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An Integrated Assessment of the European National Commitments for Climate Neutrality

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An Integrated Assessment of the European National Commitments for Climate Neutrality

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The Global Climate Hub

The UN Sustainable Development Solutions Network's (**SDSN**) response to the multifaceted contemporary challenges is the Global Climate Hub (**GCH**), which came as an initiative for change, leveraging science-based solutions for a holistic and equitable sustainability transition (Alamanos, 2024; Koundouri et al., 2024). These solutions are developed at regional, national, and sub-national level based both on the scientific expertise of its members, and the engagement with local policymakers (representatives of central and/or local government) – there are dedicated teams of GCH scientists specialized across various fields, working in research projects, as well as a network of SDSN National Hubs, facilitating communication, outreach, and solutions' implementation. The overall philosophy of the GCH can be summarized in the combination of five critical innovations, for developing acceptable and implementable sustainable pathways. These work as a framework for the analysis of any problem:

I. Cutting-edge models: This includes the use/development of system-dynamics based cross-sectoral models. Based on the simulations and the different models' results, we develop holistic pathways at national level, for all major natural and infrastructure systems (e.g., water, atmosphere, land-use, food, energy, transport, marine-use systems, etc.). The involvement of 'non-experts' and civil society in the modeling process, allows the key stakeholders' perspectives to be embedded within it and provide validation for outputs.

II. Powerful digital AI-driven infrastructure that supports the handling of big data, their harmonization and management (as several data are not subject to the same units, time-steps or geographical coverage), their update, the development of digital twins, as well as the coupling of the various models and the results' visualization. This facilitates the integration of the above models.

III. Development of the socio-economic narrative for the just and equitable implementation of the science-based pathways. Based on the results of the natural and infrastructure systems (innovation I), the socio-economic narrative is built based on mathematical models simulating the economy (e.g., equilibrium modeling, welfare distribution, investments, behavioural responses, etc.). This is a country- or region-specific process fostering the co-ownership of the pathways across stakeholders, such as scientists and technology developers, policymakers, finance and business sectors, NGOs and civil society. Again, the two-way interaction with 'non-experts' is key.

IV. Stakeholder engagement: Transformative participatory stakeholder approaches (workshop-based) for co-designing the pathways in detail. Here, we exploit the capabilities of the new technologies – even virtual and augmented reality, digital storytelling, and gaming (all based on the previous innovations) to facilitate the stakeholders' experience and understanding. The stakeholder engagement can raise awareness and promote sustainable lifestyles and behavioural changes for the adoption of the solutions.

V. Openness: The whole process of analyzing, co-designing, presenting and applying sustainable pathways supports the widespread adoption of the principles of Open Science and Open Access to data, models developed, and in general scientific infrastructure. This is paramount for the efficient and effective progress of the solutions, as well as their reproducibility and transferability.

These innovations are interlinked and complementary, feeding each other with necessary information, to deliver optimal sets of technological, policy, fiscal and financial measures to address complex sustainability challenges, build and maintain cross-disciplinary collaborations and stakeholder engagement. Thus, the GCH ensures that the proposed solutions are holistic, innovative, publicly acceptable, transferable, feasible and applicable to the unique contexts of different countries, bridging the gap between the models it produces and the non-scientific community.

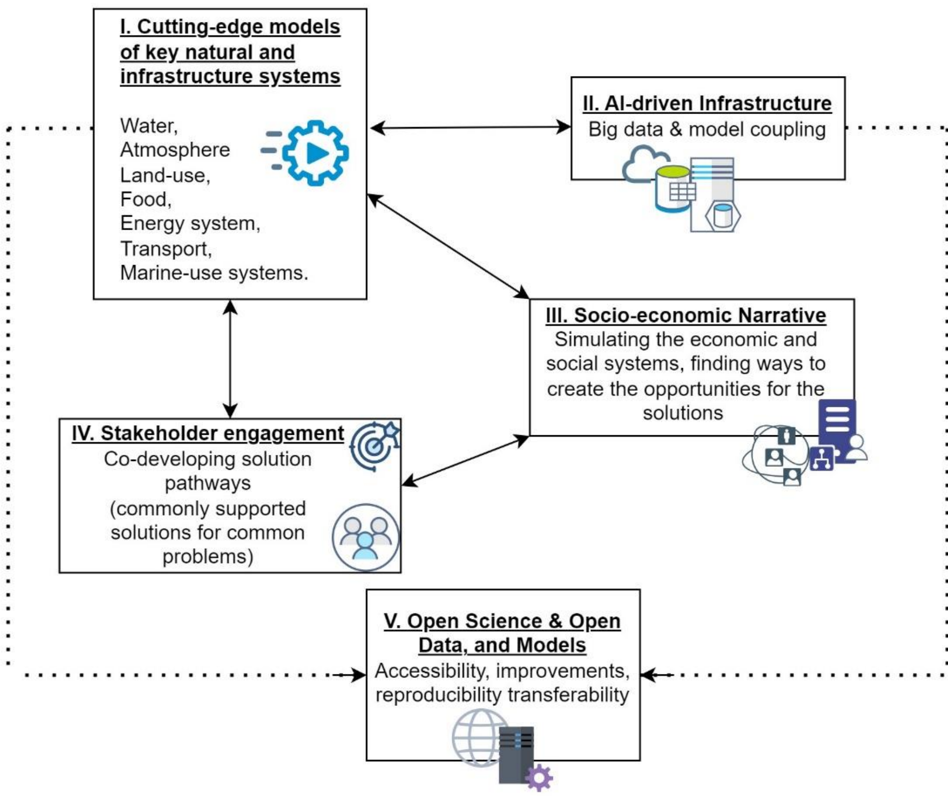

Figure a. The five innovations of the GCH, summarizing its approach to sustainability problems, in an indicative schematic showing their interactions: Integrated models are used/developed (I), which are coupled and updated (II)to simulate real-world scenarios. Based on their insights and the stakeholders' input, the socio-economic narrative is developed, simulating the social and economic systems (III). The results so far are the basis to co-design solution pathways with the stakeholders (IV), within a two-way interaction with the models (I), ensuring realistic representation of the problems and solutions. Data and models are publicly accessible to enhance reproducibility (V).

Examples of pathways can include technical solutions (e.g. for decarbonization), the consideration of existing technologies, circular economy, nature-based solutions, digitalization, innovation commercialization, sustainable finance and adaptation investment schemes (e.g., green bonds, Environment Social Governance – ESG metrics, and market incentives), and policy reforms (legislative and regulatory interventions to support the implementation and long-term viability of the pathways). To the best of our knowledge, this is a globally unique effort for science-driven, holistic, human-centric approaches aiming to sustainability, climate neutrality and resilience pathways at national level. Its nature, with the existence of national hubs in different countries ensures stability, continuation, and commitment for the long-term implementation of the solutions. This is also beneficial in terms of up-scaling potential, knowledge transfer, and international experience and capacity building across its dedicated teams.

The GCH is hosted by [Athens University of Economics and Business (**AUEB**)] and the [“Athena” Research and Innovation Center in Information, Communication, and Knowledge Technologies (**ATHENA RC**)], both integral components of the [Alliance of Excellence for Research and Innovation on Aephoria (**AE4RIA**] – in Greek ‘aephoria’ is a synonymous concept to sustainable development). Within the GCH, AE4RIA plays a vital role in securing funding from competitive projects, ensuring the necessary resources to fulfill its multidimensional mission. The Research Centre for Atmospheric Physics and Climatology of the Academy of Athens also supports the GCH.

Nine units as necessary scientific areas for sustainability

The GCH consists of nine separate units/working teams that have expertise to handle relevant research and practical applications (see the table below). These units are scientific areas, conceived as necessary ‘steps’ towards sustainability, as each one contributes a unique perspective and insight towards the development of customized strategies for climate neutrality, resilience, and sustainability. All units operate under the philosophy of the five innovations explained in the previous section, together or in combination with other units.

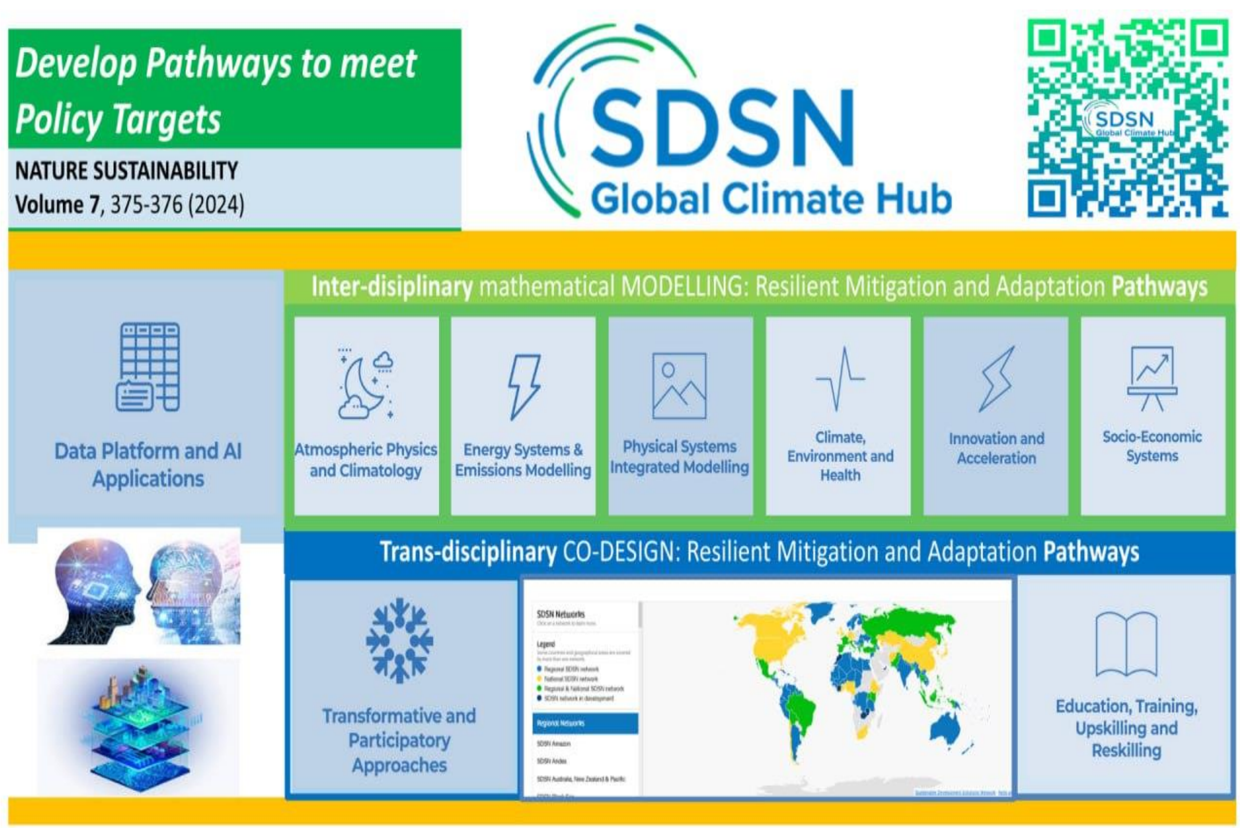

Figure b. The 9 units of the Global Climate Hub.

1. Data platform and AI applications
The Mission of the Unit is to aggregate, connect, and visualize data aligned with the Climate Hub's objectives across five components: • inputs (funding sources), • outputs (research production), • outcomes (scientific developments, data, tools, policies), • effects (interdisciplinarity, networks) and • impacts (SDG links, research outreach). Its overarching aim is to deepen the understanding of the science, technology, and innovation (STI) landscape for climate research and policy-making, by globally monitoring research activities, engaging with the key actors involved, assessing the ensuing societal and economic impacts, assessing and mapping out policy uptake across administrative scales and internationally, through interdisciplinary and intersectoral approaches. The Unit pioneers cutting-edge AI applications across strategic domains that the GCH relates to (Earth System Modelling, Climate Dynamics and Predictions, Remote Sensing and Geospatial Applications, Ecosystems and Biodiversity, Economics, Policy and Society). Further, the Unit contributes to the creation of DSS, Spatial Computing/AR/VR applications and Digital Twins. In these efforts, the systematic integration of data and models is central in elucidating the research processes involved and in supporting evidence-informed decision-making.
2. Atmospheric Physics and Climatology
This unit conducts analysis of global and regional climate using satellite and terrestrial observations, and simulations with climate models. This unit explains and forecasts climate variability, trends, extreme events and simulates their impact at various time scales. It also simulates air pollution phenomena and their interactions with climate change. This information is crucial for the development of appropriate climate change mitigation and adaptation strategies, able to withstand and cope with climate related stresses. A typical application example of this unit's work is the provision of statistically downscaled climate change projections at regional scales, or air pollution dynamics, to be used as inputs or future scenarios to examine the response and behaviour of the natural and socio-economic systems.
3. Physical Systems Integrated Modelling
This unit focuses on simulating and analyzing the dynamic interactions among natural and physical systems—land, water, marine, agriculture, biodiversity, and forestry—under climate, land-use, and anthropogenic changes. It applies system-specific or custom-developed models to explore trade-offs and sustainability pathways across interconnected systems such as water management, food production, and marine use. Scenario-based analyses integrate environmental and socio-economic drivers to support climate-neutral, economically viable resource management. Moreover, this unit assesses natural hazards and extreme phenomena, such as wildfires and floods, aiming to prediction and protection strategies, tailored at the local scale, governance and socio-cultural conditions. AI is used to enhance near-term and long-term climate projections, improve early warning systems, and strengthen attribution science for extreme weather events and their impacts. Combined with tools like GIS, TerrSet liberaGIS, water resource models (e.g. WaterReqGCH), Remote Sensing, hydraulic models, and the FABLE Calculator, it assesses future land uses, resource availability, sectoral impacts and trade-offs, informing policy and strategic planning for sustainable development.

4. Energy Systems & Emissions Modelling
This unit models national and regional energy systems using system dynamics, optimization, statistical methods and machine learning to simulate energy supply and demand, sectoral GHG emissions, and decarbonization pathways. It maps energy production by source (e.g. coal, natural gas, renewables, nuclear, bioenergy, etc.) and records sectoral energy use (transport, buildings, industry, agriculture, etc.), linking these to emissions, within physical modelling, and advanced AI applications for real-time monitoring of carbon fluxes. Climate mitigation strategies such as consumption efficiency, transitions to cleaner fuels, electrification, carbon pricing and credits are tested through scenario simulations to assess impacts on emissions and energy uses. Models used include LEAP, BALMOREL, En-ROADS, and the MaritimeGCH. Tailored models incorporate regional specifics, spatiotemporal and uncertainty aspects, supporting the development of climate-neutral, efficient, and technologically feasible energy transition pathways.
5. Climate, Environment and Health
This unit models the health impacts of climate and environmental stressors—such as floods, heatwaves, air pollution, sea-level rise, and region-specific hazards—on human morbidity, mortality, and broader physiological and psychological outcomes. It also assesses indirect consequences from disrupted food, water, and energy systems. Economic and econometric models, as well as Machine Learning models estimate the substantial associated costs, and relations among drivers and outcomes. The objective is to inform equitable adaptation strategies, including early warning systems and resilience-building measures, to mitigate these effects. Emphasis is placed on developing interventions through public health and socio-economic modeling to enhance societal well-being and reduce climate-related health inequalities.
6. Innovation and Acceleration
Partnerships among the academic, public, business, and technology sectors is needed to co-develop and implement solutions for a green, sustainable economy. This unit addressed the social and economic facets of the sustainability transition, ensuring fairness, inclusivity and equity, by mobilizing and connecting knowledge and innovation networks, start-ups, technology-holders. It includes the large-scale deployment of sustainable and breakthrough technologies, particularly in key industrial sectors. Hosting the EIT Climate-KIC Hub in Greece, it fosters innovation through multi-sector partnerships that accelerate the transition to a zero-carbon, climate-resilient society. Another example, the MENA Maritime Accelerator, advances maritime decarbonization by supporting high-impact start-ups with funding, training, and mentoring. Additionally, BRIGAID Connect strengthens Europe's climate resilience by linking innovators with stakeholders to scale impactful solutions. Through initiatives like the Climate Innovation Window, this unit cultivates inclusive, equitable innovation ecosystems that drive environmental, economic, and social transformation.
7. Socio-Economic Systems
This unit supports global and regional efforts toward climate neutrality, sustainability, and equity by aligning its work on economics and finance with key frameworks such as the 2030 Agenda for Sustainable Development and the Paris Agreement. It develops dynamic equilibrium models (e.g. CGE) with direct links to the work of units of the Energy and Physical Systems Modelling. It includes the analysis of SDG indicators, the provision of just policies, novel financial instruments, and labour market reforms, based on models (e.g. GTAP, GLOBIOM, ECM3, and AI-driven tools capturing risks and adaptive planning feedbacks), and participatory processes.

Thus, it fosters holistic assessments on the interplay between the physical and socio-economic layers of e.g. decarbonization policies, offering tailored, equitable strategies for achieving the SDGs.
Emphasis is placed on transformative action across sectors, guided by the six UN SDSN transformation areas. The unit also supports implementation of the European Green Deal, promoting cross-sectoral policy integration to foster sustainable industry, clean energy, and inclusive growth, reinforcing global climate and development objectives.

8. Transformative and Participatory Approaches

The Transformative and Participatory Approaches Unit ensures that the Global Climate Hub's scientific outputs are co-developed and grounded in local realities through inclusive stakeholder engagement. Using System Innovation and Transition Management methodologies, it establishes Transformative Living Labs, namely multi-actor platforms that co-design solutions aligned with the six UN SDSN Transformations for achieving the SDGs. These labs integrate the outcomes and processes of the Physical, Energy, and Socio-Economic Systems Modelling units with participatory processes. Thus, it mobilizes community and policy dialogue Systems Innovation Approach (SIA), Living Lab Modeler Tool, foresight methods such as Backcasting, stakeholder mapping, living Labs, participatory methods and workshops are some of its common tools and approaches, to reach to common visions of implementable context-sensitive and evidence-based policies, customized in the lived realities of those they impact.

