to neighboring countries, while positive represent imports.

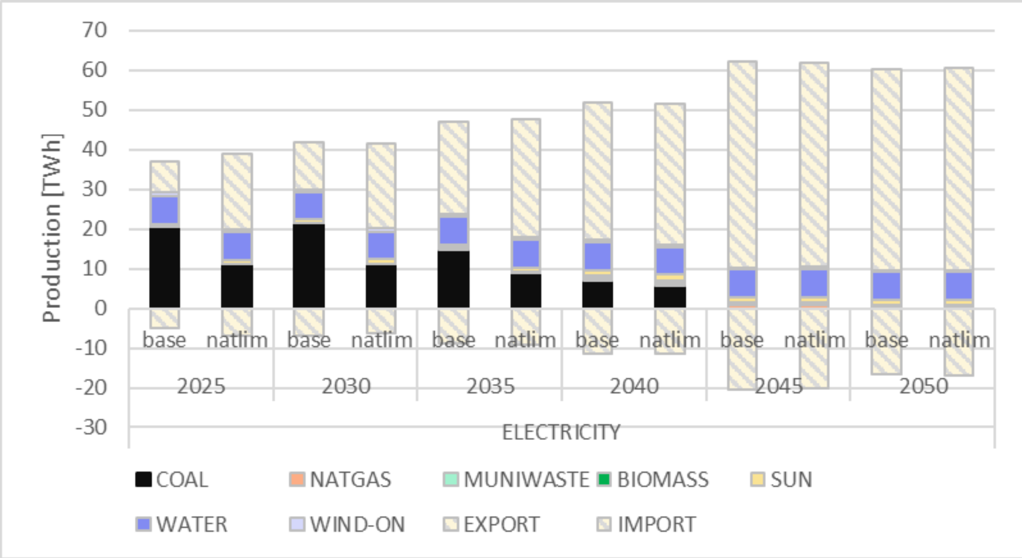
even more, as seen in Figure 16. Like Bosnia & Herzegovina, natural gas consumption for hydrogen production could be phased out in favour of imports of mainly renewable electricity and potentially hydrogen through pipelines. Montenegro sees a slight decrease in power production from lignite, but more significantly sees a reduction in natural gas usage for heat and hydrogen, as seen in Figure 17. 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 15: Power production pathway for Bosnia & Herzegovina in TWh.



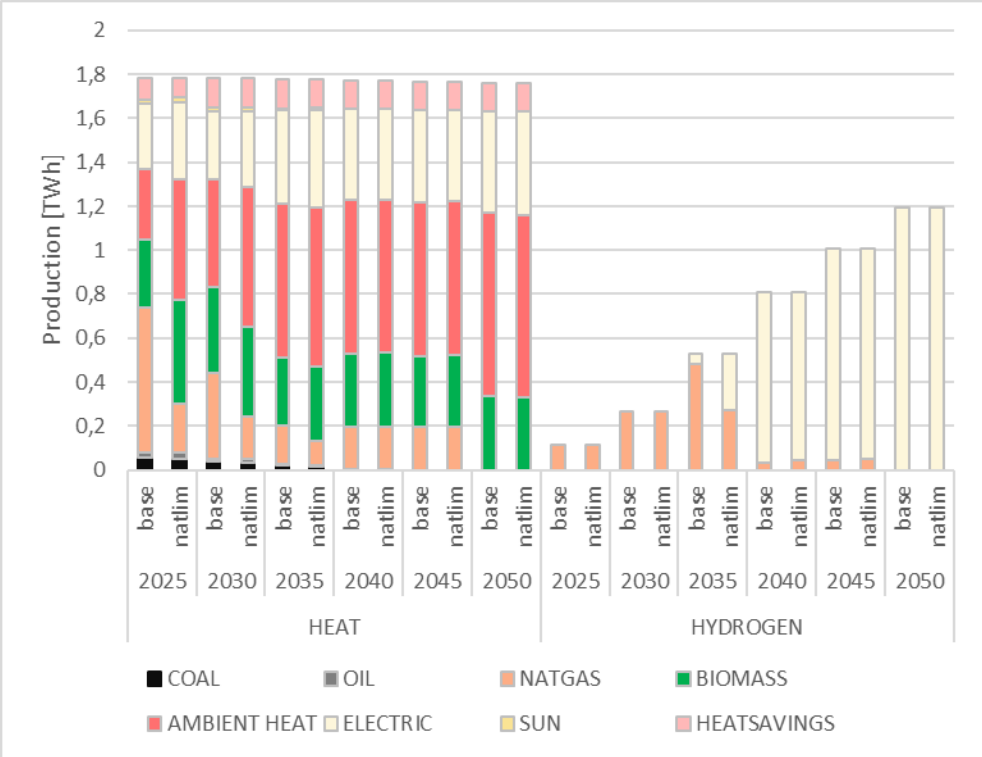
Source: Authors' calculations

Figure 16: Power production pathway for Serbia in TWh.



Source: Authors' calculations

Figure 17: Heat and hydrogen production pathways for Montenegro in TWh.

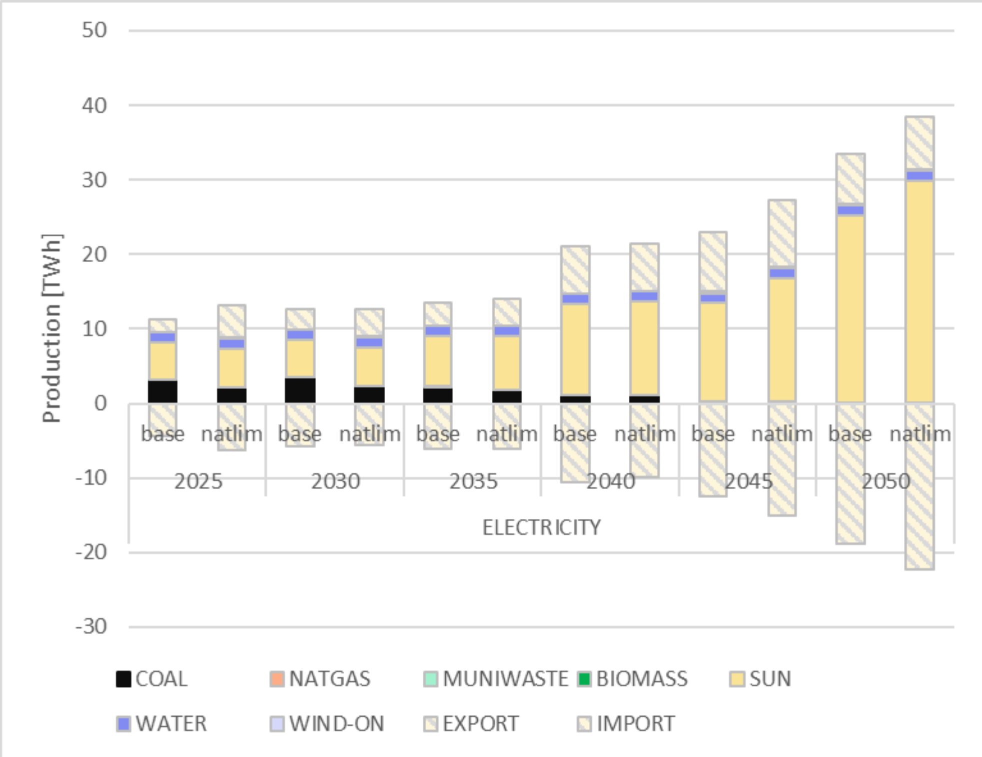


Source: Authors' calculations

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 18.

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 18: Power production pathway for North Macedonia in TWh.

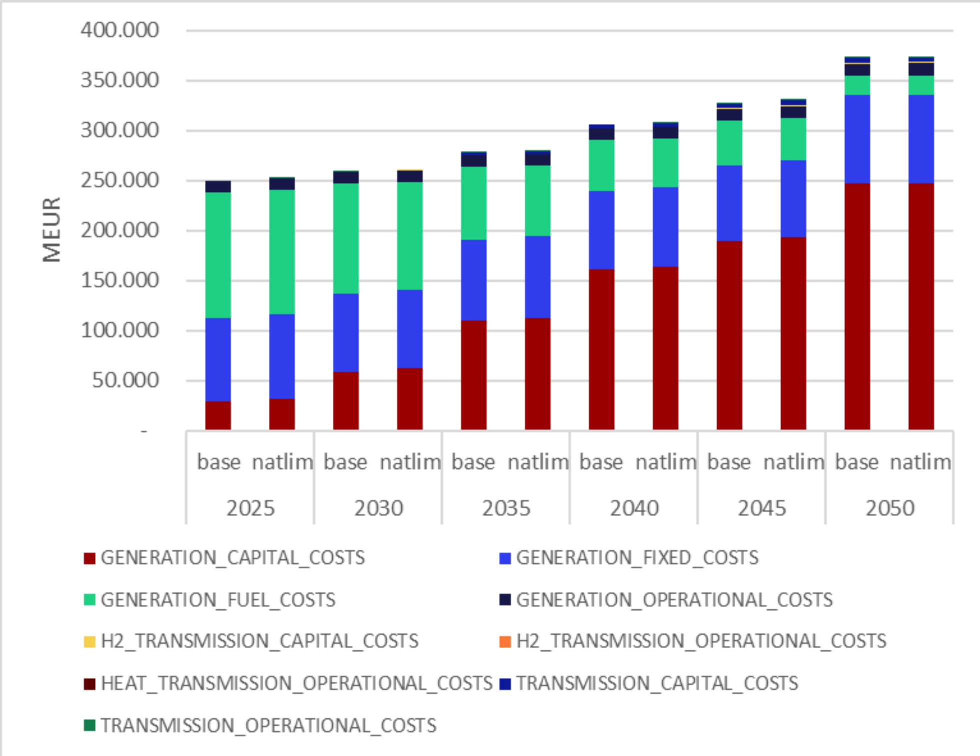


Source: Authors' calculations

3.1.6 System budget versus national budget

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. The cost reduction is balanced out by an increased CAPEX and fixed OPEX from the necessary new investments.

Figure 19: Annualized total cost in MEUR



Source: Authors' calculations

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.

3.1.7 Conclusion

Achieving the policy targets in the European Green Deal, Fit-for-55, and RepowerEU, for a decarbonized Europe is a feasible achievement in the Pan-European energy system. 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. Bosnia & Herzegovina as an example, produces 40 % of its power production from coal while simultaneously being a net exporter of electricity. Implementing emission restrictions at the national level results in a higher trade in the energy profiles in these countries, and faster phase-out of coal and lignite. In Bosnia & Herzegovina, the share of coal decreases to 25 % at the same time as exports decrease slightly and imports increase. Similarly in Serbia, the share of coal decreases from 71 % to 55 %, while imports increase from 11 to 21 TWh. In Albania on the other hand, a large capacity of hydro allows for a high renewable share with low emissions, which it utilizes as a net exporter in both scenarios.

We show that the use of a national carbon budget over a system carbon budget can improve the uptake of renewables and reduce national emissions without a significant increase in costs for the overall system.

3.2 Linking the Quest for Renewable Power to Ecosystem Healing in Southeast Asia[15]

3.2.1. Introduction

The renewable energy share in Southeast Asia's energy mix is expected to increase, driven by significant technological cost reductions, combined with governments' commitments to promote cleaner energy systems. The four key renewable energy sources for Southeast Asia are hydropower, solar, wind and bioenergy. More than 40% of power generation in Southeast Asia comes from coal (Fallin, Lee and Poling 2023). Natural gas is counted on as a key transition fuel away from coal by many governments on the assumption of cheaper cost compared to a complete immediate switch to renewables. However, natural gas still emits 490 gCO2-eq per kWh and the cheaper cost assumption no longer holds due to the ongoing conflict in Ukraine.

Solar and wind power technologies require the mining of many minerals. Greater adoption of these technologies will lead to more strain on the environment and society. By pursuing a renewable power that develops

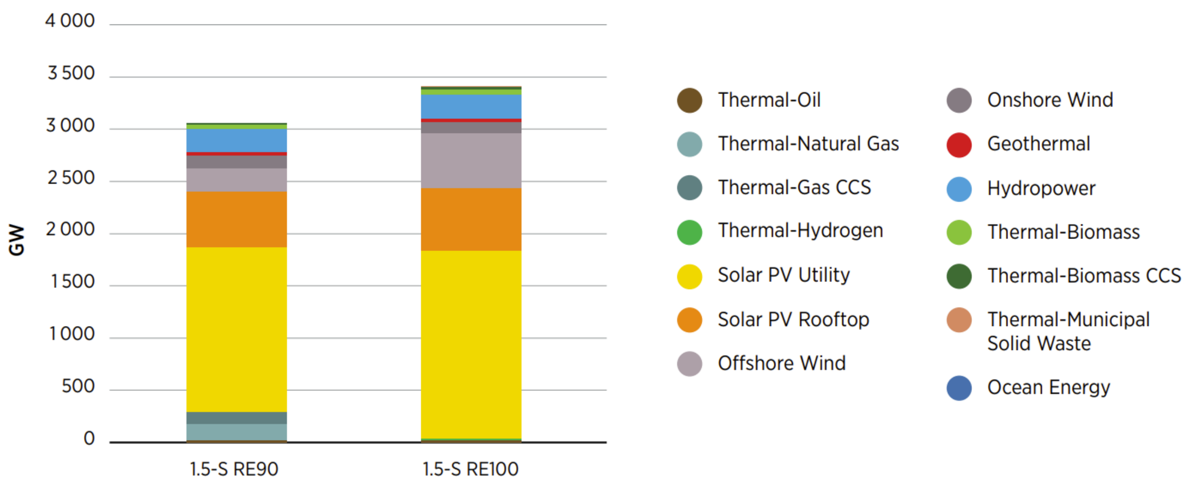
[15] The authors are deeply grateful to Huang Chi-Shou, Lin Kai-Hsuan, Dr. Angsoka Paundralingga and Avia Destimianti for patiently supporting the process of developing understanding and insights.

ecosystem understanding and healing at the same time, we might get closer to shifting nightmares to dreams.

3.2.2. Renewable power generation in Southeast Asia

In a high renewable energy scenario in Southeast Asia, the key technology will be solar PV, followed by wind, hydro, and biomass. (Figure 20)

Figure 20: Southeast Asia's power capacity alternatives for 1.5°C Scenario for ASEAN aligned with the Wind Energy Technologies Office (WETO) targeting net-zero emissions globally by 2050 (1.5-S)



Source: International Renewable Energy Agency; ASEAN Centre for Energy 2022

Southeast Asian countries have a regional target of 35% renewable energy share in installed capacity by 2025. To reach the target, the region needs to develop at least 40.3 GW of solar and 5.4 GW of wind power. (ASEAN Centre for Energy, 2022)

To enable higher variable renewable energy penetration, a flexible energy system is required. This can be achieved through:

i. More mid-merit power and peak generation in the system. The former is electrical generation that fills the gap between baseload power and peaking power, e.g. natural gas combined cycle plants, coal-fired plants, nuclear power plants, hydroelectric plants, and large-scale solar and wind farms with battery storage. The latter is electrical generation that meets sudden or unexpected spikes in demand, e.g. natural gas combustion turbines, diesel generators and hydroelectric plants with pumped storage. These plants are typically used for a few hours each day, during the periods when demand is highest.

ii. More storage capacity, for example batteries, pumped hydropower, thermal storage, and hydrogen.