9. Education, Training, Upskilling and Reskilling

The Education, Training, Upskilling and Re-skilling Unit of the Global Climate Hub (GCH) addresses the urgent need for sustainability-focused education and capacity-building to support the green transition. Recognizing the global skills gap in climate and sustainability sectors, the Unit develops adaptable learning programs across all life stages, aligned with the Six SDG Transformations. It collaborates with SDSN academic networks and the SDG Academy to deliver in-person and online education, with targeted initiatives for youth, national teams, and public outreach. Emphasizing tailored, co-designed curricula, capacity development and lifelong learning, the Unit aims to cultivate green competencies, critical thinking, and societal engagement necessary for climate action. These assets are crucial also for the local stakeholders and decision-makers to manage their systems sustainably in the long-term.

EXECUTIVE ABSTRACT

Achieving climate neutrality in Europe requires a collective effort that goes well beyond national energy plans, extending into food systems, land use, and natural resources. While each Member State's National Energy and Climate Plan (NECP) outlines individual targets, a common assessment addressing diversity in planning horizons, data detail, and resources' considerations is lacking. This report bridges these gaps by **simulating Europe's 35 NECPs through an integrated, systems-nexus framework that couples energy-emissions, food-land, biofuels and water models under two scenarios: "Business as Usual" (BAU, current trends) and the full implementation of the National Commitments (NC) for net-zero.**

Our framework links five simulation tools by 2050: i) **FABLE Calculator:** projects crop and livestock production, dietary shifts, and land-use changes, identifying cost, employment, and GHG impacts under current and CAP-aligned policies; ii) **LEAP (Low Emissions Analysis Platform):** models energy demand and supply across residential, industrial, transport (terrestrial, maritime, aviation), agricultural and services sectors, calculating multi-pollutant GHG emissions for each fuel type and use; iii) **BiofuelGCH:** quantifies domestic bioethanol and biodiesel potential, revealing import/export imbalances and highlighting countries that can scale production to serve internal or regional demand; iv) **LandReqCalcGCH:** translates renewable capacity targets (solar and onshore wind) into land area and investment cost requirements, flagging potential conflicts with agriculture, conservation, and community interests; v) **WaterReqGCH:** estimates sectoral water withdrawals, comparing them against sustainable supply to flag regional water-stress hotspots and underscore the need for integrated River Basin Management Plan (RBMP) measures.

Under BAU, agricultural emissions remain stagnant, energy-use emissions decline only marginally, renewable land expansion is limited, and water stress persists particularly in Southern Europe. **In contrast, the NC scenario** yields significant GHG emissions reductions across all sectors, and more sustainable food and land projections. Hydrogen and renewable sources replace most fossil fuels in the long-term, but net electricity imports rise in countries with limited domestic capacity. Biofuel production potential and link to sectoral consumptive uses (e.g. agriculture, maritime and aviation sectors) remain underexploited. Major economies (Germany, France, Spain, Italy) remain net biofuel importers, with Europe having an aggregate shortfall. Renewable land-use expansion is an overlooked factor, which however stays at generally feasible levels, with also feasible investment requirements, as long as smart and careful land-use planning is followed. Regarding water supply and demand, Southern countries show severe irrigation deficits. NECPs and RBMPs fail to set enforceable, sector-specific water-use targets, leaving key trade-offs (such as water for hydropower or bioenergy) unresolved.

We provide 20 main policy recommendations, addressing sectoral, per-country, and per-policy considerations, ensuring a holistic and equitable approach. Key recommendations include: Sectoral coordinated strategies by aligning building retrofits, renewable rollouts, and urban transport planning to maximize efficiency and emissions reductions in residential, services, industry, and transportation sectors. In industry, detailed roadmaps for steel, cement, and chemicals are needed, combining electrification, renewables, and circular-economy measures. In agriculture, we underline the potential of a shift toward agroecological practices and dietary changes via CAP eco-schemes, and mandate for creative land-use solutions (agrivoltaics, brownfield solar, and agro-pastoral wind) to avoid displacing farmland or forests. Embedding enforceable water-use targets tied to CAP irrigation standards and RBMPs to prevent scarcity is also crucial. Biofuels production uptake and adoption for cross-sectoral consumption should be also encouraged.

At the policy level, all NECPs must adopt a unified 2050 horizon, deepen quantitative energy-supply and demand projections, and model cross-border electricity, fuel, and hydrogen trade. Linking NECPs with CAP and RBMPs ensures agricultural, land, and water policies align with climate goals, while cross-border collaboration on grid interconnections and shared renewables fosters a coherent, resilient pathway to net-zero. Finally, equity issues should be addressed by targeting additional financial and technical support to lower-income Member States so they can build infrastructure, adopt clean technologies, and meet stringent targets without disproportionate economic strain.

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1. Introduction

Climate neutrality in terms of achieving net-zero greenhouse gas (GHG) emissions extends far beyond the energy sector to encompass food systems, land use, water resources, and their ties to natural ecosystems (Dai & Alamanos, 2024; Koundouri et al., 2024). Energy subsectors' planning (power, transport, industry, buildings) requires close coordination with agriculture (crop and livestock production), land management (forestry, conservation, bioenergy), and water use to balance resource flows, curb emissions, and maintain ecosystem health (Khan et al., 2017; Fortes et al., 2022; Alamanos & Garcia, 2024; Koundouri et al., 2024).

Key international commitments, including the Paris Agreement's Nationally Determined Contributions (NDCs) and the UN's Sustainable Development Goals (SDGs), are well integrated into European regulations, such as the European Green Deal (EGD) and "Fit for 55" package, which set binding targets for 2030 (–55% CO_2 vs. 1990 levels) and mandate a climate-neutral economy by 2050 (Koundouri et al., 2024). In this regard, the EU and its Member-States are obliged to take necessary measures at EU and national levels to meet the long-term target of climate neutrality, through integrated National Energy and Climate Plans (NECPs). In particular, the NECPs covering 10-year periods should take into consideration the 2030 targets for GHG emission reductions, renewable energy, energy efficiency and electricity (Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), 2021). The Member-States must also submit to the Commission a progress report every two years. In addition, the Member-States develop national long-term strategies (LTS) looking forward to 2050, which shall be consistent with their NECPs.

Over 30 European countries, operating within a largely unified internal energy market and common policy framework, offer an ideal regional case study for integrated decarbonization modelling (Luxembourg et al., 2025; Mikropoulos et al., 2025). Numerous energy system models and Integrated Assessment Model (IAM) frameworks have mapped EU decarbonization pathways (Weyant, 2017; Harmsen et al., 2021) with several operational applications, such as the PRIMES model (Capros et al., 2018), the TIMES-Europe model (Luxembourg et al., 2025), the Balmorel model (Madsen et al., 2025), but also resource-oriented approaches, like water-economic climate neutrality assessments (Ionescu et al., 2024). Energy efficiency improvements, increasing use of renewables, and electrification are established solutions for Europe's climate neutrality, according to the majority of the existing modelling studies, but complexities in interconnecting sectors and systems are also acknowledged as important challenges to achieve net-zero (Capros et al., 2019; Moreno et al., 2024). Yet, few studies link detailed energy-emissions simulations to food-land-water components. This gap persists despite evidence that neglecting any of these constraints can skew decarbonization analyses (Vashold & Crespo Cuaresma, 2024). We aim to cover this gap by presenting an integrated energy-emissions-land-food-water modelling approach for EU, driven by its net-zero commitments.

Another key aspect and gap of the European energy system's decarbonization refers to the individual policies as expressed in each Member-State's NECP. In terms of the NECPs, there have been a few evaluations, but they refer to an analysis of sufficiency elements (Zell-Ziegler et al., 2021), or they focus on aspects of the NECPs related to the dimension of decarbonization in the design and adoption of common European policies and integration issues (Maris & Flouros, 2021), or they assess the quality of

EU-mandated public participation in Member States' NECPs (Oberthür et al., 2025). Moreover, most of the existing modelling studies offer scenario analyses and/or optimal solutions for EU's energy system, rather than policy analyses on the NECPs and their improvement (van Greevenbroek et al., 2025). There have been country-specific analyses on specific issues, such as the case of renewables for Spain (Ramos et al., 2023), and an analysis of the Italian NECP's review (De Paoli, 2024), but there are fewer multi-country assessments (Geoffron & De Paoli, 2019). In the few available examples, Williges et al. (2022) look at Greece, Austria, and the Netherlands, indicating that the ground is not ready to address the NECPs' objectives. The review by Hyvönen et al. (2024) looks at the North European countries' NECPs (Finland, Estonia, Germany, Sweden, and Denmark), finding them vulnerable to risks related to biomass and global raw material availability for expanding their renewables. However, an assessment of the NECPs of 27 European countries, 5 Western Balkan countries, Norway, the UK and Switzerland with the objective to recommend ways to improve their NECPs as a whole with regard to their consistency and uniformity, has not yet been conducted.

We aim to cover these gaps by simulating the NECPs of 35 European countries within our integrated modelling framework, combining energy-emissions, food-land, and water models. Such an approach is essential to deliver a truly systemic view, revealing sectoral and national challenges with insights grounded on a model-driven analysis, guiding policymakers toward improved national and coherent continental strategies.

2. Context and Challenges in Europe

In this work, we assess Europe as a case study. While we are aware that Europe is interconnected with other regions of the world, it is also important to study it separately as a unit, since there is a common European energy policy framework which intends to harmonize regulations, and thus to create an integrated, competitive and secure European energy market that facilitates the transition to a net zero economy. What is more, Europe is a unified energy system which aims to reach the EU's decarbonization targets by creating a more interconnected, resilient, efficient and coordinated energy network, which creates stronger links between different types of energy carriers, energy infrastructure and consumption sectors.

For our assessment, we consider 35 countries, namely Albania, Austria, Bosnia and Herzegovina, Belgium, Bulgaria, Switzerland, Cyprus, Czechia, Germany, Greece, Denmark, Estonia, Spain, Finland, France, Croatia, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Montenegro, North Macedonia, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Sweden, Slovenia, Slovakia and the UK. These countries are assessed in a cross-sectoral way, considering their current situation, and National Commitments (NC), as we will explain below in the scenario analysis section. The cross-sectoral nature of the assessment allows us to cover the main challenges and targets among all sectors (residential and services, industry, agriculture, transportation), which share similarities across Europe, but also some differences.

Regarding the residential and services sectors, they account for more than one-third of the EU's energy-related GHG emissions, so improving their efficiency is critical (European Environment Agency, 2024a). However, most European countries struggle with an ageing, poorly insulated building stock (Churkina et al., 2020; Khosla et al., 2021). The required renovation rate is far below targets; the European Environment

Agency (EEA) estimates it must double or even triple current levels to meet climate goals (LIFE Unify, 2020; Maduta et al., 2023). Upgrading heating systems (from oil or gas boilers to heat pumps or modern district heating) is a shared goal, but high costs, supply-chain limits and split incentives (e.g. landlords vs tenants) hinder progress (Fattouh & Honoré, 2023; Johnston et al., 2024). So, the main challenges include financing deep renovations, tackling fuel-poor households and dwellings, and decarbonizing heat (e.g. phasing out coal/oil furnaces). Some countries lead with strong building codes or district heating expansion (Nordic and Central Europe), while others still rely on biofuel or gas heating (Abbasi et al., 2021; Elavarasan et al., 2022).

Industry (especially steel, cement, chemicals, manufacturing) is a major emitter and its decarbonization is crucial for Europe (Cavalett et al., 2024; Di Foggia & Beccarello, 2024). The diversity of this sector's processes and supply chains makes its decarbonization challenging to be addressed by single-focus measures, such as only electrification, renewables, energy efficiency or circular economy (Busch et al., 2025; Helm et al., 2025). All those practices are needed, but in the case of industry in Europe, research so far calls for specific roadmaps for each subsector (steel, cement, etc.) with intermediate targets and policies in all NECPs (Meckling et al., 2017). Adoption of new technologies and their costs, as well as integrated power system models accounting for such measures are still necessary for robust planning.

Transport is the EU's largest-emitting sector and the one where emissions have flatlined or even risen, with recent research highlighting that all NECPs are "clearly insufficient both in a 2030 and 2050 perspective from a transport point of view" (Transport & Environment, 2019). Most countries set electrification goals (EV quotas, charging networks) and biofuel blends, but these often fall short of the needed pace, while other measures such as the use of biofuel blends seem to be overlooked (Transport & Environment, 2019). In practice, uptake of EVs and alternative fuels varies widely (Norway/Netherlands are far ahead; others lag), and also inequalities emerge due to inherent layouts (e.g., size, population density, topography) and infrastructure levels of different countries (Kaufmann et al., 2024). Modal shift (reducing car travel) is weakly addressed; promoting public transit or active mobility is mentioned only in passing in most plans (Liotta et al., 2023). Freight and aviation decarbonization receive even less attention: hydrogen, synthetic fuels or other solutions are often cited as future potentials without concrete policies (Sharmina et al., 2021; Bergero et al., 2023).

Across Europe's NECPs the agriculture section (including energy and non-energy uses, livestock, crops, etc.) tends to be shallow. Common measures cited include improved manure management, biogas from waste and some efficiency gains, but overall ambition is low (Stid et al., 2025). A recent review finds NECPs "do not reflect sufficient ambition" for agriculture and land use (Frelih-Larsen et al., 2024): They virtually ignore food consumption (diet) changes and mainly rely on LULUCF measures (afforestation, soil carbon projects) to offset farming emissions. Also, agriculture exhibits visible differences across Europe, as other countries have larger livestock sectors (e.g. Eastern countries), others have a large cropping production (South), and so on, with the national policies differing accordingly. In terms of broader land use management, NECPs commonly include afforestation and forest-management plans to boost removals, and some address peatland rewetting. A common objective is that urbanization should stay around existing centers, and avoid agriculture or forest land losses, with reforestation being often a target (Senf & Seidl, 2021).

Source: *https://www.institut-agro-rennes-angers.fr/sites/www.institut-agro-rennes-angers.fr/files/images/focus/focus-E2C.jpg*

Climate change is significantly stressing Europe's water resources, which are vital for energy, agriculture and ecosystems (Bisselink et al., 2020; Söller et al., 2024). The EEA warns that "Europe's water is under significant pressure" and needs better resilience (European Environment Agency, 2024b). Planning within an energy-water-land nexus is still a challenge as countries may plan new energy sources without fully accounting for land requirements or potential increases in water needs, creating future resource conflicts (Larsen & Drews, 2019). NECPs generally lack detailed water-use plans, while EU guidance emphasizes aligning climate and water policies. The most relevant policy is the EU Water Framework Directive (WFD 2000/60/EC), which mainly focuses on pollution and water supply, and is weaker in terms of water consumption measures.

So, an integrated analysis combining different measures and NECPs comparisons is expected to be a useful exercise for all those sectors.

3. Methodology

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

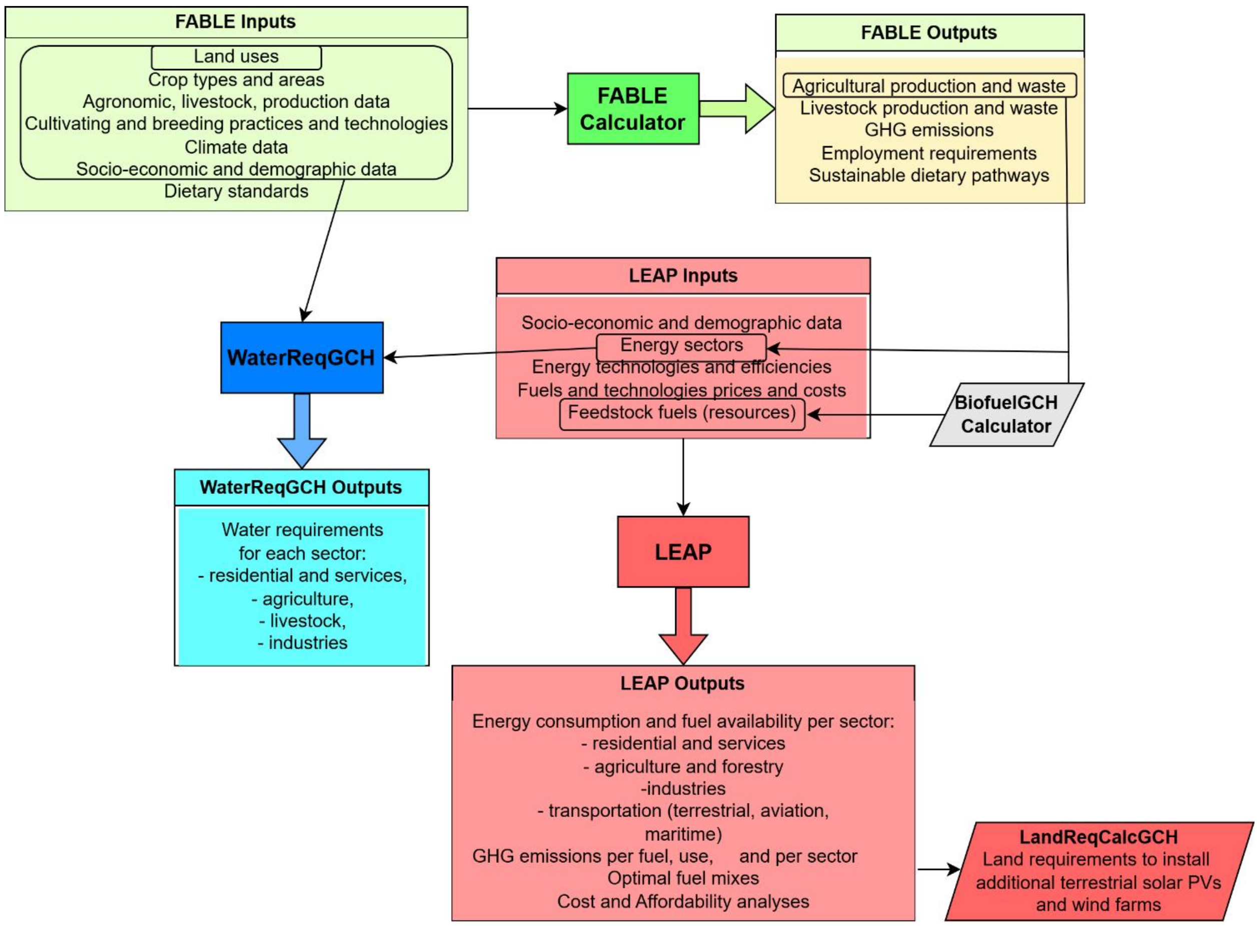


Figure 1. The modelling framework, with the tools, their inputs and outputs, and their connections.