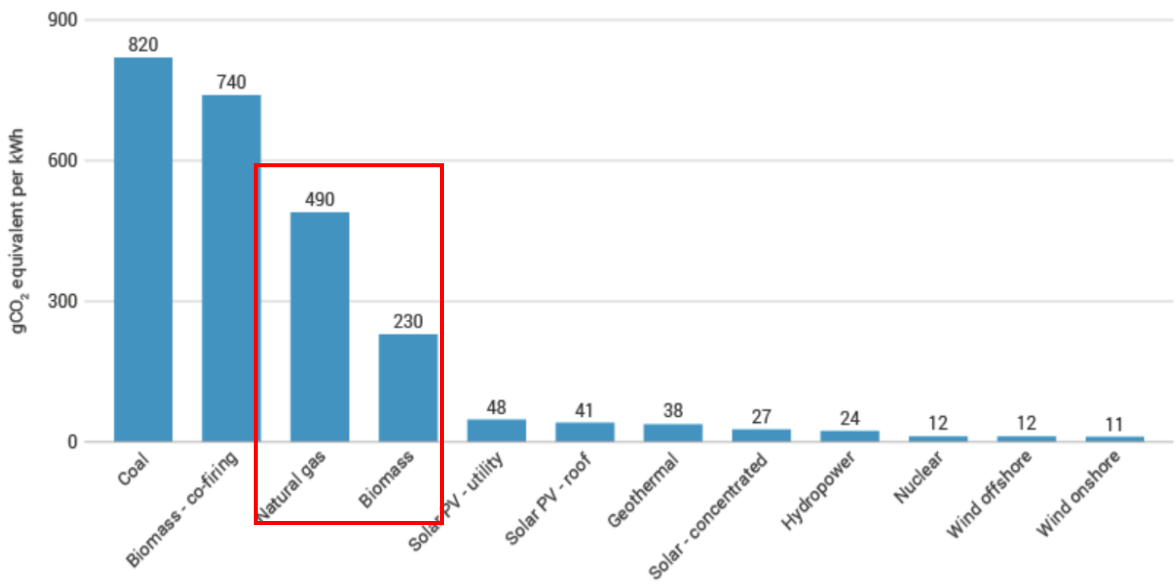
iii. More power interconnection between countries

3.2.3. Fossil power generation in Southeast Asia

Southeast Asia is the world's fourth-largest energy consumer. The region's current energy structure is skewed towards traditional forms of power generation, with fossil fuels making up 83% of its energy mix, and energy demand is expected to increase (ASEAN Centre for Energy, 2022).

In the power system, natural gas is considered pivotal in ensuring grid stability whilst more variable renewables are added (ASEAN Centre for Energy, 2022). Although gas-fired generators are the lowest emission fossil fuel for generating electricity, it still emits 490 gCO2-eq per kWh (Figure 21).

Figure 21: Average lifecycle CO2 equivalent emissions



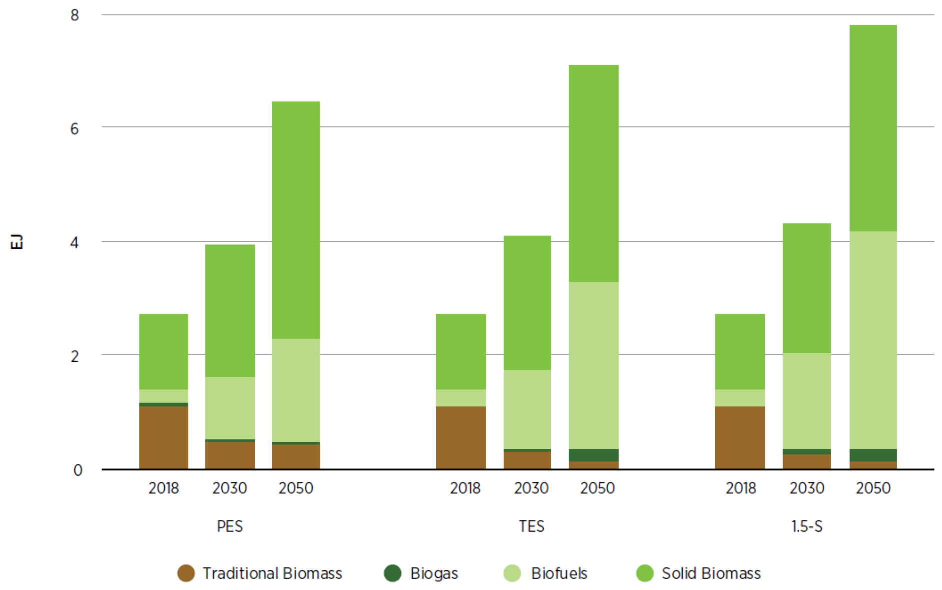
Source: IPCC

What can be a better alternative to gas-fired generators to replace coal-fired plant's baseload power and support a high renewable energy penetration scenario? Figure 21 suggests biomass, which has half the emission intensity of natural gas.

3.2.4. Biomass power generation: the Cinderella of renewables in Southeast Asia

Biomass power generation has met with obstacles such as security of feedstock, stability of biomass prices, biomass scalability and seasonality, and collection challenges in Southeast Asia. Hence, it is present, but usually does not take centre stage as a renewable fuel and investment opportunity like solar and wind, despite the expectation that biomass will be a key contributor in the bioenergy space moving forward (Figure 22).

Figure 22: Share of bioenergy in the total final energy consumption (TFEC) in ASEAN, by scenario



Source: International Renewable Energy Agency; ASEAN Centre for Energy 2022

At the G20 Summit in New Delhi in September 2023, a Global Biofuel Alliance (GBA) was formed to expedite the global uptake of biofuels. A similar alliance is needed for biomass to facilitate technology advancements, intensify utilisation of sustainable biomass, shape robust standard setting and certification through the participation of a wide spectrum of stakeholders.

In 2020, the biomass power generation capacity of Southeast Asia was around 6 GW, mainly installed in Thailand (2.2 GW) and Indonesia (1.9 GW) (ASiANPOWER, 2023). There are two types of energy related biomass utilisation in Southeast Asia – modern biomass power generation and traditional biomass demand by households – as summarised in Table 4.

Thailand and Indonesia's existing and target biomass power generation capacities are in the range of thousands of MW whilst Vietnam, Malaysia, Philippines, Myanmar, and Singapore are in the range of hundreds of MW. Out of all the Southeast Asian countries, only Vietnam has set the target of 100% coal replacement with biomass for power generation. Vietnam can set such a target because the country is the second largest wood pellets producer in the world after the US.

Biomass is the highest contributor to the total final energy consumption (TFEC) in Myanmar, Cambodia, and Lao PDR where households use biomass for cooking and heating. Cottage industries in Myanmar use biomass for power generation. Brunei does not have biomass power generation, neither does the country's residential sector use biomass for cooking.

Table 4: Overview of Energy Related Biomass Utilisation in Southeast Asia

Modern Biomass Power Generation
Thailand (Muramatsu, 2022) • Major producer of rice, sugarcane, and cassava • Industries such as Ajinomoto and Siam Cement Group Biomass utilise co-generation systems fed by rice husk, biomass pellets made from sugarcane and rice farms waste, and wood. • Biomass is leading the way in mainstreaming renewable energy, even more so than solar
Indonesia (Perusahaan Listrik Negara, 2021) • Perusahaan Listrik Negara (PLN) targets 18,895 MW of co-firing capacity in 114 coal-fired power plants in 52 locations by 2025. Currently, biomass co-firing pilot projects have been implemented at 32 locations using 5% biomass fuel (palm kernel shell, wood pellets). • Future expansion of the scheme is expected to include coal-fired power plants owned and operated by independent power producers. • The design of new coal-fired power plants that will start operating after 2025 are required to have a minimum 30% biomass fuel co-firing.
Vietnam (Barnes, 2023; Bich, 2023) • The Power Development Plan 8 issued by the Government of Vietnam on 15 May 2023 requires coal power plants to burn biomass and ammonia fuel after 20 years of operation, starting at 20% and increasing to 100%, as the country moves to phase out coal by 2050. • By 2030, the combined capacity of biomass and waste-to-energy plants is planned to reach 2,270 MW, with an aim to increase to 6,015 MW by 2050. • Biomass sources: bagasse, straw, rice husks, coffee husks, coconut shells, and sawdust

Malaysia

- The National Energy Transition Roadmap (Ministry of Economy, 2023) has six energy transition levers with bioenergy as one of them. It will involve biomass clustering and piloting biomass co-firing at the exiting 2,100 MW Tanjung Bin Power Plant in 2024, with an intention to scale up to a minimum of 15% biomass co-firing capacity by 2027.
- Biomass sources: palm empty fruit bunch pellets, wood chips, wood pellets, bamboo pellets, coconut husk and rice husk.

Philippines

- Biomass power capacities were reported at 356 MW in 2019 and potential capacity at 4,400 MW (Dia, 2023)
- Bagasse is used as boiler fuel for cogeneration; rice and coconut husks dryers for crop drying; biomass gasifiers for mechanical and electrical applications; fuelwood and agricultural wastes for oven kilns; furnaces and cooking stoves for cooking and heating purposes. These biomass technologies installations' capacity is higher than the other renewable energy or energy-efficient and greenhouse gas abating technologies' capacities (Shead, 2017).
- Biomass sources: rice husk, rice straw, coconut husk, coconut shell, banana, pineapple, and general bagasse

Singapore

- Does not have agriculture and forestry sectors but pursues biomass power generation through horticultural biomass and waste-to-energy. Tree branches, leaves and grass cuttings are combusted for energy production at Gardens by the Bay and Jurong Island.
- The Tembusu Multi-Utilities Complex (TMUC) on Jurong Island co-fires cleaner coal (i.e. low-ash and low sulphur) and biomass to generate steam and electricity with low emissions. Total output is 134 MW. (Tan, 2023; Gan, 2022)

Myanmar

- Biomass sources: rice husk, rice straw, bagasse, corn cob, cassava stalk, residues from sugarcane, coconut and oil palm, wood residues and fuelwood
- 45% forest cover
- Biomass contributes 64% of the total final energy consumption (TFEC) (Pode, Pode, & Diouf, 2016):
  - Cooking and heating in rural areas: 70% of the country's population live in rural areas.
  - Cottage industries: over 1000 rice mills across Myanmar are powered by small scale rice husk gasifiers. Rural cooperatives/committees installed several rice husk biomass power plants for rural electrification after 2001.
- The biomass rick husk power plant business model has the potential to provide grid quality power to the rural population without grant or subsidy (Pode, Pode, & Diouf, 2016).
- Total capacity potential from biomass is 6,899 MW. In 2013, the total installed capacity of biomass and biogas in 2013 was reported at 115 MW (Tun, Juchelkova, Win, & Puchor, 2019).

Traditional Biomass Demand by Household

Cambodia

- 57% forest cover
- Wood and wood charcoal account for approximately 80% of TFEC, which the residential sector uses for cooking.
- Other major biomass sources come from agricultural residues: rice husk, rice straw, corn cob, cassava stalk, bagasse, groundnut shell and husk, and coconut shell and frond.
- 2019: total installed capacity for biomass was about 23 MW. Target to reach 73 MW of installed capacity by 2030. (Tun, Juchelkova, Win, & Puchor, 2019)

Lao PDR

- 68% forest cover
- Agriculture economy
- Biomass consumption has the highest share in the TFEC, with the residential

sector as the main consumer (Phouthonesy, 2021) - 80% of the households rely on firewood and charcoal.

- Installed biomass energy capacity: 40 MW; target: 58 MW by 2025 (Tun, Juchelkova, Win, & Puchor, 2019).

The biomass power generation obstacles mentioned earlier result in a supply consistency challenge that constrains it as a mid-merit power. To transcend this constraint, strategic thinking needs to go beyond improving the collection efficiency of agricultural and forestry residues.

Biomass power plants that are fuelled by wood pellets can provide baseload power because it is a standardised fuel that can be easily transported, traded, purchased, and stockpiled in advance of need. Tree plantations are necessary to ensure a reliable supply of feedstock for producing wood pellets.

Wood pellets' commercial inception as a heating source in both residential and commercial structures started in the 1980's. Global utilities and large-scale power generators subsequently adopted it as a renewable fuel to produce reliable baseload power, either in stand-alone biomass power stations or co-firing in coal-fired power stations.

One example of a large biomass power station fuelled by pellets is Drax in the UK, which supplies on average 9.3% of the UK's electricity needs. Drax was the biggest coal-fired power station (3906 MW) ever built in Britain, and the last too. By 2010, the station was co-firing biomass. Four out of six 650 MW generating units are now fully powered by wood pellets, and the plan is to convert the remaining two coal units to combined cycle gas turbine units and 200 MW of battery storage (Wikipedia, 2023). This is an example of combining baseload power (wood pellets) and mid-merit power (natural gas combined cycle and battery storage).

The pellets used at Drax are mostly made from sawmill refuse and other by-products in America; they are then transported by rail, ship, and rail to the site where they will be pulverised and burned (The Economist, 2013). In 2021, Drax acquired its Canadian biomass pellet supplier, Pinnacle Renewable Energy, a key producer of wood pellets. At that time, Pinnacle had C$6.7 billion of long-term contracts with high quality Asian and

European customers, including Drax, and a significant volume contracted beyond 2027 (Gardiner, 2021).

The Drax example is instructive for Southeast Asia's power generation because the tropical region has the advantage of local sourcing of woody fuels. Trees grow faster in the tropics than in temperate countries like Northern America and Europe. When power generators get serious about sourcing biomass fuel, it will stimulate local investment in wood pellet production.

3.2.5. Global wood pellet market

Wood pellet production is a global business because wood pellets are widely used in Sweden, Finland, Italy, UK, US, Canada, South Korea, and Japan as a fuel for boiler and furnaces to generate heat for residential and industrial requirements (Jara, Daracan, Devera, & Acda, 2016). Implementation of the European Union Renewable Energy Directive has triggered rapid growth in trading of wood pellets. Over 18 million tons of wood pellets were traded by EU member countries in 2018 (Eurostat, 2019), (Proskurina, Junginger, Heinimö, Tekinel, & Vakkilainen, 2018).

The index of wood-pellet prices published by Argus Biomass Markets rose from an average of USD152/MT in August 2010 to USD166/MT at the end of 2012. These are the delivered prices into the ports of Amsterdam, Rotterdam, and Antwerp (The Economist, 2013). A decade later, in January 2023, the 90-days spot price of wood pellet for deliveries to northwest Europe was USD303.06 a tonne (Argus, 2023).

In Southeast Asia, wood pellet price is USD130-150/MT FOB MVT. The high price in northwest Europe is due to the Russia-Ukraine war and soaring shipping cost. Most of the wood pellets used in Europe comes from America and Canada. For the same reason, Europe's import price for LNG from the US is four times the indigenous price in the US.

In Southeast Asia, Vietnam is the largest wood pellet producer and exporter, and the second largest in the world after the US. Vietnam's shipment of pellets rocketed to 3.2 million tonnes in 2020 (mainly to Japan and South Korea for biomass energy production) from just 175.5 tonnes in 2013. The export revenue increased 15.3-fold from nearly US$23 million in 2013 to $351 million in 2020. (Phuc, 2021)

Wood pellets there are typically made from waste wood such as sawdust, shavings, and tree branches. Some large-scale producers have their own acacia or eucalyptus plantations, some of which are Forest Stewardship Council (FSC) certified. It is noteworthy that Vietnam's wood pellet industry grew rapidly without industry association support or government attention and regulation on production and export. (Viet Nam News, 2021; Phuc, 2021).