Food-Land System

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

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

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

Currently, not all European countries have a FABLE Calculator, or at least sharable. The ten (10) countries that we were able to simulate in the present report, using their own built-Calculators were: Denmark, Finland, France, Ireland, Germany, Greece, Norway, Poland, Spain, Sweden, while for the other countries, we used the official "Rest of Europe" FABLE Calculator. This includes: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Portugal, Romania, Slovakia, and Slovenia. Then the results for those countries were disaggregated based on each ones' size (area).

Cross-sectoral Energy-Emissions Analysis

LEAP is at the core of the modelling suite, as it simulates the energy demand (consumption) across various sectors, the fuel supply and their production, as well as the associated GHG emissions for each process. LEAP is a software tool for long-term integrated energy, climate mitigation, and air pollution planning and analysis, developed over the last 40 years by the Stockholm Environment Institute (SEI). It has been developed as a scenario-based modelling tool that explores how emissions may change in the future. LEAP has been employed in numerous applications globally, from local municipalities to national governments (Fall & Mbodji, 2022). For instance, countries have utilized LEAP to develop their Nationally Determined Contributions (NDCs) under the Paris Agreement, showcasing its relevance in climate policy formulation. The model's flexibility enables it to accommodate various methodologies, including bottom-up end-use accounting and top-down macroeconomic modelling, making it suitable for integrated resource planning and GHG mitigation assessments (Fall & Mbodji, 2022). This functionality allows for the simulation of specific policies as modelling scenarios, enabling detailed evaluation of their impacts and trade-offs. The model's ability to simulate different scenarios has been particularly useful in exploring future conditions and/or ways for decarbonization (Liu et al., 2021; Xu et al., 2024).

To address the considerable heterogeneity across the NECPs regarding the level of detail that they entail in their description of the planned interventions, we developed two modelling approaches within LEAP. The first approach calculates the energy demand (D) as the product of an activity level (AL) and an annual energy intensity (EI, energy use per unit of activity), according to LEAP's Final Energy Demand Analysis method (Equation 1). In addition, this approach allows for the simulation of multiple different uses within each core sector (residential, industry, agriculture, transportation, and services). This makes it very suitable in cases where we have sufficient data, and we might be interested in examining sector-specific policies and scenarios.

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

In contrast, to deal with cases where we faced data scarcity, we developed a second modelling approach that is based on LEAP's Total Energy Demand method. This means that the main required input is the total final energy consumption for each sector. This second approach simulated the same sectors as the first, but with a lower level of detail (i.e. fewer energy uses). Table 1 below offers a one-on-one comparison of the two approaches.

LEAP's energy supply-side module simulates the resources (representing the availability and characteristics of primary and secondary energy forms), and transformation processes (simulating how energy is converted, transmitted, and distributed through technologies like power plants, refineries, and grids). The supply system ensures alignment with the per sector demand-side inputs and can simulate constraints, imports, exports, and system losses, offering detailed insights into energy flows. Again, there are some differences between the two approaches, reflecting data availability (Table 1). The main difference is that the second approach considers fewer fuel types than the first approach. This is achieved by classifying the fuel types used in the first approach into less fuel categories in order to comply with cases with insufficient data.

In order to ensure that our results, and thus our conclusions, are not sensitive to the choice of modelling approach, we tested the implications of the two approaches for selected countries (i.e. for countries where we had sufficient data to implement both versions of our model). Our analysis showed that the results remain qualitatively the same. This is in line with the findings in Koundouri et al. (2025) for the case of Greece. Overall, the lack of detail of the second approach should not be viewed as a weakness. Instead, this approach could be very useful and deliver trustworthy results in cases of data scarcity. Finally, note that the results of both approaches were validated for the current account (i.e. year 2022) using data from EUROSTAT.

The GHG emissions are then estimated based on the emission coefficients of the IPCC's Fifth Assessment Report (IPCC, 2014), in order to estimate emissions per sector, use and fuel type. In particular, LEAP's "effects" menu provides the option to select different sets of Global Warming Potential (GWP) values corresponding to one of the IPCC Assessment Reports. LEAP includes 20, 100 and 500-year GWP values. These values reflect the relative potential of each effect over each period. Each value is specified in units of tonnes of CO2 equivalent per tonne of pollutant (T CO2e/T). That is, the GWP values measure the warming potential of a tonne of each gas relative to a tonne of CO2.

Table 1. Characteristics of the two modelling approaches.

Simulated sectors/ parameters	Modelling Approach 1	Modelling Approach 2
Energy Demand		
Residential	**Method**: Final Energy Intensity Analysis **Activity Level**: Population divided into urban and rural. **Uses**: Space Heating, Space Cooling, Water Heating, Cooking, Lighting, Appliances	**Method**: Total Energy Demand **Uses**: Residential as a whole
Agriculture	**Method**: Final Energy Intensity Analysis **Activity Level**: Value added	**Method**: Total Energy Demand
Industry	**Method**: Final Energy Intensity Analysis **Activity Level**: Value added **Sub-sectors**: Food & Tobacco, Textiles & Leather, Wood & Wood Products, Paper Pulp & Printing, Chemicals, Rubber & Plastic, Non-Metallic (excluding cement), Basic Metals (excluding steel), Machinery, Transportation Equipment, Other Manufacturing, Mining, Construction, Cement, Steel	**Method**: Total Energy Demand **Sub-sectors**: Industry as a whole
Aviation, Maritime & Terrestrial Transportation	**Method**: Final Energy Intensity Analysis **Activity Level**: ktoe per Passenger-km **Sub-sectors**: Cars & Light Trucks, Freight Trucks, Motorcycles, Buses, Trains, Freight Trains, Domestic Airplane, Maritime	**Method**: Total Energy Demand **Sub-sectors**: Terrestrial Transportation, Aviation, Maritime
Services	**Method**: Total Energy Demand **Sub-sectors**: Services as a whole	**Method**: Total Energy Demand **Sub-sectors**: Services as a whole
Energy Supply (fuels' generation & transformation processes)		
Primary Resources	Solar, Hydro, Wind, Geothermal, Solid Waste, Biomass, Crude Oil, Lignite, Other Coal, Natural Gas	Renewables (includes: Solar, Hydro, Wind, Geothermal), Biomass (includes: Biomass, Solid Waste), Crude Oil, Coal (includes: Lignite, Other Coal), Natural Gas (includes: Natural Gas, CNG)
Secondary Resources	Electricity, Hydrogen, Synthetic Fuels, Heat, Biogas, Refinery Feedstocks, Diesel, Petroleum Coke, Fuel Oil, Kerosene, CNG, LPG, Gasoline, Other Petroleum Products	Electricity, Hydrogen, Synthetic Fuels, Heat, Biogas, Refinery Feedstocks, Petroleum Products (includes: Diesel, Petroleum Coke, Fuel Oil, Kerosene, LPG, Gasoline, Other Petroleum Products)
Transformation Processes	Transmission and distribution, synthetic fuel production, generation of hydrogen, electricity, heat, oil refining – with the associated losses	Transmission and distribution, synthetic fuel production, generation of hydrogen, electricity, heat, oil refining – with the associated losses
GHG Emissions		
Type of Pollutants	CO_2, CH_4, N_2O, PM2.5, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), Black Carbon (BC), Organic Carbon (OC)	CO_2, CH_4, N_2O, PM2.5, Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), Sulfur Hexafluoride (SF_6), Black Carbon (BC), Organic Carbon (OC)
Validation		
	For the current account, both energy consumption and fuel supply results were	For the current account, both energy consumption and fuel supply results were

	validated with data from a single source (EUROSTAT).	validated with data from a single source (EUROSTAT).

Agriculture's Residuals Potential for Biofuels Production

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

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

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

Figure 2 below summarizes the conceptual computational process of the BiofuelGCH Calculator.

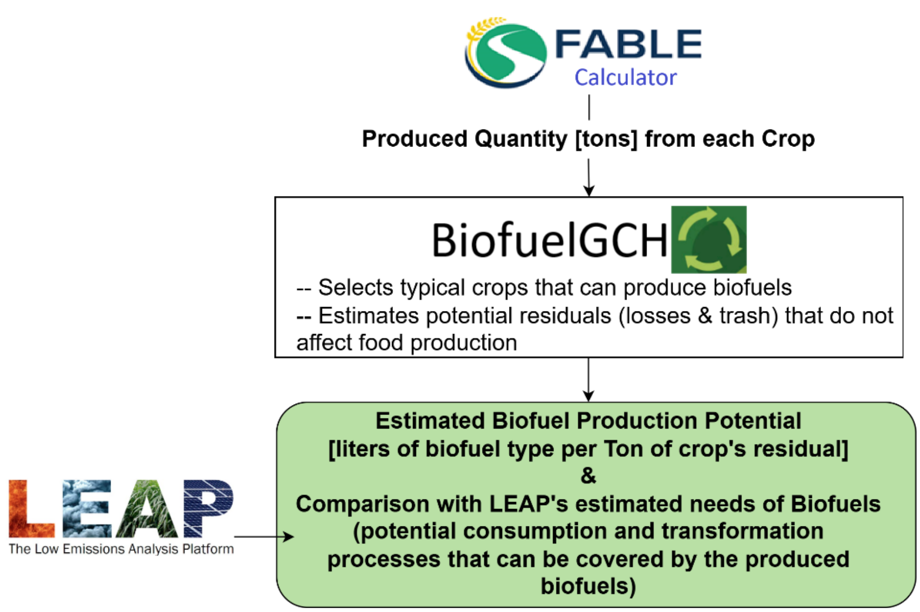


Figure 2. The conceptual diagram of the BiofuelGCH Calculator's inputs, process, and outputs.

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

Needs for Additional Renewable Energy Infrastructure

LandReqCalcGCH

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

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

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

Source: *https://www.brsolarsystem.com/news/revolution-in-irrigation-how-solar-water-pump-79336885.html*

Most NECPs includes information about centralized/decentralized solar power (e.g. rooftop PVs), and onshore/offshore wind power installed capacity projections. These are also accounted for in the model, which provides the net onshore centralized solar and new onshore wind power requirements.

Moreover, the LandReqCalcGCH model calculates the expected costs (in million €) for the installation of the additional net onshore solar panel and wind farm areas, based on typical installation cost values.

Water Requirements and Supply

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

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

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

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

Regarding the water supply side (abstractions per source), since large-scale hydrological models for surface and groundwater availability can be quite uncertain and miss water abstraction information, a data gathering and processing approach was followed. In particular, we integrated historical data from (EUROSTAT, 2024) with supplemental insights from hydrological studies, national statistics, and global datasets including FAO and OECD water resources reports (OECD, 2025). This data-mining process started by extracting average annual supply values (1970–2020) from EUROSTAT, categorizing them into surface water, groundwater, desalinated water, and reused water (supply sources). Recognizing inconsistencies and gaps (e.g., especially regarding surface versus groundwater shares) we applied country-specific corrections based on documented hydrogeological characteristics, official government reports, and scientific literature (European Environment Agency, 2024c; EUROSTAT, 2024). Where data was unavailable or inconsistent, interpolation and expert-based assumptions were employed to ensure realistic continuity. The final dataset reflects updated supply values in hm^3/year, with plausible minimum and maximum bounds accounting for interannual variability and data uncertainty. This process aims to ensure consistency, realism, and comparability across all countries. The supply-demand difference was also explored to give a picture of the annual water balance per country.

Policy Scenario Analysis

Our assessment includes two main scenarios by 2050:

- **The BAU** (Business-As-Usual), "current accounts", or do-nothing scenario. For the energy-emissions LEAP model, and the WaterReqGCH model, this means that the situation of today remains unchanged by 2050. For the food-land model, this scenario follows the FABLE Calculator's current trends that assume a continuation of existing policies and socioeconomic trends without major new climate or sustainability interventions. It reflects moderate population growth (SSP2), current dietary patterns, ongoing yield improvements, and limited land-use or emissions regulation. Diets and food waste remain unchanged, there is no expansion of protected areas, agricultural productivity remains static, and there are no additional efforts to reduce losses or promote sustainability, making this a continuation of current trends with limited ambition (FABLE Consortium, 2024; Koundouri et al., 2024). For the water sector, this just reflects the average consumption per sector, according to a typical (average historic year) 2022.
- **The NC** (National Commitments), reflecting the legally binding objectives for each country. For the LEAP model, these are explicitly expressed through each individual NECP, and are detailed per sector. The NC scenario for the food-land model follows the build-up case of NC for each country's FABLE Calculator. This assumes the implementation of current national climate and sustainability targets, which are more explicitly expressed in the Common Agricultural Policy (CAP) and the national land policy plans (Koundouri et al., 2024). So, the NC scenario includes GHG reduction goals, reforestation plans, and agricultural policies. It follows the SSP1 pathway, assuming greater sustainability efforts and environmental awareness. Diets transition to the Lancet model with reduced meat and more plant-based foods. Food losses and waste decline, productivity in crops and livestock grows moderately. In general, it incorporates stronger dietary shifts, reduced food waste, and increased productivity compared to BAU, aiming to align land-use and food systems with each country's official climate and biodiversity pledges (Mosnier et al., 2023). For the water sector, the WFD 2000/60/EC is the relevant policy, which is translated into national plans through the national RBMPs. However, the RBMPs do not have any specific recommendations on the water consumption which we explore.

Unavoidably, the NECPs are the most central part of this analysis, as they include all sectors and set specific technology and fuel-related goals per country. Therefore, a necessary step for our assessment was to carefully review all 35 countries' NECPs under specific criteria to facilitate their simulation in LEAP. The outcome of this process is summarized in the Annex, Table A1, and is discussed after the results, in order to put the review-finding into the broader context.

The NECPs of the 27 EU countries are available at the European Commission's website[1], and the NECPs of the 5 Western Balkan countries, namely Albania, Bosnia and Herzegovina, Montenegro, North Macedonia

[1] Available here.

and Serbia, are available at the Energy Community's website[2]. Norway's Climate Action Plan for 2021-2030 is available at its government's website[3], and Switzerland's long-term climate strategy to 2050 is available at the website of its Federal Office for the Environment[4]. As far as the UK is concerned, it should be mentioned that the UK, although it is not a member of the EU anymore, submitted its NECP to the Commission shortly before the end of 2020.

Our analysis focused on the following criteria:

a) The level of NECP readiness of each country, namely checking whether the countries have submitted a draft or a final version of their NECP.

b) The planning horizon of each NECP, as some countries set their objectives for 2040 or 2050, providing a long-term strategy.

c) The approach considered in the NECPs in terms of emphasizing on a "supply-management" (more fuel- and technology-focused), or a "demand-management" (more efficiency- and consumption-focused), or on a seemingly balanced approach.

d) The level of detail on how to achieve decarbonization targets, as some NECPs provide more detail and data-driven analyses, projections and specific breakdowns of measures, while others tend to be more descriptive.

e) The GHG emissions reduction targets (e.g. the percentage reduction in GHG emissions compared to 1900 or 2005 levels).

f) Data on renewable energy in final energy consumption and in electricity generation. The NECPs consider renewables and electrification as major drivers for net-zero, so we noted which countries provide explicit numbers on the renewable energy shares in the final energy consumption and energy generation by 2030 and/or 2050.

g) The reliance on imports and/or exports of each country. Some NECPs include explicit projections for their expected imports and/or exports of specific fuels (e.g. fossil fuels, biofuels, hydrogen, electricity, etc.), so we noted whether this data is included, as well as the respective available information.

Having taken into account these criteria while reading the official translated in English version of the NECPs, we gathered all the relevant data that we found in the NECPs and created a summary comparative table, which we attach as an Annex.

These criteria were necessary for their simulation in LEAP, but we also consider them central for the identification of potential areas for further coordination and collaboration among European countries, and the provision of sectoral and international recommendations.

[2] Available here.
[3] Available here.
[4] Available here.

4. Results

All models described in the previous section run under a common simulation period, from 2020 to 2050, at an annual time-step. The BAU and NC scenarios were considered, as mentioned above. The NECPs, the CAP, and the WFD capture~~s~~ each sector's formally established, legally binding targets for emissions, food, land use, and water management. These represent the core NC under international and EU law. Economic instruments like the EU Taxonomy, Circular Economy rules, or the ETS serve as supporting frameworks to finance or incentivize investments, but do not themselves set or alter sectoral quotas or consumption benchmarks. Therefore, omitting them from our analysis does not overlook additional mandatory commitments, since we do not present an economic model here. Our analysis remains comprehensive by relying on the primary legal documents that define each country's cross-sectoral decarbonization, land-use, and water-use obligations. In our ongoing and future research plans, we are developing an economic model (Computable General Equilibrium – CGE model) to account also for the economic aspects of the framework we present here. Table 2 summarizes the modelling aspects of the NC scenario.

Table 2. The description of the NC scenario within the modelling framework presented.

Sectors	Planned pathway according to sector-specific policies
Residential, Industry, Transportation, Services	The National Energy and Climate Plans (NECPs), as defined by each country's Ministry of Energy (and Environment in some cases), assume certain interventions per sector. These refer to improvements of energy use efficiencies and cleaner energy mixes. So, for all sectors, the NC scenario - expected energy consumption - led to the respective energy intensities assumed in this simulation. Also, for each sector, the NC's expected fuel mixes (phasing out fossil fuels and replacing them with cleaner ones) were simulated. Note that for the energy consumption, fuel mix and the associated GHG emissions of the transportation sector, there is an important difference between the NECPs. On the one hand, several NECPs focus only on domestic transportation (i.e., terrestrial, aviation, and navigation). On the other hand, there are countries that consider international transportation (i.e., aviation and navigation) as well. To ensure consistency in our analysis, we adopt the latter approach for all countries by filling the missing data in the first group of countries based on reasonable assumptions about the growth rate of international transportation and the corresponding fuel mix.
Food-land system, Agricultural production-based and energy-based systems	The broader EU CAP framework clearly acknowledges the need to boost agricultural productivity, promote sustainable diets (reducing meat) within the constraints of limited land, and enhance energy efficiency in agriculture. However, while these objectives are articulated as strategic goals, the policy largely outlines broad priorities and financial support mechanisms rather than prescribing specific, technical interventions or detailed action plans (Kyriakopoulos et al., 2023; Doukas et al., 2024). The NC scenario focuses primarily on the generic agroecological practices, GHG emissions and costs within the country-specific FABLE Calculator NC build-in scenario, corresponding to their actual National Commitments by 2050.
Water consumption	The EU's Water Framework Directive (WFD) 2000/60/EC establishes a comprehensive framework for water policy, aiming to protect and enhance the quality of water resources across Member-States. While the WFD sets overarching objectives for achieving 'good status' of all water bodies, it does not prescribe specific water consumption reduction targets for individual sectors (European Commission, 2023). In all Member-States, the implementation of the WFD is carried out through River Basin Management Plans (RBMPs), assessing the status of water bodies and outline Programmes of Measures (PoMs) to address identified issues. While the RBMPs focus on protecting and managing water resources, they do not set explicit sector-specific water consumption reduction targets or measures. Instead, they emphasize the need to improve water efficiency and sustainable use across various sectors (Karavitis & Oikonomou, 2024).