3.2.6. Deforestation in Southeast Asia and the challenges of replanting

During the period 2001-2019, Southeast Asia lost 61 million hectares of forest - an area larger than Thailand - 31% of which occurred in mountainous regions where highland forest was converted to cropland and plantation in less than two decades. This is equivalent to a rate of 3.22 million ha per annum. (Feng, et al., 2021) Mining is another major driver of deforestation.

National governments usually mandate timber and mining companies to replant on areas that they have deforested, and even have measures to induce compliance. In Indonesia, for example, mining companies are required to pay the government a high deposit per hectare that will only be returned after their required replanting work has been verified. The replanting verification is needed for mining permit renewal too. The government also requires the mining companies to engage a replanting consultant for three years to ensure that the newly planted tree seedlings are taken care of sufficiently and have a chance to grow to maturity.

Besides replanting trees in ex-mining areas, the Indonesian government also requires mining companies to seek out nearby riverbeds and plant trees by the river, which will improve water quality and reduce flooding. Despite these government measures, the replanting results are often unsatisfactory. The reasons are both human and technical as summarised in Table 5.

Table 5: Reasons for unsatisfactory replanting

Human
• Timber companies use people whom they trust as contractors. Some of these people whom they trust are not qualified. Some are qualified, but not ethical. Timber companies are short of management talent who are ethical. • Contractors who are engaged to do the replanting work do not execute the work seriously. This is the reason why some timber companies' forest plantations are doing poorly despite them doing logging according to the book and replanting. • Replanting consultants propose budgets that are too low (e.g. 63% below what is needed) for good quality replanting in their quest to win the job. Such unprofessional practice tends to come together with a consultant's demand for a 10% commission, which is drawn from the already inadequate budget. • Timber companies engaging a replanting consultant for one year, instead of the required period of three years. • Local government officers not enforcing the replanting mandate, but signing off papers confirm that the mining companies have done the replanting so that their mining permits can be renewed
Technical
• The soil on deforested and mining land are poor in fertility. Soil rehabilitation is required for tree seedling to have a better chance of surviving and thrive. • Quality of planting materials is not good enough due to inadequate budget

All the reasons identified in Table 5 could be attributed to the lack of intent for replanting to be successful because the economic benefit is not clear to the timber and mining companies. By pursuing replanting and tree plantation development together, both environmental and economic goals can be achieved.

Having an economic motivation is necessary, but insufficient, for successful tree planting in degraded areas.

3.2.7. Soil fertility: the principle of symbiosis

For replanting in degraded areas to be successful, timber and mining companies and their replanting consultants need to first work on improving soil fertility. This begins with the realisation that soil is a living being that needs to be fed appropriately, so that the symbiotic relationships between microbes in the soil and plants can be vibrant. The fertility that lives in the soil – the microbes - is the productive capital asset. Not nurturing this capital asset is a crippling blindness that will lead to much lower yields and far more plant sickness. (Platts & Leong, 2020)

This involves thinking at the level of first principles, and embodying the principles in systems and public practice so that those principles have their proper influence in society's thinking, decision making and acting. Vocabulary reflects the mindset and influences the way systems are designed and implemented.

When ecosystems are damaged or destroyed, their ability to regenerate naturally is impeded. Hence, healing ecosystems requires planting materials. Establishing planting material nurseries requires access to fertile land and water, seeds and cuttings, knowledge of pest and disease management, and qualified workers.

Nurseries growing new seedlings and the planting out of new seedlings will require organic matter and microbial soil ameliorant. In Kalimantan, Dr. Yusanto Nugroho from the University of Lambung Mangkurat found that two rounds of soil improvement are required in the planting process. The first is at the time of planting, and the second is when the seedling has grown, and the roots are reaching the boundaries of the improved soil environment. The second round of soil improvement expands the space of the improved soil environment for the roots to continue growing. Two rounds of improvement are sufficient for a tree seedling to grow to maturity.

Soil fertility is the starting point of a successful tree planting exercise. When a forest ecosystem is restored, the populations of insects, birds, animals improve too, and they will feed back into the soil ecosystem and strengthen its vitality. This is the principle of symbiosis, and the cycle reinforces itself.

Wherever the principle of symbiosis is practised – be it is in the remote areas of Borneo Island or cosmopolitan Hong Kong (e.g. the Kadoorie Farm and Botanic Garden), vibrancy can be seen all round in the flora, fauna, and humans. "Vibrancy" is the flow of life (the "qi") that can be seen and shared in (Platts, 2021).

3.2.8. From nightmare to dream

Solar and wind power technologies require the mining of many minerals such as silicon, copper, rare earth elements, silver, aluminium, cadmium, tellurium, and selenium. Mining can lead to deforestation, water pollution, air pollution, displace indigenous communities and contribute to human rights abuses. More adoption of these technologies will lead to more strain on the environment and society.

Biomass power generation with wood pellets, on the other hand, can be a vehicle for ecosystem healing and properly establishing the existential relationship between humans and the environment.

The nightmare of climate change can become a good dream when decarbonization efforts are aligned with the principles of nature. Doing more will then improve ecosystems all round, restore the balance of nature, and not trigger imbalances elsewhere. When we work with nature, rather than against it, we can create a more sustainable and resilient future.

3.2.9. Integrated assessment modelling (IAM) of the dream

IAMs can help us understand the complex interactions between developing tree plantation on degraded land, wood pellet production, biomass power generation and ecosystems.

ASEAN Green Future (AGF) is a multi-year research project that involves the UN Sustainable Development Solutions Network (SDSN), *Climateworks Centre* and nine country teams from leading universities and think tanks across Southeast Asia. The researchers undertake quantitative and qualitative climate policy analysis and develop net zero pathways to inform policy recommendations and support the strategic foresight of policy makers.

AGF is currently in a stage of optimising the amount of renewable energy possible in the Southeast Asian countries with storage. The biomass power generation scenario outlined in this paper, which involves developing tree plantations on degraded land, will lead to a different biomass power potential estimation from what is currently estimated by governments based on agricultural and forestry residues.

If this dream can come true, this is how Southeast Asia's renewable power mix may look like in the future:

i. Baseload power: biomass, hydro

ii. Mid-merit power: solar, wind, storage

iii. Peak power: pumped hydro storage, green hydrogen

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

3.3.1 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.

3.3.2 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.

3.3.3 Results using the FABLE Calculator

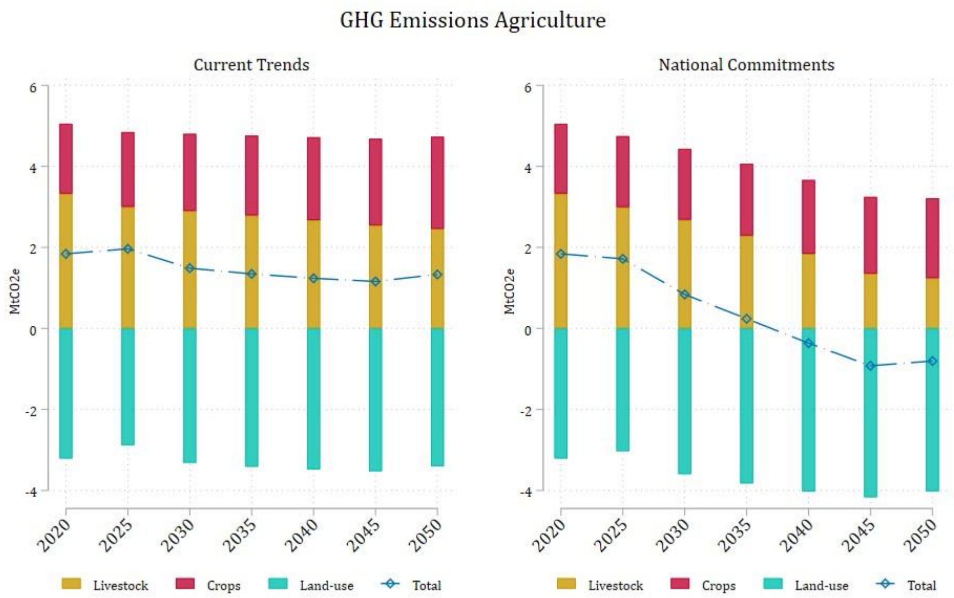
The pathways characterizing current trends and national commitments are calculated through the choice of options for 22 distinct scenarios following the data outlined in table A1. The FABLE calculator projects the trajectories for a battery of variables covering food consumption, GHG emissions, trade in agricultural products, agricultural jobs, land use, and biodiversity[16]. 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 23). 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 24) 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

[16] The module on Water use is still under modification, hence no relevant results are produced in the current version of the Calculator (Update 43).