Food-Land System Results

The results of the FABLE Calculator for Europe are presented in the next panel Figure (Fig.3).

GHG emissions from agriculture remain essentially flat at ~600 $MtCO_2e$ in the BAU scenario, indicating no meaningful mitigation. In the NC scenario, GHG emissions drop by roughly 15% (to ~510 $MtCO_2e$), reflecting expanded eco-schemes and reduced fertilizer/livestock intensity.

Under BAU, Europe's agricultural production costs drift upward from about €62 billion in 2020 to nearly €70 billion by 2050, reflecting rising input prices and stagnant productivity. In the NC scenario (assuming each country meets its current climate pledges) production costs rise more sharply, from ~€58 billion to ~€80 billion, due to intensive investments to increase productivity.

Figure 3. The overall results of the FABLE Calculator for Europe: First row: Production costs; Second row: Employment requirements in Full-Time-Equivalent (FTE); Third row: GHG emissions from agricultural production processes; Fourth row: Land use changes. All results are presented for the BAU and the NC scenarios.

Farming employment in the BAU declines slightly from roughly 4.2 million FTEs (Full-Time-Equivalent) in 2010 to about 3.9 million by mid-century, driven by small drops in both livestock and crop jobs. Agricultural employment falls more markedly in the NC scenario, to around 3.6 million FTEs by 2050, as stricter environmental rules curb extensification in livestock and cropping.

On the land-use front, in the BAU, cropland and forests hold steady (cropland ~120,000 km²; forest ~155,000 km²), new afforestation is minimal, and pastureland erodes slowly, while urban areas creep upward by a few thousand square kilometers. In the NC scenario, land use edges toward sustainability: cropland shrinks by ~10,000 km², new forests gain momentum (adding some 15,000 km²), and pastureland declines more steeply, while urban footprints remain stable.

The map-plots below show the results of GHG emissions per country (Fig.4). By 2050, under the BAU scenario, the largest agricultural emitters remain France (~80 MtCO_2e), Spain (~50 MtCO_2e), Italy (~45 MtCO_2e) and Germany (~40 MtCO_2e), with mid-sized contributions from the UK, Poland and Romania (20–30 MtCO_2e) and most smaller states under 15 MtCO_2e. If each country meets its current climate pledges (NC scenario), emissions fall by roughly 30–40% across the board: France drops to ~35 MtCO_2e, Spain to ~30 MtCO_2e, Germany to ~35 MtCO_2e, Italy to ~18 MtCO_2e, and the UK to ~12 MtCO_2e. Eastern-European and Nordic nations likewise slim down to under 10 MtCO_2e in most cases.

The results of agriculture production costs per country do not change significantly by 2050. Under all scenarios, France, Spain and Italy exhibit the higher total costs.

The next map-plots show the employment results per country (Fig.5). By 2050, under BAU, agricultural employment remains heavily concentrated in Southern Europe. Greece leads at roughly 550,000FTE, followed by Italy and Spain at about 300,000FTE each, and France at 280,000FTE. Eastern and Northern states show much smaller workforces, typically under 100,000FTE, reflecting lower-intensity farming. Under the NC scenario, overall farm jobs shrink across the board. France's workforce actually edges up to about 350,000FTE (thanks to targeted rural support), while Greece's falls to 280,000FTE, Italy to 290,000FTE and Spain to 300,000FTE, narrowing the Southern-Northern divide. Most smaller countries drop into the 50,000–150,000FTE range as stricter environmental rules and mechanization bite.

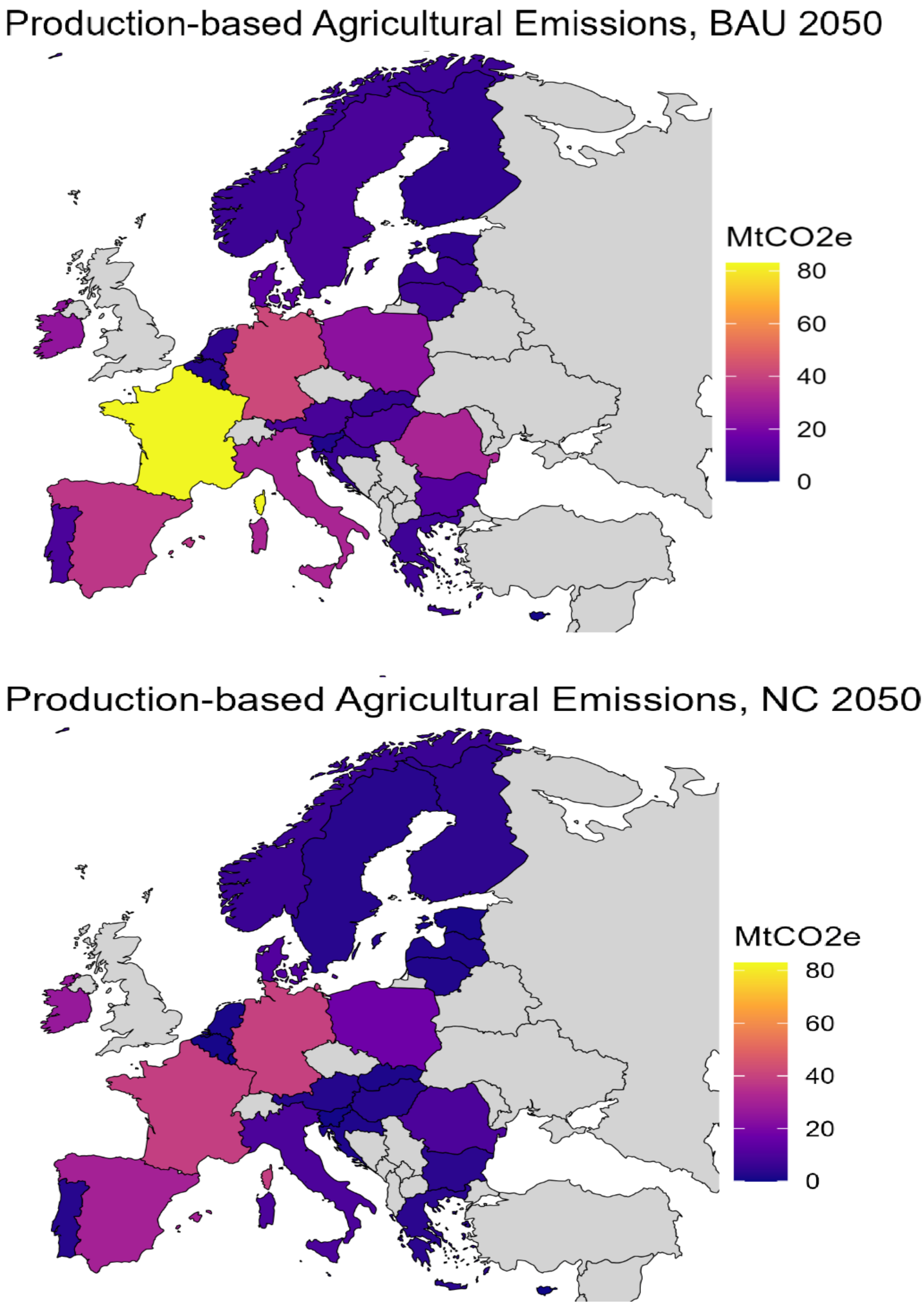


Figure 4. The production-based agricultural GHG emissions results of the FABLE Calculator for Europe, per country, and scenario, in 2050.

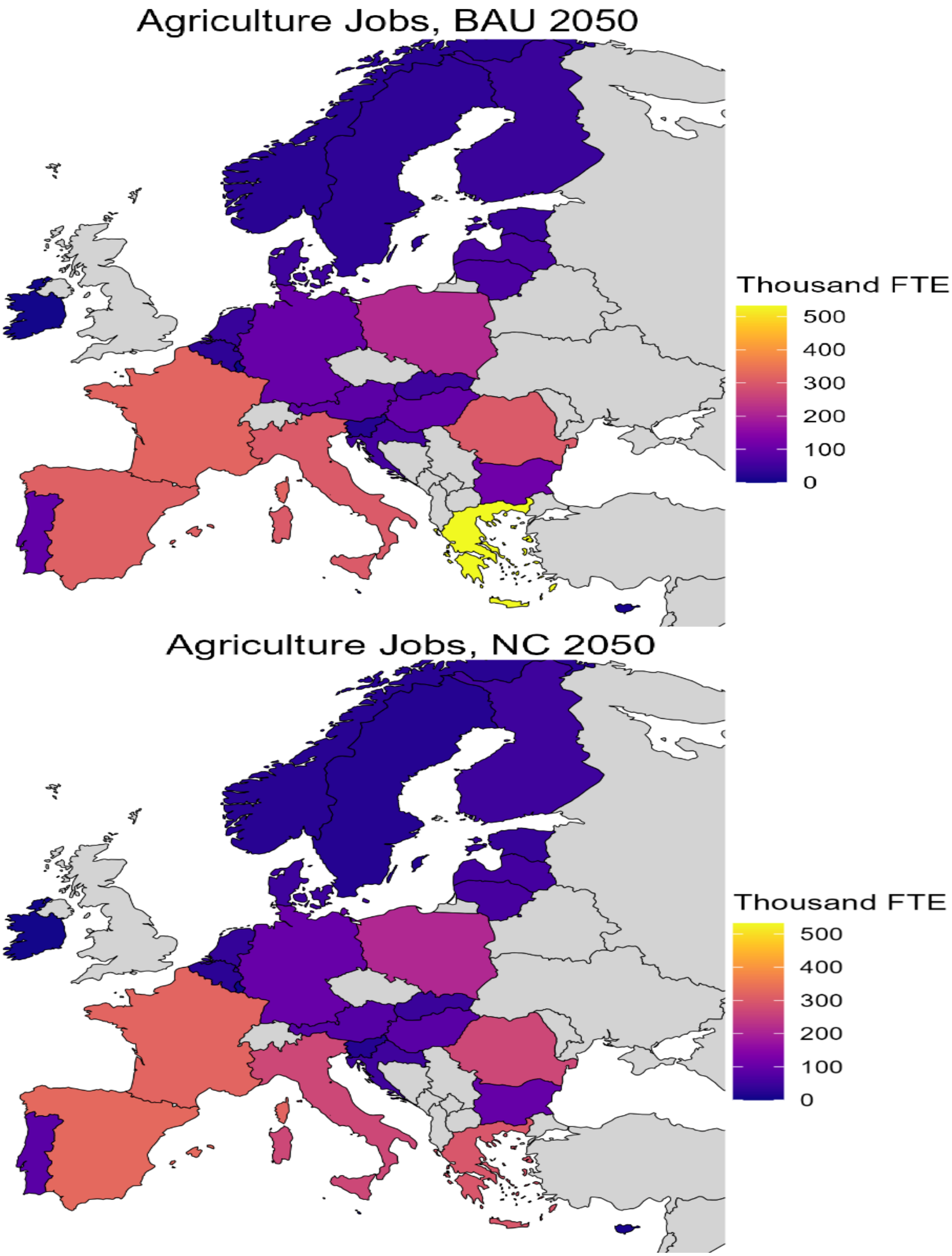


Figure 5. The agriculture jobs results of the FABLE Calculator for Europe, per country, and scenario, in 2050.

Cross-sectoral Energy-Emissions Systems' Results

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

The results for Europe as a whole under the NC scenario indicate a steady decline in energy demand (meaning consumption) from 2025 to 2050, driven by decreases in all major sectors. Most notable reductions are observed in the transportation (red) and residential (green) sectors, while services (blue) and industry (yellow) also contract gradually (Fig.6a). One of the main reasons for the modest decrease in energy consumption in the tertiary sector, despite the adoption of similar to the residential sector measures, is the increasing role of data centers, which leads to high demand for electricity. Correspondingly, demand-side emissions drop sharply, with most sectors emissions' shares being steady by mid-century (Fig.6b). On the supply side (Fig.6c), oil refining (dark brown) contracts significantly, while electricity generation (brown) gradually expands to become the dominant supply source by 2050, accompanied by a gradual increase in hydrogen generation (green), while traditional heat generation (dark green) remains stable over the whole planning horizon. Supply-side emissions from the energy generation processes fall dramatically from around 1,000 $MtCO_2e$ in 2022 to roughly 200 $MtCO_2e$ by 2050 (Fig.6d), reflecting the transition to low-carbon technologies. These results underscore Europe's NECPs expected progress toward decarbonization, driven by reduced demand and a shifting supply mix, yet also highlight persistent emissions from remaining generation and refining activities, emphasizing the need for continued policy support and technology deployment.

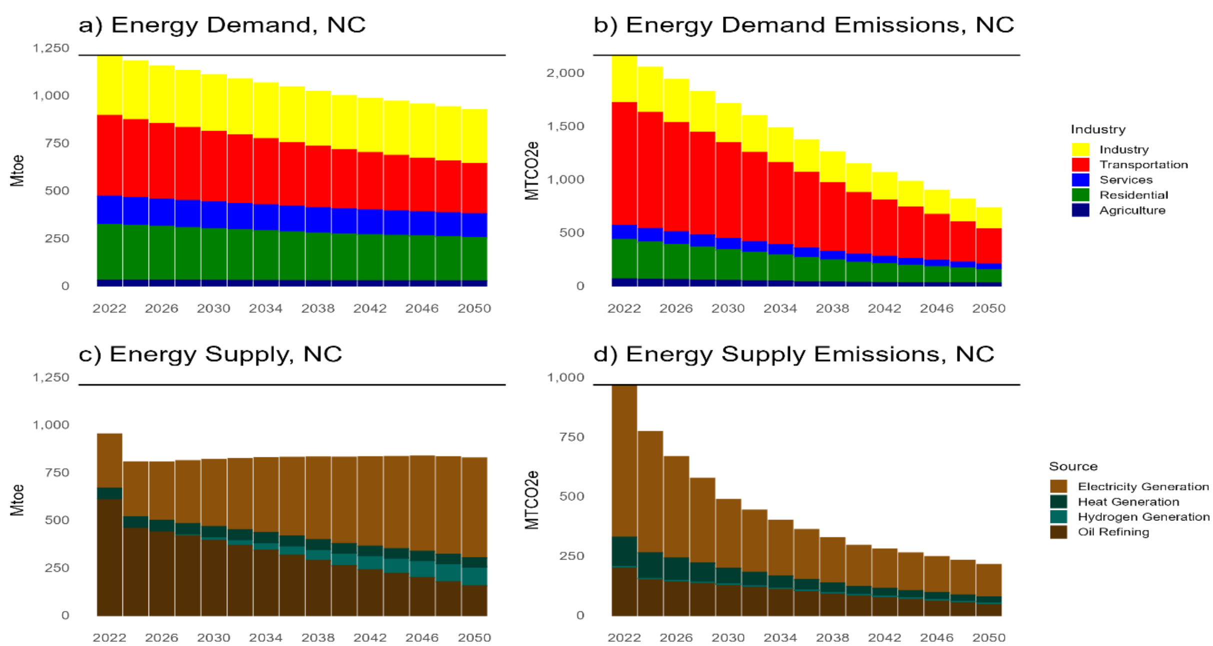


Figure 6. The overall results of the European NC scenario, including: (a)Total energy consumption per sector, with (b) the respective GHG emissions (100-Year GWP). (c) The energy supply generated amount per source, with (d) the respective GHG emissions (100-Year GWP).

Figure 7 shows the per country results of the evolution of energy consumption and associated emissions. In 2025, as expected, larger economies (Germany, France, the UK, and Italy) display higher total energy consumption. Industry (yellow) and transportation (red) dominate in Central and Western Europe, whereas Southern and Eastern countries (e.g., Greece, Poland, Romania) show relatively larger residential (green) and services (blue) shares. By 2050, our pie-chart diameters shrink uniformly (normalized to their respective minimums/maximums in the legend), reflecting overall declines in projected demand under NC. The sectoral mix shifts modestly: industrial shares reduce slightly, while services and residential shares remain more stable. Geographically, Northern Europe (Sweden, Finland) maintains a noticeable industrial component despite lower total volumes, whereas Mediterranean countries exhibit pronounced transportation and residential slices, underscoring persistent reliance on mobility and building energy. Commitment dates (shaded 2040 or 2050, depending on the NECPs' planning horizons) do not radically alter pie-sizes but indicate earlier-committing nations generally exhibit somewhat smaller 2050 pies relative to later adopters. In 2025, emissions are higher in Germany, Poland, and Italy, driven by substantial transportation (red) and industrial (yellow) shares (in line with the respective consumption). Western countries like France and Spain have comparatively lower pies due to larger renewable uptake. Northern states (Sweden, Finland) show small but significant residential (green) and services (blue) emissions. By 2050, pie sizes shrink dramatically across all countries, reflecting the aggressive NC decarbonization, yet transportation remains a consistent share, especially in Southern Europe. Eastern EU members (e.g., Bulgaria, Romania) still display sizable industrial emissions slices, indicating slower phase-out of fossil-heavy processes. Notably, early-commitment countries (shaded lighter grey) achieve more pronounced emission reductions by 2050 than those committing in 2050 (darker shaded grey), highlighting the impact of earlier policy implementation on decarbonizing national energy consumption.