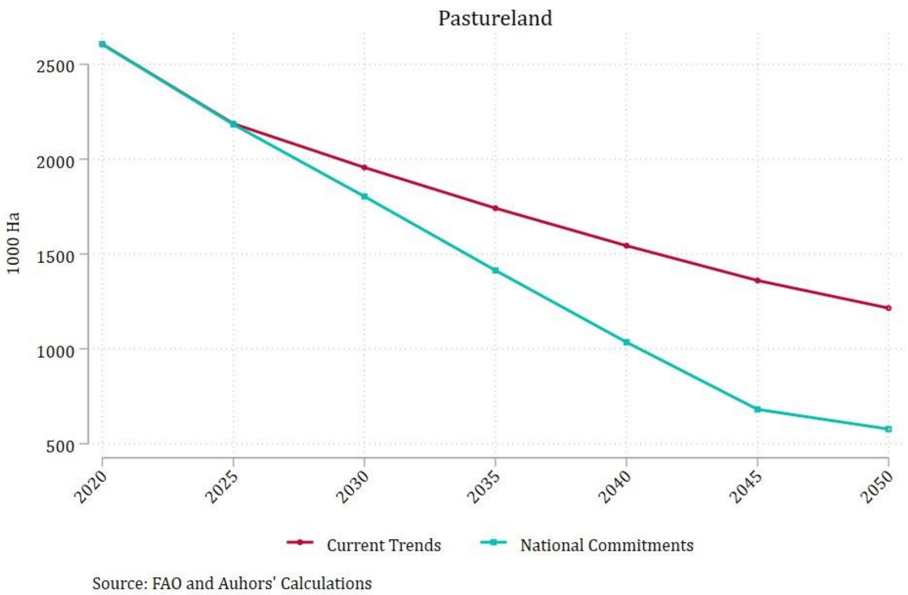
protected areas and the enhanced stringency regarding the land available for agricultural use, there are no significant gains to be modelled with the Calculator from afforestation or ceasing deforestation. The reason is the lack of a comprehensive strategy for afforestation which includes quantitative 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.

Figure 23: Agricultural Emissions Projections for Greece



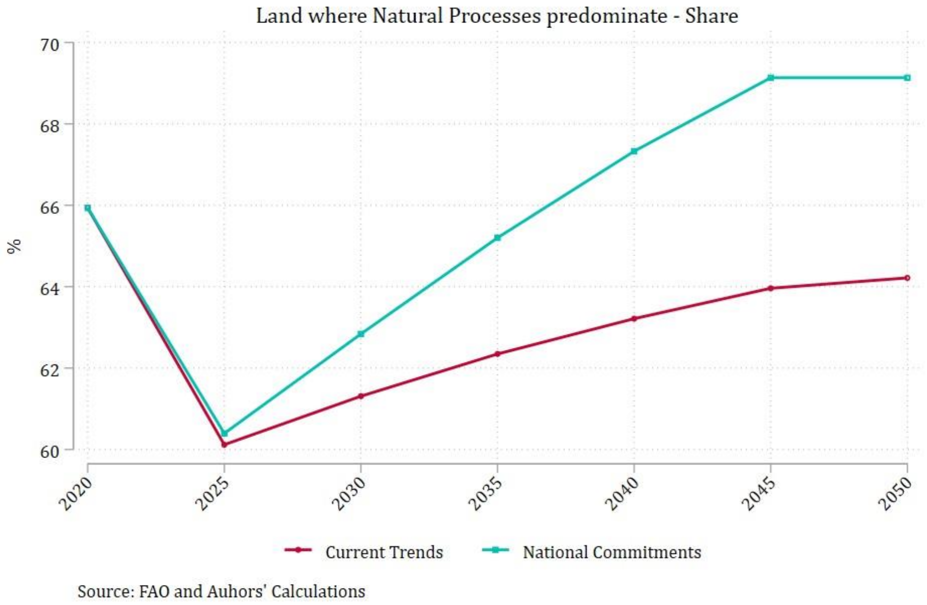
Source: FAO and Auhors' Calculations

Figure 24: Evolution of Pastureland for Greece



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 25). 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 25: 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 26). 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 27).

Figure 26: Agro-ecological Farming Practices

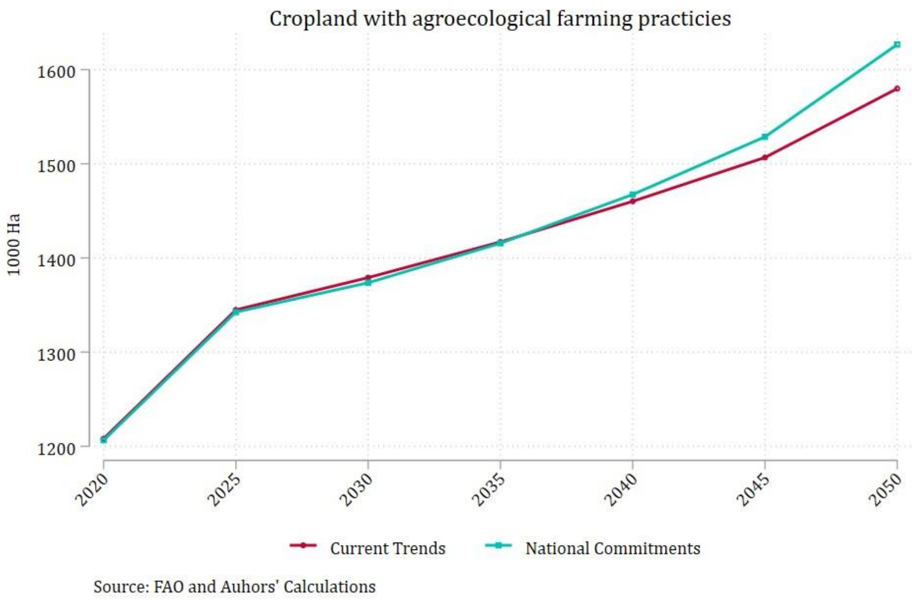
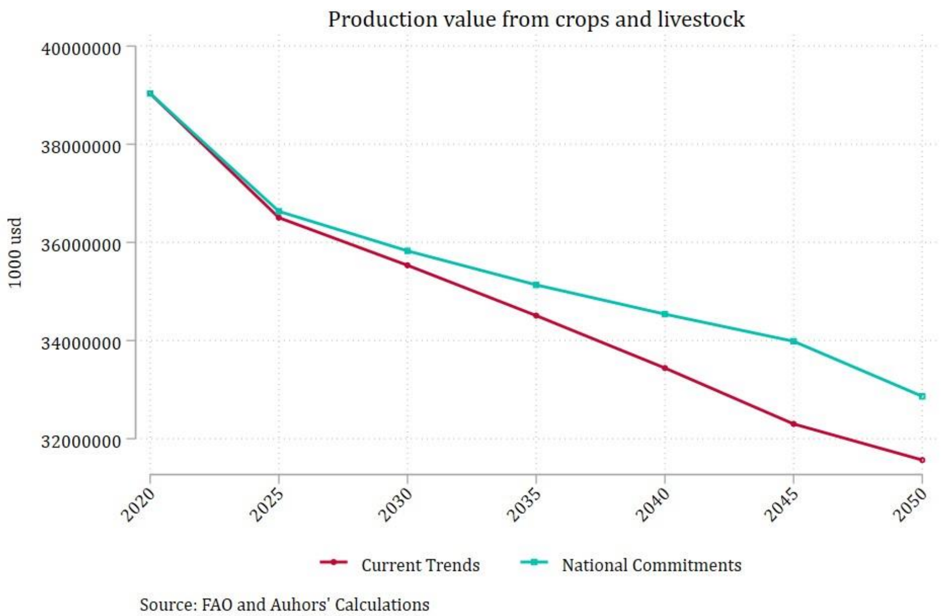