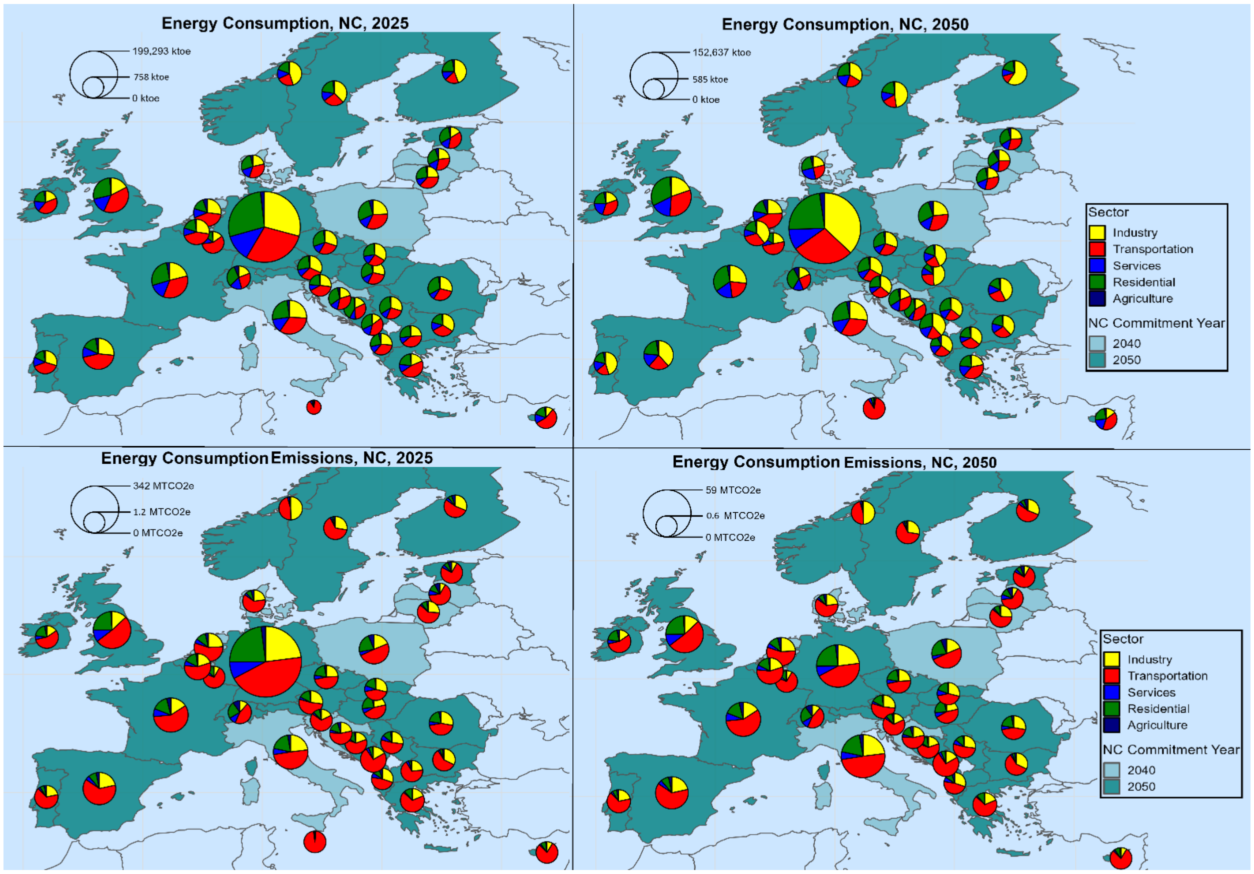


Figure 7. The evolution of energy consumption, according to the NC scenario: In 2025 (upper left) and 2050 (upper right), along with the respective GHG emissions in 2025 (bottom left) and 2050 (bottom right), per sector. To accommodate the scale of the pie charts, they were normalized according to their min and max sizes, as indicated in the legend.

Figure 8 shows the per country results of the energy supply sources and their associated emissions. In 2025, Europe's largest energy suppliers (Germany, France, UK) exhibit sizable electricity generation shares (brown), while Baltic and Scandinavian countries display notable heat generation (dark green). Oil refining remains significant in Eastern and Southern countries (Poland, Italy, Spain, Greece), reflecting persistent domestic refinery activity. Green Hydrogen production (teal) is minimal overall. In 2025, supply-side emissions peak in Germany, Poland, and Italy, where electricity generation (brown) drives most CO_2 output, due to the large share of coal and natural gas in the electricity generation mix. Oil refining contributes substantially in Eastern Europe and the UK.

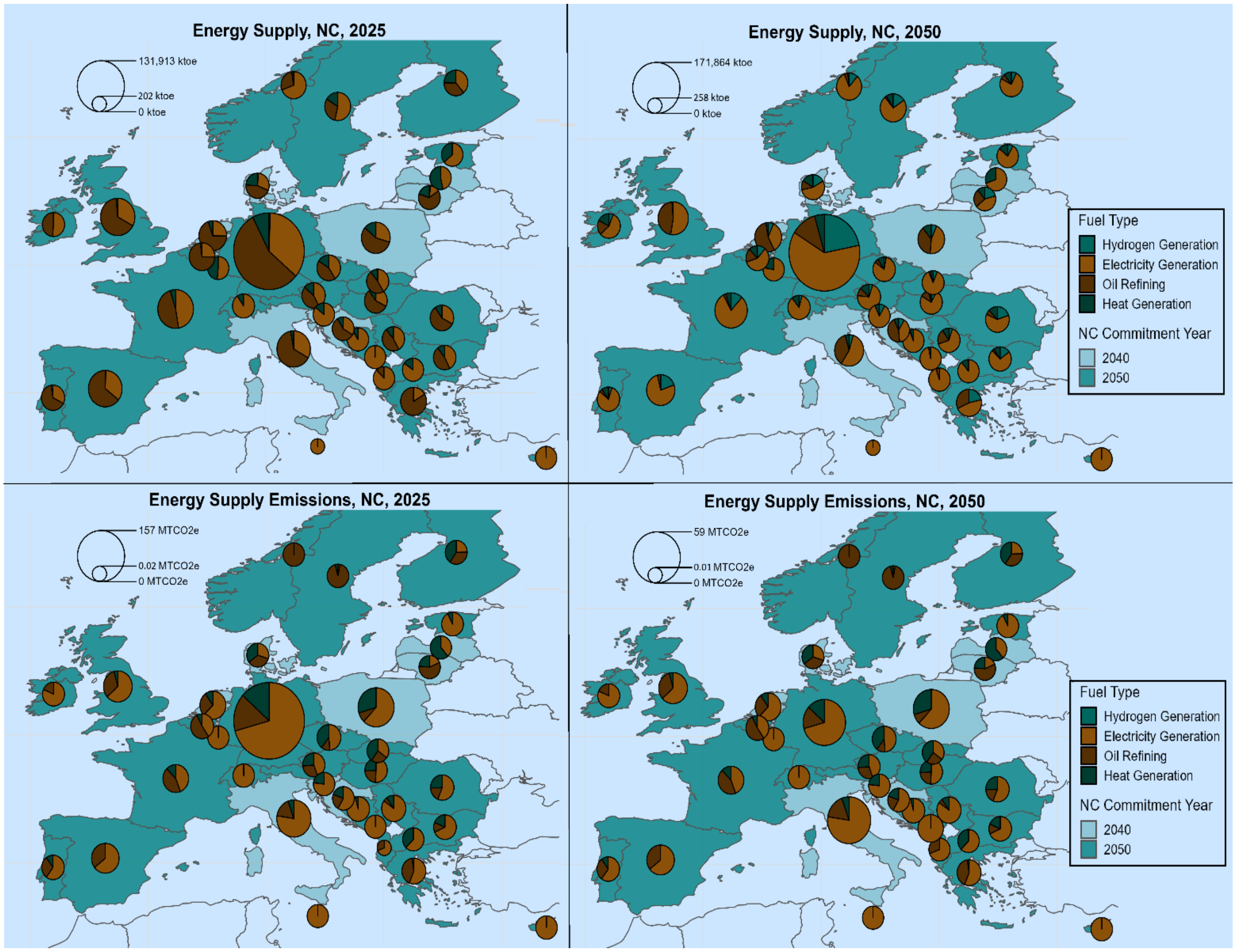


Figure 8. The evolution of energy generation from the main supply sources, according to the NC scenario: In 2025 (upper left) and 2050 (upper right), along with the respective GHG emissions in 2025 (bottom left) and 2050 (bottom right), per sector. To accommodate the scale of the pie charts, they were normalized according to their min and max sizes, as indicated in the legend.

By 2050, the NCs project a general grow in the share of hydrogen, especially in Northern Europe (Sweden, Finland) and Central Europe (Germany, Austria), indicating a regional pivot toward hydrogen. Electricity generation remains dominant in all countries, while the share of oil refining decreases significantly. Eastern and Southern countries still rely more on oil refining in 2050 compared to their Northern peers, highlighting divergent decarbonization speeds. The respective NC-projected emissions in 2050 are significantly lower than the 2025 levels, (pie-sizes are normalized to min/max), with Germany and the UK reducing electricity emissions most, while Northern European nations use renewables and have minimal remaining emissions. Eastern and Southern states (e.g., Poland, Romania, Greece) still have visible oil refining emissions, indicating lagging decarbonization. Hydrogen's clean production yields near-zero emissions, so countries with larger hydrogen slices in 2050 (e.g., Sweden) exhibit negligible supply-side emissions compared to fossil-dependent peers.

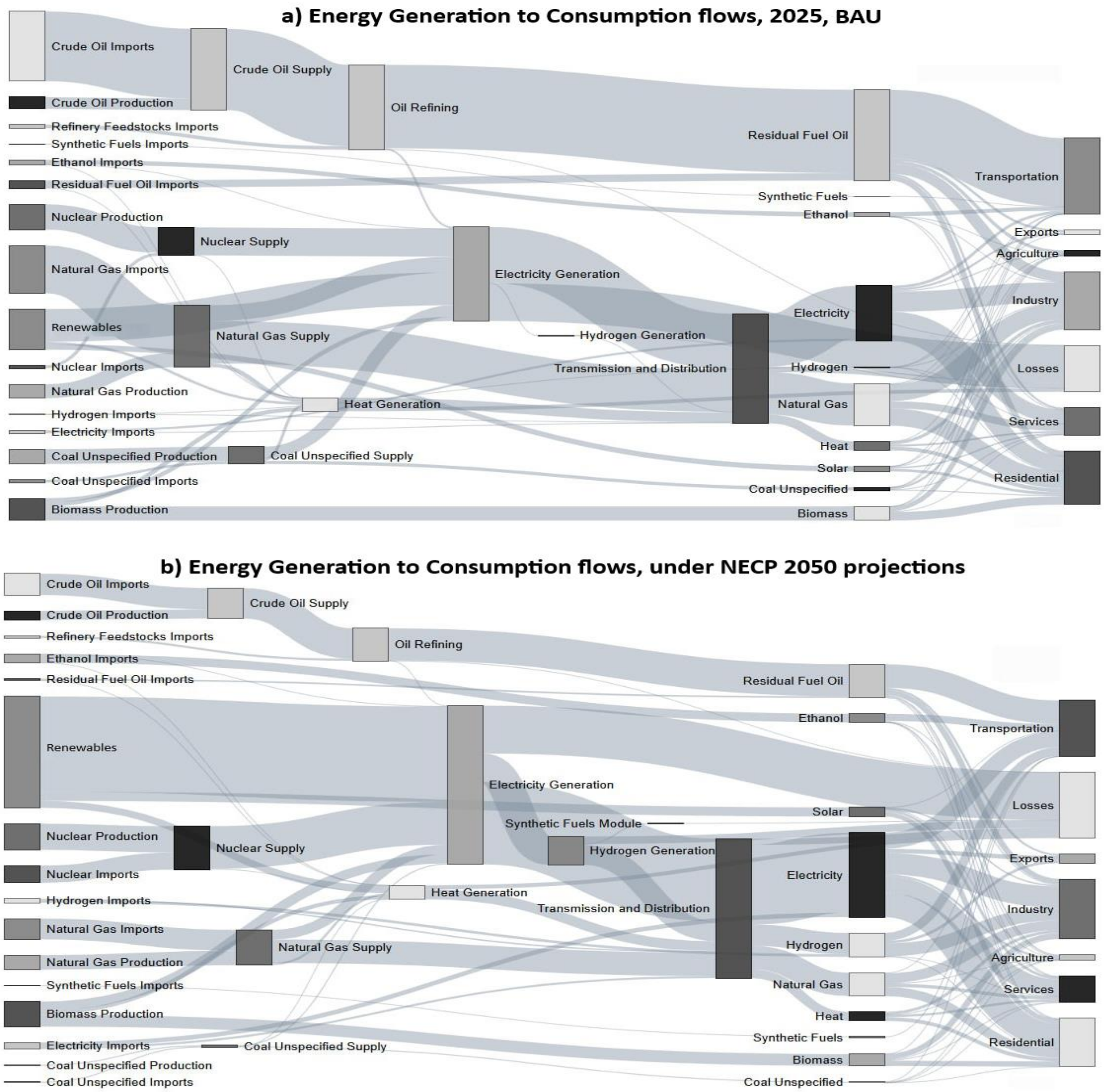


Figure 9. Sankey diagrams for the energy generation and consumption flows in 2050, for the BAU (a) and the NCPP scenario (b), for the whole of Europe.

In general, regarding the total GHG emissions, the primary driver of the reductions in the total emissions (both from energy consumption and energy generation) is the significant decrease in fossil fuel use across the residential, industrial, and transportation sectors, which is one of the core recommendations of the NECPs. Additionally, the adoption of renewable energy sources in electricity production further contributes to these reductions.

Under the BAU scenario (Fig.9a), Europe's energy system remains heavily reliant on fossil imports (crude oil and natural gas flow into large refining and gas-fired power plants) supplying transport, industry, and buildings with residual fuel oil, natural gas, and a modest share of renewables and nuclear. Electricity generation is dominated by gas and nuclear, with renewables playing a secondary role, and hydrogen is negligible. In contrast, the NECP 2050 projection (Fig.9b) reveals a dramatic transformation: renewables supply the bulk of electricity, displacing gas and oil; solar and biomass enter the end-use mix; hydrogen generation ramps up alongside a new synthetic fuel module; and oil refining shrinks to serve niche transport segments. Electricity becomes the primary carrier for residential, services, and industry, while transport increasingly uses hydrogen and synthetic fuels. Imports of fossil feedstocks vanish, reducing supply-side emissions. These flows underscore the feasibility of deep decarbonization (provided massive investments in renewables capacity, grid expansion, hydrogen infrastructure, and synthetic-fuel facilities are achieved) and highlight the need to phase out legacy fossil assets, bolster system flexibility, and secure supply chains for low-carbon fuels.

Biofuel Production Potential

As mentioned, the agricultural output results of the FABLE Calculator are analyzed through the BiofuelGCH Calculator, to account for the residues available for biofuel production (without affecting food production), and estimate this potential. This refers to the amount of bioethanol (produced from corn, sugarbeets, and wheat residuals), and the amount of biodiesel (produced from sunflower and olive residuals). So, it does not take into account the wooden and pellet potential production, which is however the major use of biomass for residential heating and cooking. Table A2 in the Annex provides in detail the biofuel production potential (min-max range) and the per-sector projected demand. The results are summarized in Figure 10.

The results indicate that by 2050, major biofuel demand centers (Germany, France, Spain, Italy, and Sweden) show transportation as the dominant consumption sector, reflecting large vehicle fleets and agricultural needs. Northern countries (Finland, Sweden) and Southern states (Spain, Greece) face pronounced import requirements due to limited domestic feedstock. In contrast, Eastern and Central Europe (Bulgaria, Romania, Hungary, Croatia) reveal production potentials comfortably exceeding modest local demand, enabled by larger agricultural land and strong biomass yields.

Spain, Italy, Germany, Sweden, Finland, the Netherlands, Norway, and the UK should invest in advanced biofuel feedstock conversion (e.g., second-generation ethanol, waste-to-fuel), remediation of marginal lands, and precision agriculture to boost yields, reduce production costs, and replace substantial import dependencies. On the other hand, Bulgaria, Romania, Hungary, Croatia, Portugal, Lithuania, Latvia, and Slovenia could redirect a share of their exportable biofuel output toward domestic transportation or industry (e.g., blending mandates), supporting local decarbonization with perhaps previously overlooked ways. Overall, Europe’s biofuel import-export balance indicates an ongoing need for net imports (around 2-5Mtoe), underscoring a need for both expanded domestic capacity and strategic imports.

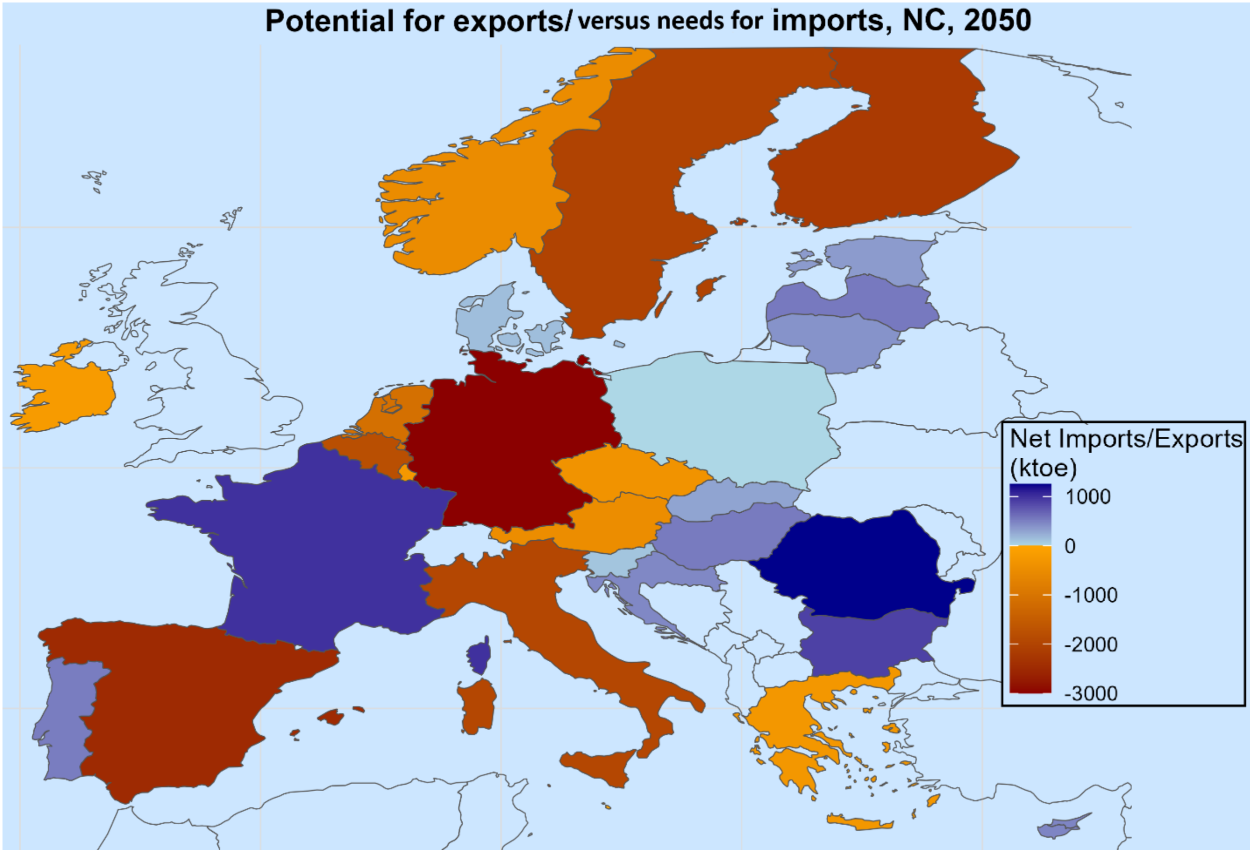


Figure 10. The biofuel potential for export (positive values) or need for imports (negative values), per country under the NC scenario, in 2050.