Figure 27: Production from Crops and Livestock



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. Model Integration for Sustainable Pathways

4.1 Global Climate Hub's Modelling Suite

This chapter discusses the potential for system integration under the auspices of the GCH and highlights the areas of Hub's future work in promoting net zero pathways. Model-based scenario quantification will support impact assessments and analysis of policy options towards decarbonization, using the classification and evaluation of IAMs described in Section 2.

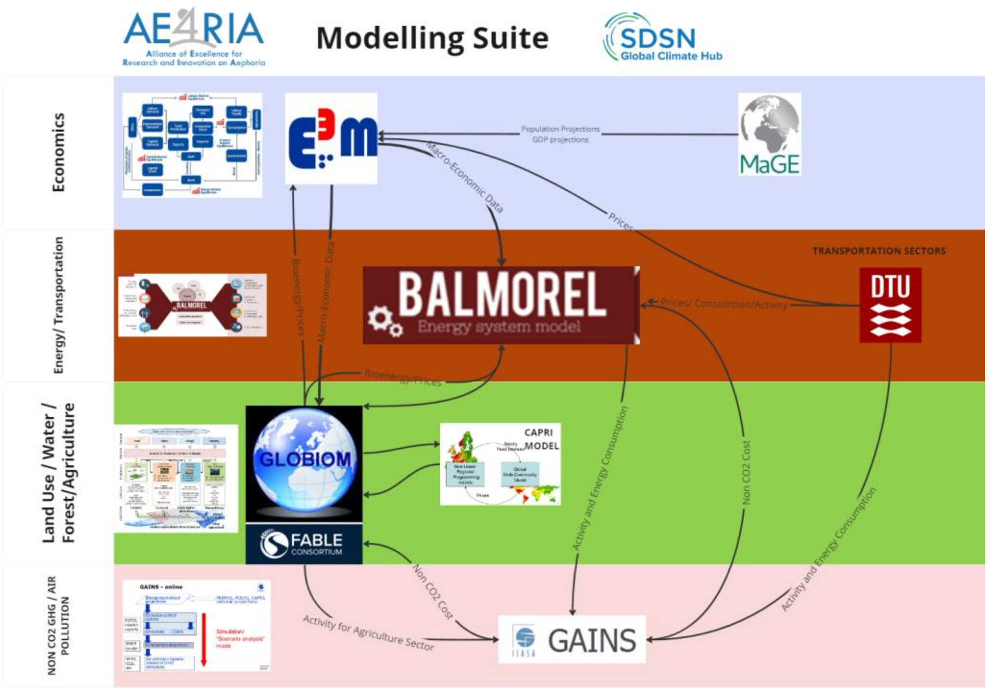
Model-based scenario quantification is a technique used to evaluate and measure the potential outcomes of different scenarios using mathematical or computational models. It is commonly employed in various fields, including economics, finance, environmental science, and engineering. The primary goal is to assess the impact of various inputs or assumptions on the model's outcomes under different scenarios. Scenarios represent different possible future states, conditions, or events. These scenarios could be based on different assumptions, policies, external factors, or interventions. For example, in economics, scenarios might include different economic growth rates, inflation levels, or economic policy changes. In environmental science, scenarios could involve varying levels of greenhouse gas emissions or climate change impacts.

The GCH's Modelling suite aims both to identify the interlinkages between the different models (Economics, Energy/ Transportation, Land Use/ Forest/ Agriculture and Non GHG emissions Air Pollution), as well as to improve the predictive accuracy by applying achieving a soft integration and model averaging techniques, which involves combining the predictions or outputs of multiple models in a way that allows for a gradual or weighted influence of each model's input.

4.2 Model inter-linkages

Harnessing the inter-linkages and complementarities of different models is the key for generating and evaluating diverse sustainable pathways which entail environmental, energy and socio-economic outcomes. Figure 28 presents a working scheme using the interlinkages between a series of models presented throughout the current report. The models are linked in formally defined ways to ensure consistency in the building of scenarios.

Figure 28: Model inter-linkages



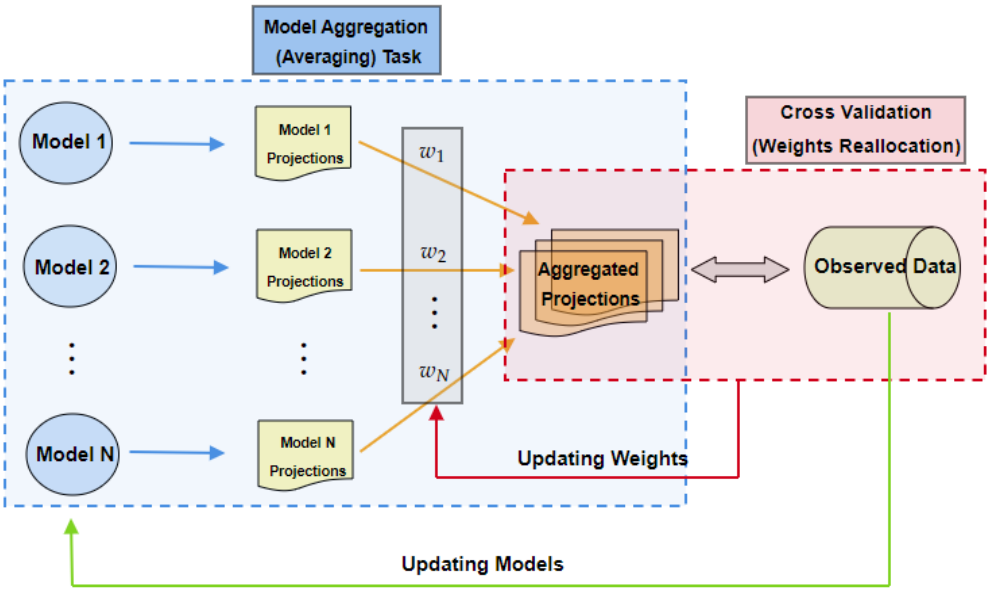
The models included in Figure 28 are indicative and intent to cover all GHG emissions and removals. It covers emissions from energy and processes (BALMOREL), CH4, N2O, fluorinated greenhouse gases (GAINS), CO2 emissions from LULUCF (FABLE), air pollution SO2, NOx, PM2.5-PM10, ground level ozone, VOC, NH3 (GAINS). Considering emission reduction and removals, the models cover the structural changes and technologies in the energy system and industrial processes (PRIMES), technological non-CO2 emission reduction measures (GAINS), as well as changes in land use (GLOBIOM-FABLE).

Finally, the integrated modelling suite includes impacts on energy, transport, industry, agriculture, forestry, land use, atmospheric dispersion, health, ecosystems (acidification, eutrophication), ecosystem services, macro-economy with multiple sectors, employment, and social welfare.

4.3 Modelling Averaging Techniques

The task of the optimal combination of different models for predicting the future evolution of quantities of interest is of particular importance in economics and in many other fields. This interdisciplinary modelling approach is met in the literature with various terms like model averaging (Hansen, 2007; 2012; Moral-Benito, 2015), model fusion (Hassan, 2007) or model aggregation (Papayiannis, 2018). This task refers to the situation when a set of different models which provide projections for the same quantity of interest (e.g., evolution of GDP, labor, inflation, etc.) are available and the decision maker needs to optimally combine these different sources of information to derive the most accurate aggregated projection. The great advantage of this approach is that it allows the aggregation of different models (allowing for them to be built under conflicting assumptions) since this approach is assumption-free. It can be implemented either at a static or at a dynamic setting allowing for a proper update and re-tuning of the aggregate model (Bayesian-type approaches, see e.g., (Fragoso, 2018; Raftery, 1997; Wasserman, 2000 and references therein). A sketch of how this aggregation scheme works is illustrated in Figure 29.

Figure 29 Model Averaging



A crucial step for the accurate tuning of the aggregate model, i.e. the one which output will be used as the optimal projection, is the availability of both historical data for the quantity of interest (actual values) and both projections of all the models in the set. Both outputs are compared and combined during the training stage of the aggregate model (which is usually repeated at certain time instants) to determine the optimal model by assessing the accuracy of each one of the models that contribute to the aggregate one, and accordingly increase or reduce its model's impact. The averaging scheme that is used depends on the field of application, the data availability, and the data nature. For simple point estimates a linear aggregation scheme may suffice but when complex data forms occur (e.g. measure-valued data, matrix-valued data, functional data, probabilistic projections, etc.), more sophisticated modelling approaches are considered and implemented. In the simplest case of a linear aggregate model, a set of weight is determined based on the empirical evidence compared to each model's performance under several appropriate criteria. Moreover, the model averaging approach can be also used to aggregate models which provide projections for various quantities of interest (it is not necessary all the models to provide projections for the same quantities) by partially averaging the components of interest but considering in the assessment stage the total performance of each model. This is quite the case when one wishes to combine general equilibrium models since could be quite different in nature and subject to much different assumptions. In this manner, it is possible for the resulting aggregate model to play the role of a data-driven integrated model able to provide more accurate projections for all projected quantities by the models in the set, respecting each model's philosophy.

Conclusion

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. A key pillar of the work in the GCH includes using advanced modelling techniques to estimate the projection of key economic, environmental, and social outcomes for the medium- and long-term horizon. Having said that, all calculations are contextualized within the policy and behavioral narratives dictated by internationally established targets (such as the SDGs and the Net Zero Transition) and national commitments for their achievement. During its first year, the GCH initiated a holistic approach to climate, economic, and energy modelling to deliver a first set of results. The process described in this report consist of a thorough review and assessment of potent Integrated Assessment Models (IAMs) and the delineation of a first set of sustainable pathways on the EU energy sector, the deployment, and effects of renewable energy transition in Southeast Asia and the development of sustainable pathways for land-use and food systems in Greece. In addition, the researchers of the GCH are examining interlinkages and complementarities across diverse IAMs which will yield horizontal and vertical synergies and elaborate on the potential pathways to net zero for 2050.

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 trough investment into renewable technologies like solar and wind, combined with energy trade-enhancing interconnections between European countries. We also show that the use of a national carbon budget over a system carbon budget bolsters renewable use and capacity and helps abating emissions at the national level without a significant increase in costs for the overall system. For Southeast Asia, the pathway towards net zero goes through enhancing renewable capacity and use. The renewable energy share in Southeast Asia's energy mix is expected to increase, driven by significant technological cost reductions, combined with governments' commitments to promote cleaner energy systems. The four key renewable energy sources for Southeast Asia are hydropower, solar, wind and bioenergy. The plan to replace coal with natural gas needs to change. To be able to integrate more of Southeast Asia's abundant variable renewable power into the grid, more storage and interconnection are necessary, which will take time. Meanwhile, Southeast Asia should give focused attention to developing dispatchable renewables such as wood pellets, which can substitute coal for baseload power. 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.

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 manner.

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Appendix

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

Policy area	Policy ambition	FABLE team's proposed quantitative national targets	Justification
Food	Undernourishment	0% undernourished share of population	By 2030, double the agricultural productivity and incomes of small-scale food producers. SDG achieved. On track or maintaining SDG 2 achievement (2.5% by 2030)
Food	Overweight / obesity	Priority reduction of childhood obesity from 25% (2017) to at least 10% (EU average) by 2030	The National Food Policy Plan aims to integrate healthy dietary habits and exercise into the daily lives of the Greek population. A specific online questionnaire, to collect statistical data on infant nutrition, was disseminated in public and private nurseries and kindergartens. Moreover, initiatives were taken scoping on raising awareness, dietary specifications were issued for the School Meals program and a specific section regarding nutrition and exercise was introduced in schools under the Skills Labs as seen in SDG4.
Food	Diet-related disease		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.
Climate mitigation	Total GHG emissions reduction (by Gas or in CO2e - if in CO2e indicate what is the global warming potential factor used to	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	GHG Emissions reduction targets are aligned with the EU Climate Law and the EU Green Deal.

	convert non-CO2 emissions into CO2)	MtCO2e in 2030.	
Climate mitigation	Agriculture GHG emissions reduction		In our data analysis using resources from the European Parliamentary Research Service (EPRS), the sectors with the lowest emissions reductions between 2005 and 2019 were agriculture and transport (13 % and 21 % respectively).
Climate mitigation	Land use and land use change GHG emissions reduction	-3 MtCO2e by 2030	In our data analysis based on the EPRS, as land use, land-use change and forestry (LULUCF) emissions remained stable from 2005 onwards, net emissions followed the trend set by total emissions in the country.
Climate mitigation	Reduce or halt deforestation		In line with the EU Green Deal to stop deforestation, and SDG 15.
Biodiversity	Reduce or halt loss of natural ecosystems	Halt the loss of biodiversity and the degradation of ecosystem services by 2026	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.
Biodiversity	Promote afforestation		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.
Biodiversity	Expand protected areas or 'Other effective area-based conservation measures' (OECMs)	Protected areas represent 30% of land and water by 2030	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.
Biodiversity	Expand cropland area under agroecological practices		The European Commission has set the target of 25% of the EU's agricultural area under organic farming by 2030
Biodiversity	Reduce or halt use of agrochemicals and other agricultural practices that harm biodiversity	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 market (sold), and therefore used, in each Member State, and the hazard properties of these active substances Target 2 - 50% reduction in the use of more hazardous pesticides
Fertilizer use	Limit N use	Reduce the use of N fertilizer by 20% by 2030 compared to 2015	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%.
Fertilizer use	Limit P use	Reduce the use of P fertilizer by 20% by 2030 compared to 2015	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%.
Water	Limit water use	Reduce water consumption in agriculture by 10-20% by 2030 compared to 2020 levels	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.

Water	Other water related targets		Compliance with Water Infrastructure Pillar and sustainable resource use in the National Recovery and Resilience Plan (NRRP).
Economy	Farmers' income	10-15% increase by 2030 compared to 2020	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.
Economy	Agricultural exports		According to the Pissarides report, in foreign trade, the agro-food sector is in deficit. However, during the crisis, the deficit narrowed significantly, to €1.4 billion in 2017 from €3.1 billion in 2008, as food imports stabilized in the €6.0-€6.7 billion range, while exports continued to grow (from €3.7 billion to €5.3 billion).
Economy	Timber exports	3x wood & wood product exports by 2030 compared to 2020	According to our data analysis, wood & wood products exports averaged ~ 200 mil 2012-16 and dropped to ~60 mil 2017-2020.
Economy	Employment in agricultural sector		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.