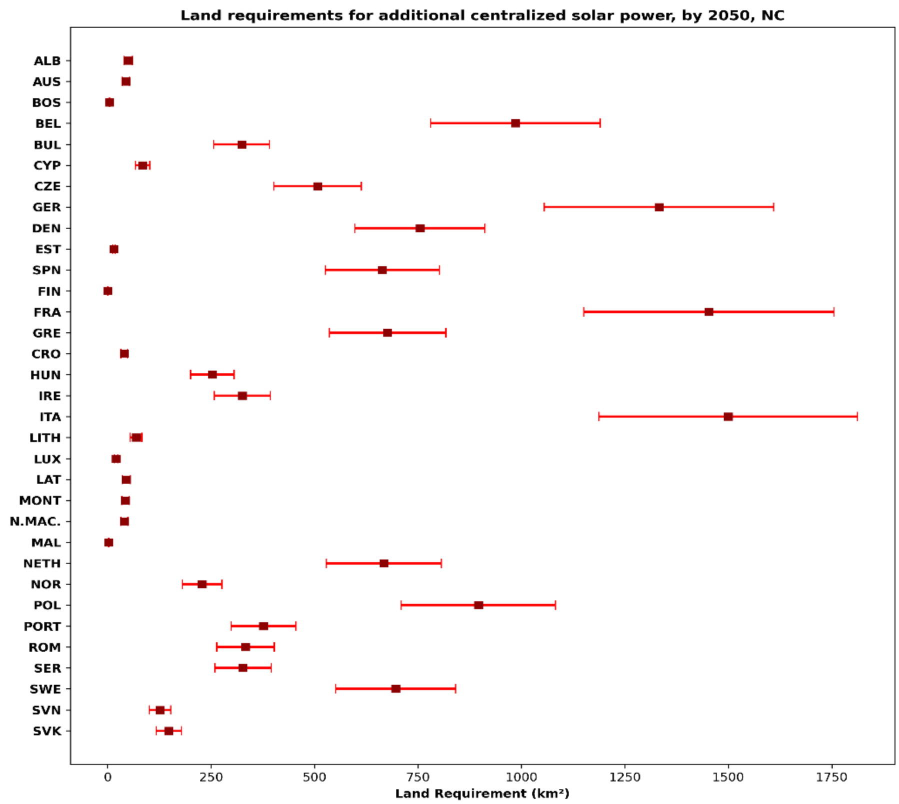
Land Requirements

The implementation of the NC, as simulated in LEAP, provides also results on the requirements for renewables over the planned years. In particular, it is important to further scrutinize the additional needs in solar energy and wind power by 2050, as these will shape the need for land to install them, beyond the offshore infrastructure. Table A3 in the Annex provides detailed information on the existing and the NECP-projected capacity in solar and wind power in their target year.

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

Figures 11 and 12 illustrate the land and respective cost requirements for the expected renewable infrastructure according to the NECPs. The projected land requirements for centralized solar installations by 2050 under NC vary widely across Europe, from as little as 0.236 km^2 in Finland (reflecting a small population and lower baseline demand) to nearly 1,500 km^2 in Italy. It is worth noting that these additional land (and cost) needs are not estimated or considered in the NECPs; however, the results of the LandReqGCH model indicate that these can be important factors and constraints, echoing previous relevant considerations at national scales (Geissler et al., 2022; Penca et al., 2025). In particular, in large countries, such as France (≈1,453 km^2) and Germany (≈1,332 km^2), the areas required for solar power represent only about 0.2–0.4 % of national territory, so they account for relatively modest shares. However, in smaller, densely populated countries like Belgium (≈986 km^2, nearly 3% of its 30,000km^2 land area) or the Netherlands (≈667 km^2, roughly 15 % of its 4,475 km^2), dedicating this much land exclusively to solar and/or wind farms would compete heavily with agriculture, urban areas, and/or protected landscapes. Onshore wind requirements are generally far smaller than solar ones, yet these footprints still must be sited in regions with favorable wind regimes, often prime agricultural or forested areas (Becker & Thrän, 2018). For instance, Romania's ≈40 km^2 of wind versus 333 km^2 of solar reveals that wind can alleviate some pressure on cropland, but grid and community acceptance issues remain (Jijie et al., 2021). Of course, this is an issue in several other countries, but receives limited attention and coordination in most national policies (Bertsch et al., 2016; Batel, 2018; Segreto et al., 2020). Nordic states exhibit minimal land demands for wind power, reflecting a combination of lower demand growth with significant offshore wind potential (Hjelmeland & Nøland, 2023; Jåstad & Bolkesjø, 2023).

The LandReqGCH model also provides estimates of the expected costs for the installation of these projects, considering their typical costs (EWEA, 2010; Tamesol, 2023). The projections of the NECPs indicate that (most countries by 2050), would need to invest in solar deployment from roughly €0.35 billion (Finland) to over €2.2 billion (Italy and France), reflecting large capacity targets. For major economies [e.g., Italy (€2.25 bn), France (€2.18 bn), Germany (€2.00 bn), and Spain (€0.996 bn)] these figures for solar power investments, represent only about 0.5–1% of their projected GDPs, suggesting financial feasibility, provided competing priorities (e.g., grid upgrades, industrial decarbonization) are balanced. Smaller economies like Belgium (€1.48 bn) or Greece (€1.01 bn) face proportionally larger burdens for solar power expansion relative to GDP, requiring careful budget allocation or external support. Onshore wind costs are far lower, reflecting also the land requirements: Spain (€60 mil.), Poland (€40 mil.), and Sweden (€29 mil.) dominate wind expenditures, yet relative to their GDPs, these are negligible (<0.1 %), indicating wind projects can be highly cost-effective. Overall, while aggregated investments in renewables are substantial, they remain realistic if integrated into multi-sector budgets and supported by EU funds and/or private capital.



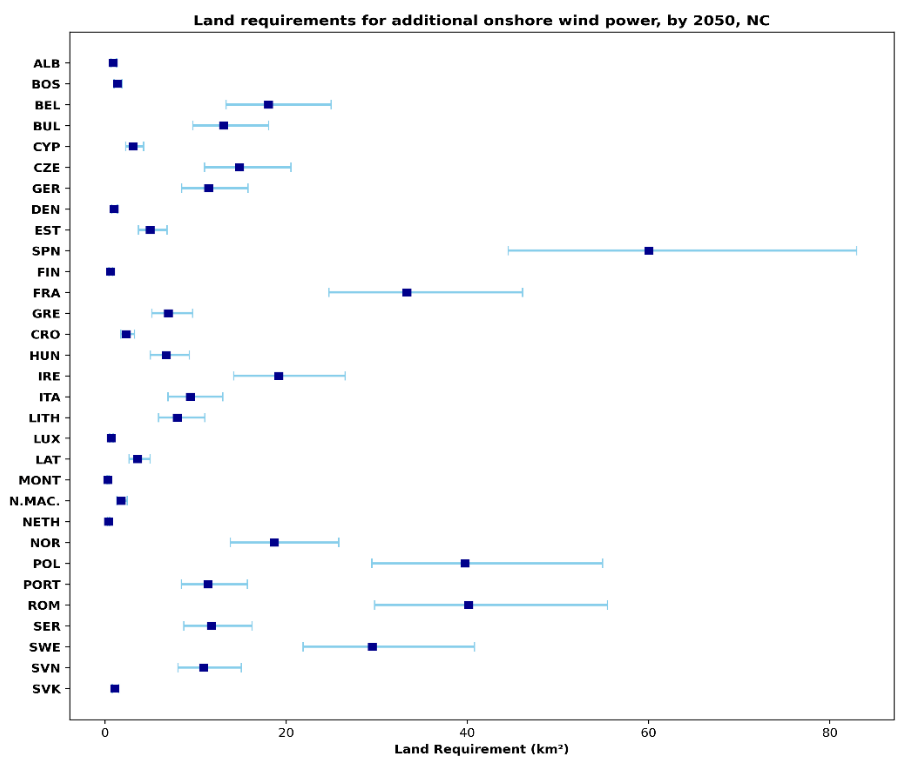


Figure 11. The required land for the installation of additional centralized solar panels (upper) and onshore wind farms (lower) by 2050, according to the NC. [No data: SWI, UK, AUS and MAL for wind].

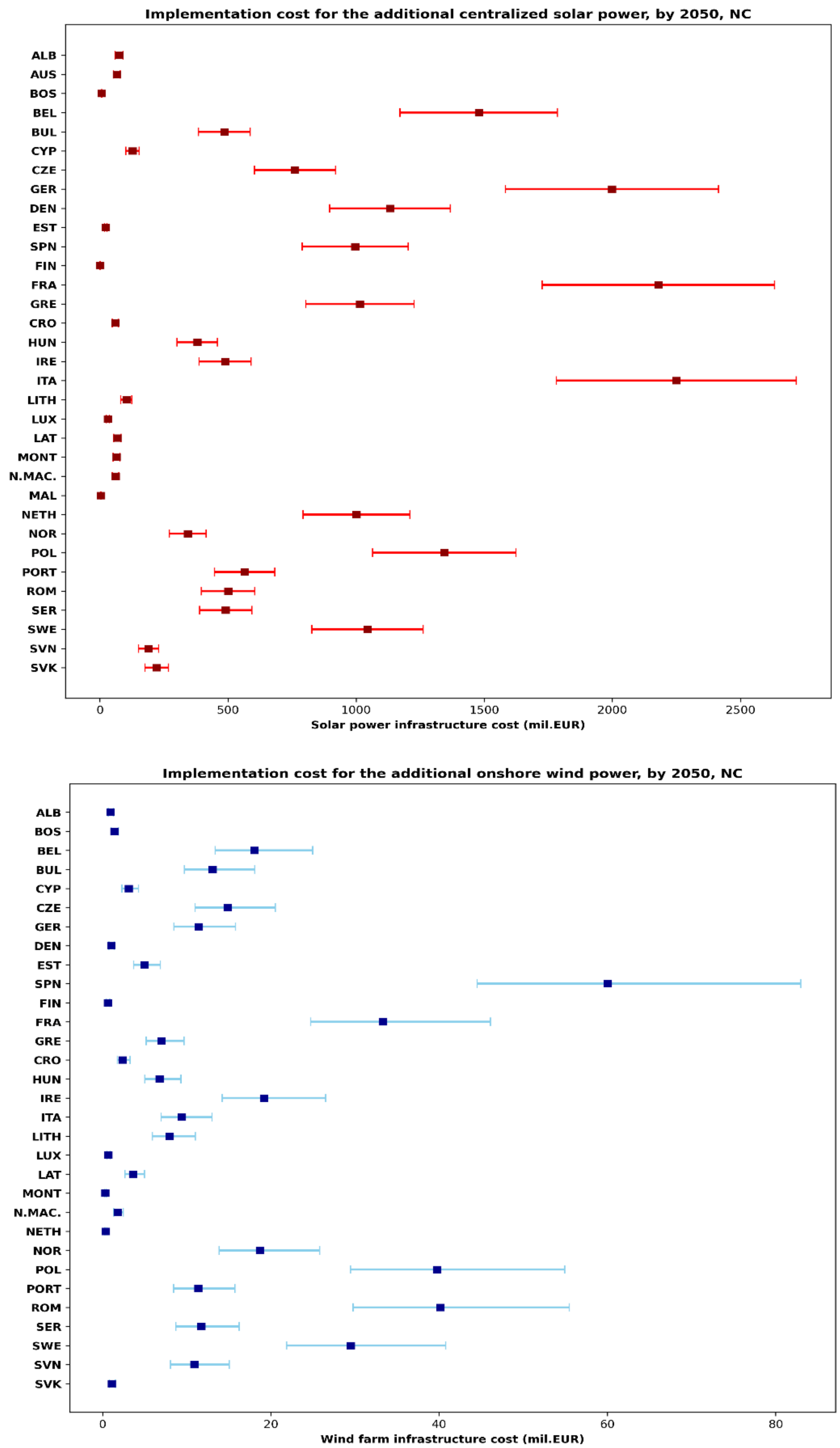


Figure 12. The required costs for the installation of additional centralized solar panels (upper) and onshore wind farms (lower) by 2050, according to the NC. [No data: SWI, UK, AUS and MAL for wind].

Water Requirements and Supply Results

The WaterReqGCH model was applied for all sectors and years of the studied period. The water sector faces the higher uncertainties, as consumption is affected by various socio-economic, infrastructure, and hydro-climatological factors that are inherently uncertain. The synthesis of the water requirements per sector and the supply sources is presented in Figures 13 and 14, while the detailed breakdown of sectoral demand and per source abstractions with the uncertainty ranges are presented in the Annex (Fig.A1-A3).

The results indicate regional and sectoral distinctions. In Southern Europe (e.g., Spain, Italy, Greece), agriculture dominates (Spain averages ~16,792 hm^3 and Italy ~11,161 hm^3) over urban and industrial withdrawals. France and Romania also exhibit strong agricultural demand (~15,360 hm^3 and ~2,293 hm^3, respectively), although France's industrial share (~7,041 hm^3) is significant. By contrast, Northern and Western European economies lean heavily on industry and services (e.g. Germany's large industrial water needs, as well as the Netherlands). Nordic states such as Sweden and Finland have modest agricultural and livestock use (<108 hm^3 and <30 hm^3, respectively), but high industrial or energy-related demand. Eastern Europe, Poland and Hungary show balanced profiles: Poland's industry and agriculture are both substantial. Balkan countries, like Bulgaria and Serbia, reflect strong industrial draws and variable agriculture. Smaller economies (Luxembourg, Malta) have minimal agriculture and industry, focusing on urban and services uses. These patterns illustrate how climate, crop intensity, economic and industrial structure shape water demand across Europe.

Regarding water supply, Southern European countries exhibit heavy reliance on groundwater, reflecting extensive irrigation in arid zones (Wriedt et al., 2009; Alamanos, 2021b). In contrast, Northern and Western Europe depend predominantly on surface water. Desalination and reuse are minimal, but regionally concentrated (e.g. Cyprus, Malta, Sweden pilots desalination) (Speckhahn & Isgren, 2019). Bosnia-Herzegovina leverages modest reuse (300 hm^3), as well as Austria (585 hm^3). Most other countries show zero desalination or reuse, indicating untapped potential. Overall, supply patterns align with climate, hydrology, and infrastructure (Alamanos, 2021a).

Historical data show that both sectoral water demands and source-based supplies have remained primarily stable over the last decade. Year-to-year fluctuations seldom exceed 5%, with a few exceptions. As a result, it is reasonable to assume that present demand–supply balances might be also similar in the near future, barring major structural changes (for instance, a nationwide shift to drip irrigation or a large-scale desalination rollout). Forecasting future water use or availability falls however outside this study's scope.

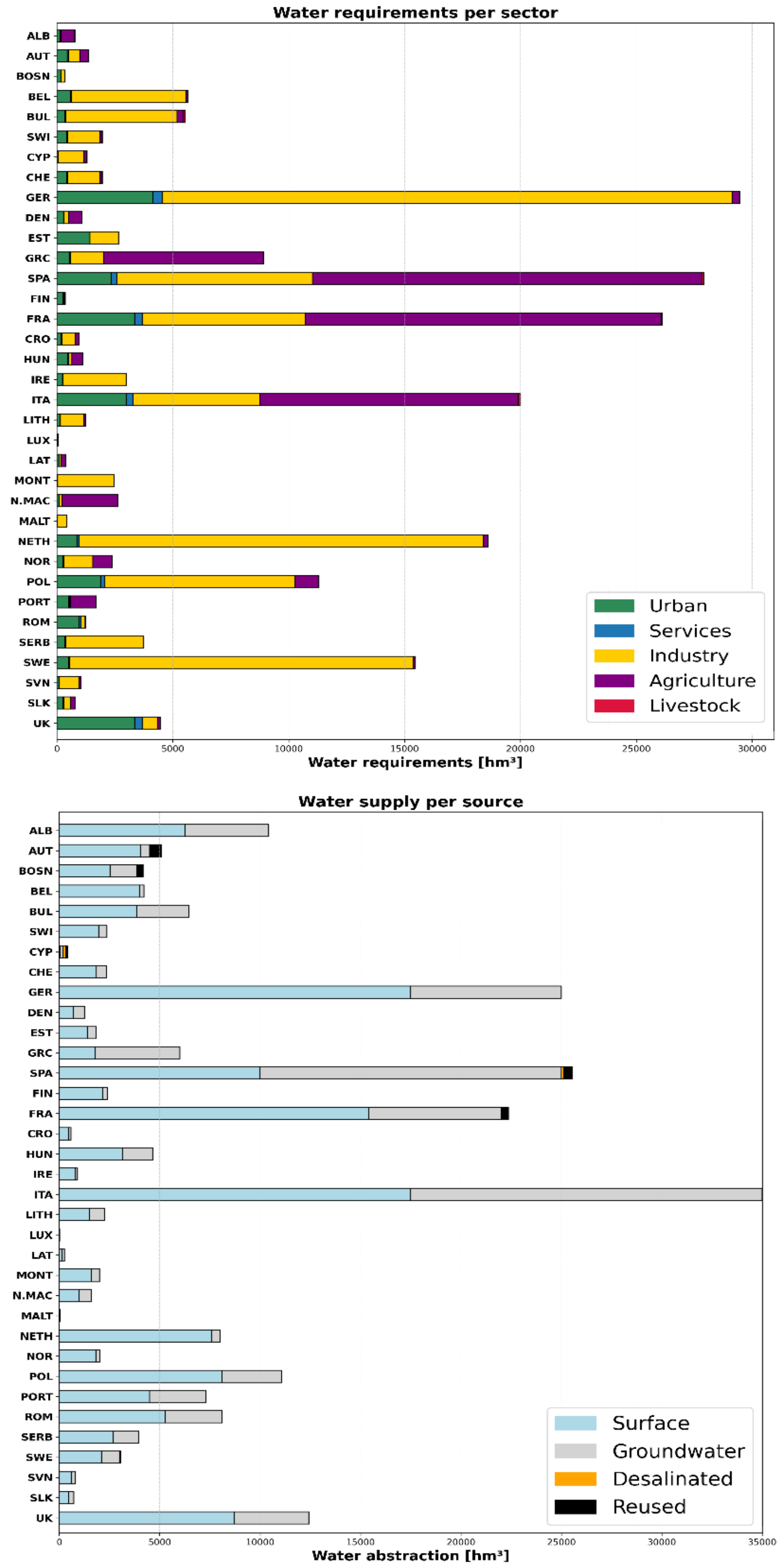


Figure 13. Typical annual water consumption (average for the period 1970-2022) per sector (upper), and per supply source (lower).

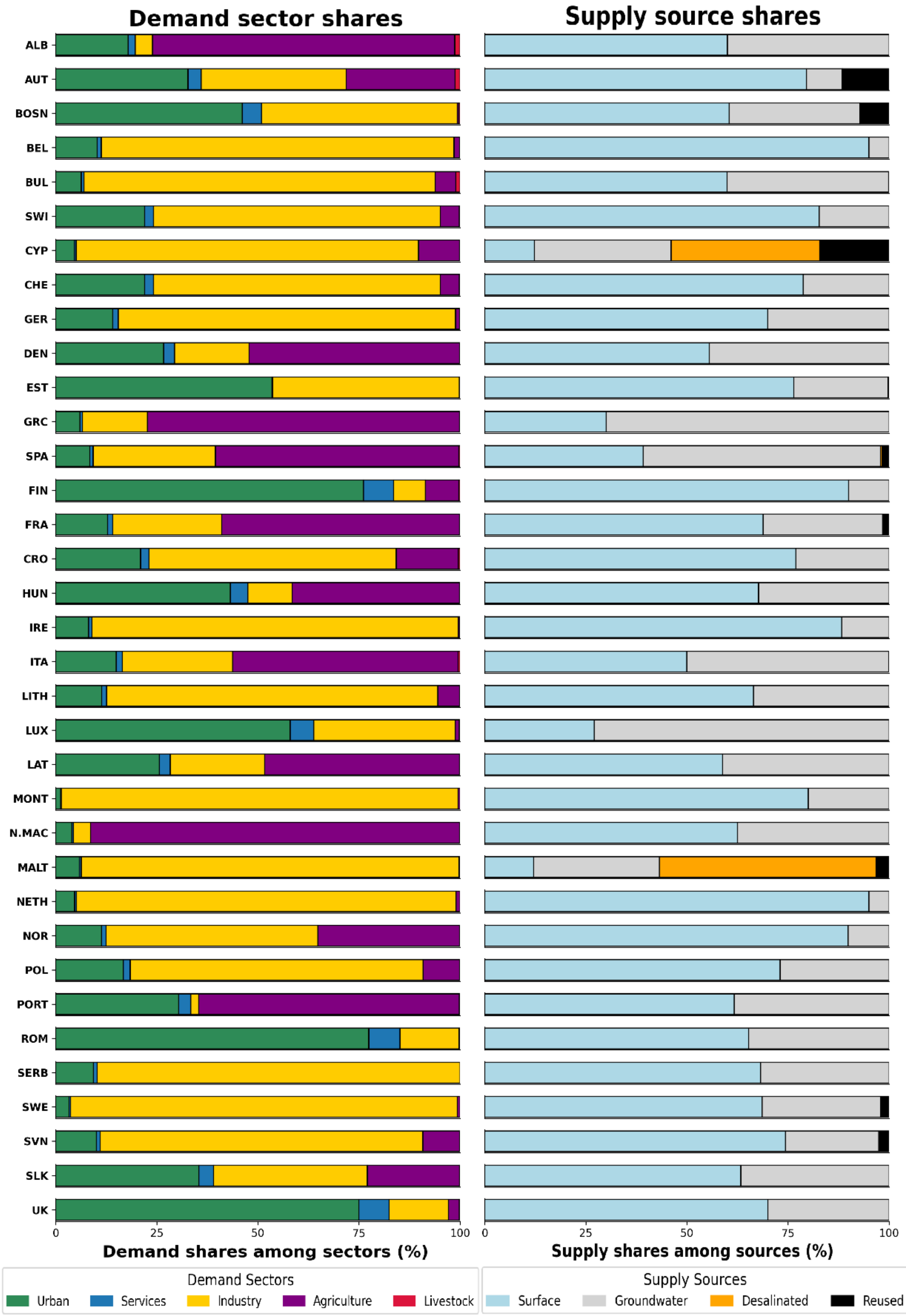


Figure 14. Percentage shares of the typical annual water consumption (average for the period 1970-2022) per sector and supply sources.

The water supply-demand balance (Fig.15) indicates that there are distinct regional patterns across Europe. A few Southern and Eastern Mediterranean states such as Italy, Romania, Bosnia, and Portugal exhibit large surpluses, mainly because of rainfall patterns and high river inflows (e.g. Alps, Danube, Carpathian basins) (Schiller et al., 2010; Aili et al., 2019). Mid-latitude countries with balanced economies, like Austria (3,706 hm^3), Hungary (3,542 hm^3), or Finland (+2,039 hm^3), maintain modest surpluses due to mixed industrial–agricultural profiles and rich surface or groundwater resources (Hietala et al., 2023). Smaller deficits appear in Croatia (−368 hm^3), Slovenia (−237 hm^3), and Ireland (−2,097 hm^3), reflecting potential water use inefficiency, moderate tourism and service-sector demands (Alamanos & Linnane, 2021; Ferina et al., 2021). By contrast, densely industrialized or cooling-intensive economies show sizable deficits, such as the Netherlands and Sweden, driven by manufacturing and energy cooling, or Germany and France, which rely on imports or shared river basins to satisfy large industrial and agricultural withdrawals (Krause & Bronstert, 2007; Malmquist, 2025). Mediterranean countries are in general more stressed, and the islands (Cyprus, Malta) depend heavily on desalination and external sources yet still run slight deficits (Cleridou et al., 2014; Hartfiel et al., 2020).

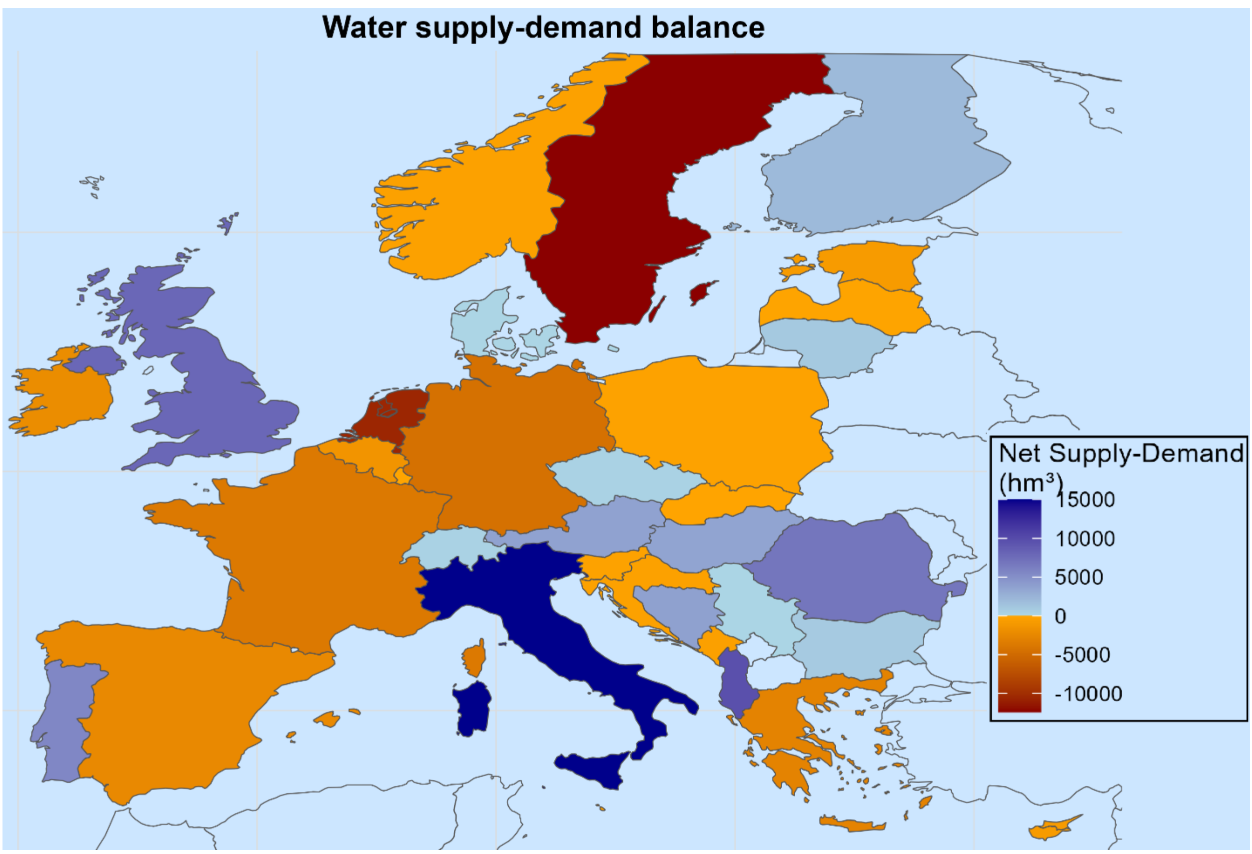


Figure 15. The per country total supply-demand estimated water balances.

Neither the NC nor the River Basin Management Plans (RBMPs) impose binding restrictions on total withdrawals or sectoral allocation that would alter these baseline values. Although RBMPs identify water-stress areas and outline general "good-status" objectives, they lack concrete, quantified constraints on withdrawals for individual sectors (or alternative "what-if" scenarios that would change water-use volumes in any of the five sectors) (Jager et al., 2016). Consequently, we cannot simulate an alternative scenario (e.g., X% cut in agricultural or other abstraction, or supply sources) based on any parameter within the RBMP framework itself. This absence of enforceable, sector-specific targets even as the NC references climate impacts constitutes a critical gap (Terrado et al., 2016; Koundouri et al., 2024).

The Assessment of the National Energy and Climate Plans (NECPs)

As mentioned, the core policy framework at the national level that is designed to address climate neutrality is the NECP. Table A1 in the Annex summarizes the 35 NECPs reviewed in a comparative way. This review reveals both elements of coherence, but also elements that need further attention to avoid policy inconsistencies.

Regarding the degree of readiness (Final/Draft plans), of the 35 countries that we examined, 28 have developed and submitted a final NECP. Only 7 of them, namely Bosnia and Herzegovina, Belgium, Estonia, Croatia, Montenegro, Poland and Slovakia, have not yet submitted a final NECP. It is noted that both EU Member States and the Energy Community members had the obligation to submit their final NECP, having taken into consideration the assessment and recommendations of the Commission and the Energy Community Secretariat, by 30 June 2024.

As far as the planning horizon is concerned, we found that the majority (19) of the countries (Albania, Austria, Bosnia and Herzegovina, Belgium, Bulgaria, Switzerland, Czechia, Germany, Greece, Estonia, Croatia, Hungary, Ireland, Italy, Montenegro, North Macedonia, the Netherlands, Romania and Serbia) have set in their NECP 2050 targets. Ten (10) countries, namely Denmark, Finland, Lithuania, Luxembourg, Latvia, Malta, Portugal, Sweden, Slovenia and Slovakia, provide in their NECPs projections until 2040, whereas 6 countries, namely Cyprus, Spain, France, Norway, Poland and the UK include in their NECP 2030 projections, but have or are developing their long-term strategy (LTS status) for 2050.

While assessing the 35 NECPs to simulate them in LEAP, we observed that there were some differences in the approach they follow towards net-zero. Some countries emphasize their "supply-side", the primary consumption per fuel, including mainly electricity, natural gas, renewables, hydrogen (6 countries, namely Albania, Czechia, Estonia, Croatia, Portugal and Romania); Some countries emphasize their "demand-side", the reduction of energy consumption per sector (9 countries, namely Bosnia and Herzegovina, Finland, France, Lithuania, Montenegro, North Macedonia, Malta, Sweden and Slovakia). A more "balanced" analysis of the energy supply and demand sides across multiple sectors, including buildings, households, industry and transport, is provided by most countries (19 countries: Austria, Belgium, Bulgaria, Switzerland, Cyprus, Germany, Greece, Denmark, Spain, Hungary, Ireland, Italy, Luxembourg, Latvia, the Netherlands, Poland, Serbia, Slovenia and the UK). Finally, Norway follows an emissions-based approach as it mainly focuses on the reduction of GHG emissions, without discussing explicitly supply- and or demand-side measures.

Similar differences are observed in the planning of imports/exports. Figure 16 summarizes the simulated evolution of the energy imports/exports according to the NECPs, focusing indicatively on electricity (a potential product of renewable energy), and green hydrogen (an emerging green fuel). The NC scenario can shift electricity trade patterns between 2025 and 2050. France and Sweden emerge as net exporters (blue), while Italy and Germany run significant deficits (red), reflecting combinations of heavy demand

and less domestic low-carbon capacity. By 2050, France's surplus grows even larger as other countries decarbonize, while Germany remains a major net importer despite expanding renewables. Southern states (Spain, Italy) reduce their deficits moderately, aided by solar and wind growth. Regarding hydrogen, 2025 shows early exporters like France and the Netherlands (blue), contrasted by Germany's deep import needs (dark red) as it builds demand before scaling domestic production. By 2050, France becomes the main green hydrogen hub, followed by the Scandinavian countries and the Netherlands. Overall, we observe that the total electricity deficit more than doubles (54 TWh in 2025 vs 115 in 2050), while the corresponding deficit in green hydrogen sharply increases as well (11 TWh in 2025 vs 79 TWH in 2050). This raises significant concerns about the feasibility of the existing NECPs.

We have also observed several inconsistencies between projected installed capacity, generation, consumption and expected net imports/exports of electricity and green hydrogen by 2050 in four (4) countries, namely Croatia, Denmark, Lithuania, and Poland. The reasons for these inconsistencies vary. Croatia seems to underestimate the necessary net electricity imports to support domestic electricity consumption and planned green hydrogen generation. The Netherlands seems to expect to switch from net electricity importer to net exporter without building (or analyzing the progress for) the necessary capacity to meet demand. In the case of Lithuania, there is an expectation to become net exporter in both markets (electricity and hydrogen), but based on the planned investment in power generation capacity this is feasible only in one of the two markets. Finally, Poland underestimates its net exports potential in both markets, implying that they cannot exploit the full potential of the projected installed electricity capacity.

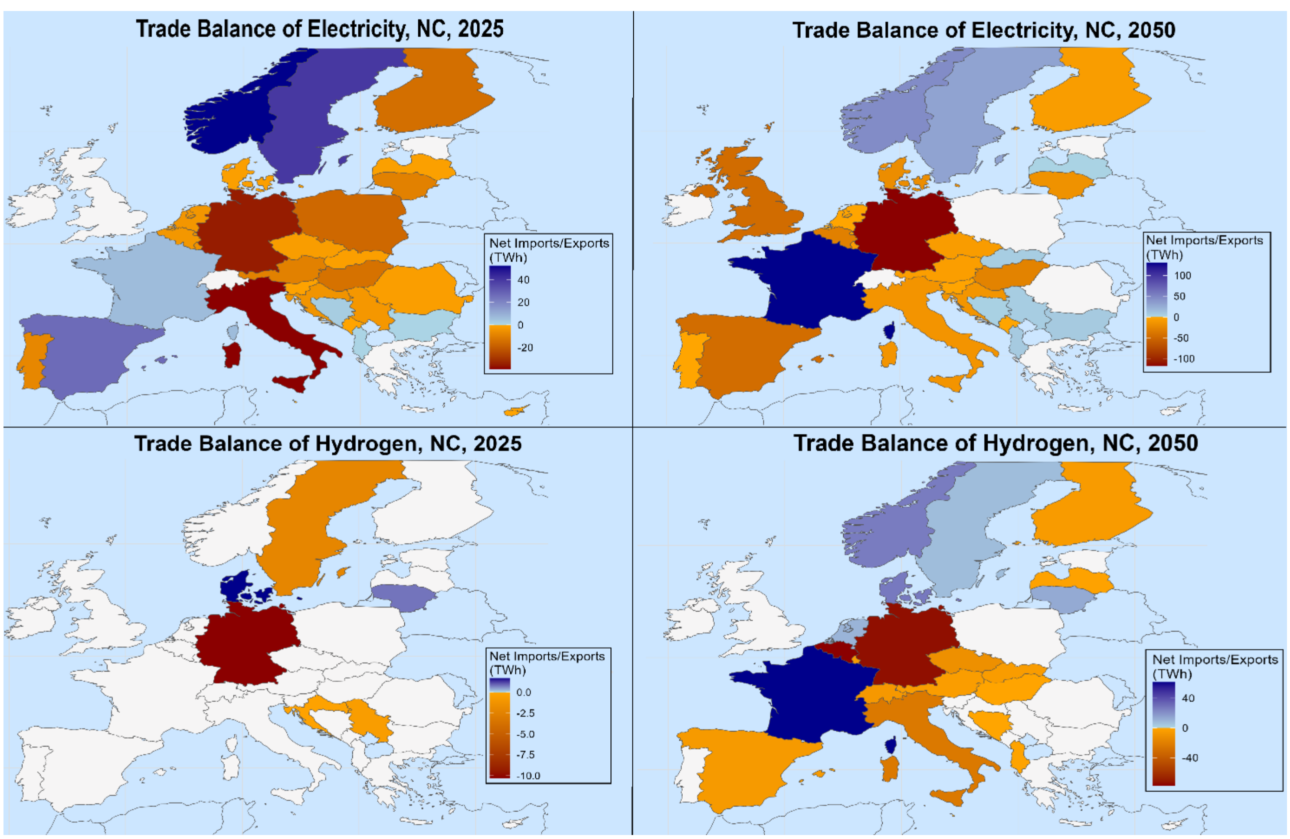


Figure 16. Trade balance maps, indicatively in 2025 and 2050, for electricity (upper row) and green hydrogen (bottom row).

Regarding the level of detail in the different NECPs, on data and ways to achieve the long-term net-zero emissions target, we observed again differences. Only seven (7) countries (Albania, Bulgaria, Czechia, Greece, Hungary, Montenegro, and North Macedonia) have conducted a very detailed analysis in their NECPs, providing extensive data to support their policies and measures toward climate neutrality by 2050. On the other hand, nine (9) countries (Bosnia and Herzegovina, Belgium, Germany, Estonia, Finland, Latvia, the Netherlands, Poland, and Sweden) have not provided a detailed analysis or sufficient data. In addition, nine (9) countries (Spain, France, Croatia, Ireland, Italy, Lithuania, Norway, Slovakia, and the UK) have followed a descriptive approach in their NECPs, supplying the least amount of relative data. These patterns largely reflect differing institutional and financial drivers, with Southern-Eastern countries being more "finicky" than Northern-Western ones. The former countries, still integrating EU frameworks or reliant on Cohesion and Just Transition Funds front-load, tend to detail technical data to demonstrate compliance and "absorption capacity" and justify external funding (Streimikiene et al., 2007; Dani & Haan, 2008)[5]. In contrast, wealthier, long-standing EU members tend to house their deep sectoral analyses in specialized energy and climate strategies outside the NECP itself (e.g., Germany's Energiewende documents, Sweden's green transition plans). Their NECPs serve more as high-level roadmaps, with granularity delegated to parallel plans, hence the descriptive format and apparent "lack" of data, even though highly granular analyses may exist elsewhere (Oppermann et al., 2021).

Furthermore, from our analysis we have identified some geographic patterns. For instance, the 'wealthier' countries of Western and Northern Europe (Germany, France, the Netherlands, Belgium, Denmark, Sweden, Finland, Austria, Ireland, and Luxembourg) have set very ambitious GHG emissions reduction targets, compared to the Southern and Eastern ones. Germany stands out as the only country bound to achieve climate neutrality by 2045. Denmark is also aiming to reduce its GHG emissions by 110% in 2050 compared to 1990 levels. These countries generally benefit from robust technological readiness and secure infrastructure: high-capacity grids, sophisticated energy storage, and mature supply chains for renewables and hydrogen (IEA, 2024). Their strong trade relations also help absorb shortfalls or export surpluses of low-carbon technologies (Den Elzen et al., 2022). Consequently, they can adopt more aggressive targets with confidence that domestic manufacturing, interconnection capacity, and import–export frameworks will support rapid deployment, grid stability, and resilient supply chains through 2050.

5. Discussion: Limitations, Gaps, Fragmented Approaches, and Policy Implications

The analysis presented here, including the NC frameworks and their integrated modelling reveals several trade-offs that must be considered. The examined policies (NECP, CAP, RBMPs) face challenges due to differing planning horizons, target years, and implementation responsibilities. As noted, there are even inconsistencies across the different NECPs. Such fragmented approaches can lead to scattered efforts and potential inefficiencies in achieving Europe's sustainability goals.

[5] Bulgaria, Hungary, Greece and Czechia rely heavily on EU grants for infrastructure upgrades, so they need more robust analysis to secure support from the Modernization Fund, Just Transition Fund, and recovery grants. In essence, "detail" becomes a way to make a stronger case for external financing.

Limitations

First, it is important to acknowledge the limitations of our effort to simulate the NC from an integrated modelling lens. Specifically, we treated Europe as a single, closed system; however, it is a realistic (and necessary way) to explore its NC, as expressed under a common framework for all Member States, the NECPs. Also, in our current setup, countries are modeled independently within LEAP, without any simulation of cross-border energy flows (e.g. imports/exports). This approach, however, mirrors the way NECPs conceptualize Europe, with most countries outlining their national targets and strategies without accounting for specific import/export dynamics. While the presented integrated modelling approach overall aligns with the structure of the NECPs, and thus realistically reflects their framing, it inherently restricts the analysis by omitting the interconnected nature of real-world energy markets. So, practically, no economic data such as prices and other marker data were considered (also in the modelling of biofuels, land requirements, water analysis, potential assessment of other economic policies). This is, however, the objective of our ongoing and future research, with the development of a CGE to complement and extend all models presented here. In addition, several assumptions were necessary due to the lack of detailed data within many NECPs, particularly regarding sector-specific technological pathways or timing of investments. Lastly, the NC scenario simulation is based on the assumption that the NECPs are fully implemented, which in turn requires certain behavioural changes (e.g. adoption of technologies to improve energy efficiency and mixes of cleaner fuels). Even if this is achieved, it is worth noting that not all NECPs achieve complete decarbonization by 2050, there are still emissions, but significantly lower.

NECPs and Other Frameworks

Next, we provide specific gaps identified in this analysis. In particular, the current NECPs set targets for 2050 and sometimes 2030 or 2040, while CAP operates on a seven-year cycle (with the current one running from 2023 to 2027), and the RBMPs are updated every six years to manage water resources at the river basin level, and their third and final cycle ends in 2027. This misalignment in timelines and objectives can result in uncoordinated strategies, where policies may not effectively complement each other. Specific sectoral (and policy) trade-offs are discussed below.

NECPs among Different Countries

The NECPs across Europe exhibit differences in planning horizons, emission targets, granularity of analysis, and treatment of cross-border flows. While some countries set short-term milestones to 2040 or 2045, others extend goals only to 2030 or broadly to 2050, leading to misaligned timelines that complicate regional coordination. Targets themselves vary often, reflecting differing domestic priorities rather than a unified EU strategy. Moreover, wealthier Member States frequently submit high-level, narrative plans with limited data, whereas newer or less affluent members provide detailed projections but focus solely on national supply and demand without addressing imports or exports. This patchwork of approaches undermines collective progress, as energy markets and infrastructure inherently transcend borders.

Trade-offs with Agriculture

For the case of agriculture, most NECPs do not explicitly indicate technological and fuel mix changes to be considered. Our modelled NC scenario in the FABLE Calculator is actually more ambitious than the NECP itself, because it draws more upon the CAP and national land use policies. For instance, the European food policy aims for higher productivity and resilience, along with the decarbonization goals. The NC scenario in FABLE Calculator simulated such interconnected objectives like higher productivity, same land use, and lower emissions, suggesting that it is possible to achieve them and at a lower cost than the BAU. However, in some countries, this led to a slight increase in energy use (e.g. Greece, ~15%), while it cannot directly account for the potential increases in water use. The FABLE Calculator did not have solid restrictions on their potential expansion. So, there might be more feasibility constraints to achieve this target. In reality, the high productivity NC scenario can be water-intensive, especially for Southern countries, even if the irrigated areas do not expand, due to the expected drier climate, which increases crop evapotranspiration, demanding more irrigation.

Trade-offs with Land

Our findings indicate potential competition for land due to some NECPs' projected expansion of renewables. The NC scenario requires an increase of wind and solar power deployment by 2050. Land capacity and economic feasibility concerns were explored by the LandReqGCH tool, and the results were cross-checked with the CAP and national land use policies. It seems that no policy so far has considered in detail the potential land use requirements and conflicts with agriculture, forestry, biodiversity, smallholders and farmers' ownerships and interests, with the expansion of green energy and the respective expectations on decarbonization. Although in most countries our results show that it is feasible to cope with NC requirements, that would need careful planning. Realistically, large-scale solar farms in southern and western Europe will require creative land-use strategies, such as rooftop and parking-shade agrivoltaics, brownfield redevelopment, or dual-use systems, rather than carving out vast contiguous fields. Equally, wind projects should incorporate agro-pastoral coexistence models to sustain food production. Holistic land-use policies must integrate environmental protections, agricultural viability, and local community consent, ensuring that climate targets are met without undermining critical non-energy land functions.

The role of Biofuels

Biofuel production is an overlooked area in most NECPs, since little data and strategies were described. According to the BiofuelGCH tool, considering a conservative estimation of bioethanol and biodiesel production potential, we showed that several countries can cover the biofuel demand from certain uses and even export (while currently they might be importing). However, this production potential is outsized by a projected grow in demand, which according to most NEPCs is not accompanied by respective production planning (e.g. adoption of production technologies, or incorporation of biofuel production in farming processes). A gap from our analysis is the lack of planning in terms of allocation of produced biofuels to uses that can benefit from it. For instance, currently no policy considers their role in transportation (terrestrial or shipping) decarbonization, although their role has increased significantly with the IMO's FuelEU Maritime regulation that suggests their adoption and sets strict emissions controls.

The Water Sector

The analysis of the water sector (supply, demand, balance) highlights priorities for water policy and management across Europe. Countries that have particularly high dependance on a supply source should pursue diversified supplies, aiming to reduce their footprint, while countries that are intensive in certain consumptive uses should target their water-use efficiency. The biggest gap from the analysis was the inability to frame a NC scenario due to the lack of detail and unified supply- and demand- oriented measures by national policies. Under the EU Water Framework Directive (WFD), Member States are legally obliged to update and report their River Basin Management Plans (RBMPs) and associated Programmes of Measures every six years. However, delays in reviewing or reporting these plans have led to legal actions by the European Commission (some countries have been referred to the Court of Justice of the European Union), reflecting broader gaps in water governance. This inaction contributes to ongoing ecological degradation, as repeatedly emphasized by scientific studies, and undermines the EU's objectives for sustainable and integrated water resource management.

Policy Coherence

The implementation of the main policies considered (NECP, CAP, RBMPs) often falls under the jurisdiction of different ministries and regional authorities, such as Ministries of Environment and Energy overseeing the NECP, Ministries of Agriculture or Rural Development and Food managing the CAP, and Regional Authorities being responsible for the implementation of their respective RBMPs. Also, sectoral efforts towards climate-neutrality will be challenging, requiring the coordination of policies between Ministries of Environment and Energy, Ministries of Transportation, Ministries of Economics, along with divergent interests among private stakeholders. These fragmented governance structures have been hindering progress to several member-states as they can create siloed communication channels, challenging effective collaboration and integrated policy execution.

6. Recommendations

Drawing upon the findings of this assessment, we summarize the main policy recommendations in Table 3.

Table 3. Policy recommendations concerning sectors (first colour-block), countries (second colour-block), and regulatory frameworks (third colour-block). The order is indicative, and all recommendations are complementary.

Category	Recommendation
1. Industry sector, Energy	**Develop more comprehensive & diversified measures for industry sub-sectors:** Recognize the diversity of industrial subsectors by creating tailored roadmaps for steel, cement, chemicals, and other high-emission industries. Each roadmap should combine electrification, renewable power sourcing, energy-efficiency upgrades, and circular-economy practices. Encourage policymakers to move beyond single-technology fixes toward coordinated portfolios of measures that address each subsector's (e.g. steel, cement, etc.) unique energy and emissions profile.
2. Transportation sector, Energy	**Invest in public transport infrastructure:** Address policy fragmentation between development and transport portfolios by prioritizing large-scale rail upgrades, bus rapid transit corridors, and urban tram expansions. Strengthening government coordination, such as joint transport-land use planning, will speed up necessary infrastructure investments. Enhanced public transit networks will reduce reliance on private cars, cutting transportation emissions and alleviating urban congestion.
3. Transportation sector, Energy	**Promote adoption of cleaner fuels in transportation with equity:** Introduce incentives and regulatory mandates to increase the use of clean fuels (e.g. biofuel blends) in shipping and aviation. For instance, establish national blending requirements for sectoral transportation fuels and offer tax credits or direct compensation to airlines that integrate sustainable aviation fuels. This will ensure that biofuels help decarbonize hard-to-abate transport modes while meeting emerging emissions standards.
4. Agri-food sector, Energy	**Transformative agricultural practices beyond technology fixes:** Move from incremental improvements (e.g. optimized feeding and fertilizer application) to systemic changes that include dietary shifts and large-scale organic or regenerative farming. Integrate incentives for crop diversification, agroforestry, and reduced meat consumption into CAP and rural development schemes.
5. Biofuels1	**Expand advanced biofuel production in high-demand countries:** In countries with projected high biofuel demand (Spain, Italy, France, Germany, Sweden, Finland, the Netherlands, Norway, and the UK), invest in biofuel generation technologies and establish remediation projects on marginal lands.
6. Biofuels2	**Redirect exportable biofuel supply to domestic uses in surplus countries:** Countries with potential biofuel-export capacity (Bulgaria, Romania, Hungary, Croatia, Portugal, Lithuania, Latvia, and Slovenia) should allocate a portion of their production to meet domestic blending mandates in transportation and industry. Prioritizing local decarbonization needs rather than potential exports, internal markets for sustainable fuels and reduced fossil fuel consumption can be achieved in sectors that currently overlook biofuel use.
7. Biofuels3	**Link biofuel production projections to specific end-use applications:** Address the gap between forecasted biofuel output and concrete deployment by mapping biofuel yields to priority decarbonization sectors. For example, tailor national fuel planning to allocate volumes explicitly for land transport fleets, maritime shipping (under FuelEU Maritime rules), and selected industrial processes. This approach ensures that policy targets for biofuel production directly translate into measurable emissions reductions in the most relevant end-uses.

8. Cross-sectoral, Energy	**Integrate residential, services, and transit sectors within NECPs:** For example, synchronize funding for thermal retrofits of residential blocks with the rollout of district heating or rooftop solar, and coordinate this with public transit improvements. Adopting integrated energy–economy–urban planning models will ensure that efficiency measures, grid investments, and zoning regulations reinforce one another rather than being implemented in isolation.
9. Southern Europe, Energy	**Strengthen transport decarbonization in Southern Europe:** Southern Europe is marked by high private vehicle ownership, tourism flows, and limited rail networks, so transportation remains a challenge. Prioritize the expansion of intercity and urban public transit systems (e.g., regional rail, bus rapid transit). Introduce vehicle-scrappage incentives tied to electric or low-emission models, and coordinate road-pricing or low-emission zones to discourage fossil-fuel cars. Align infrastructure grants with local municipal transport plans, ensuring that new bus depots and charging hubs serve dense corridors to maximize ridership and slash tailpipe emissions.
10. Eastern Europe, Energy	**Target industrial emissions in Eastern Europe:** Key Eastern EU industries (steel, cement, chemicals) are large emitters. Many facilities are owned by foreign multinationals or joint ventures, driving an outsourcing trend by lower labor and environmental costs. Mandate comprehensive emissions reporting and introduce sector-specific decarbonization roadmaps, requiring annual reduction milestones (e.g., 10% CO_2 cut per five years). Offer tiered funding for clean-tech retrofits, while conditioning EU funds on visible progress. Strengthen labor retraining programs to support workforce transitions in high-emission subsectors.
11. Southern & Eastern Europe, Energy	**Refinery transition in Eastern and Southern Europe:** Despite declining demand, many Eastern and Southern European countries will still depend on oil refining in 2050. Target these refineries with dedicated support packages, low-interest loans or grants, to retrofit units into biorefinery hubs that process waste oils, biomass, or produce green hydrogen.
12. Southern Europe, Agri-food, Land & Water	**The agri-food sector in Southern Europe:** Balance increasing agricultural demand with limited resources and competitive land uses. Implement land-use zoning regulations, including areas marked for solar rooftops or agrivoltaic systems. Incentivize agroecological intensification (cover cropping, drip irrigation, and organic farming subsidies) to raise productivity on existing acreage. Water management plans to incorporate projections of energy, agriculture and land uses, accounting for induced water stress. Incorporate multi-criteria spatial planning tools so policymakers can balance food security, biodiversity, and renewable infrastructure without displacing critical farmland.
13. Cross-country considerations	**a)** **Accelerate action:** Early-commitment countries achieve more pronounced emission reductions by 2050. Accelerate commitments in lagging Member States. **b)** **Urban-driven sustainable growth:** Urban-dominated countries (especially those with high population densities) should urgently upgrade water distribution systems and align future city growth with sustainable, resilient water sourcing strategies. **c)** **Smart land use in densely populated countries:** Compact nations such as Belgium and the Netherlands should prioritize rooftop, floating, and agrivoltaic solar to reduce land-use conflicts with agriculture, urbanization, and conservation. **d)** **Support smaller economies with renewable investment needs:** Countries with smaller GDPs require targeted EU and international funding support to meet solar and wind expansion goals without straining public budgets.
14. NECPs1	**Unified 2050 planning horizon and deepen modeling:** All Member States should align their NECPs on a common 2050 endpoint for climate neutrality. Critically, countries must explicitly model cross-border trade in electricity, fuels, and low-carbon technologies (e.g., hydrogen). Harmonized timelines and richer data are highly recommended.
15. NECPs2	**Cross-border infrastructure and policy collaboration:**

	Governments must establish regular dialogue with neighboring countries to coordinate grid interconnections, shared renewable energy projects, and joint infrastructure investments and trade. This collaborative approach ensures that new capacity serves multiple markets efficiently and supports balanced electricity flows, ultimately lowering costs and enhancing grid stability across Europe.
16. NECPs3	**NECP transparency:** Member States should treat NECPs not just as funding applications but as fully transparent roadmaps[6]. Every country, regardless of GDP, EU-seniority, or administrative capacity, must include detailed sectoral data (e.g., technology costs, capacity trajectories, policy impacts, cost-benefit analyses) to enhance credibility and enable rigorous EU-wide assessments.
17. Agri-food & land policy	**Creative, multi-use strategies:** To minimize conflicts with agriculture and ecosystems, develop policies that promote rooftop and parking-shade "agrivoltaic" installations, brownfield redevelopment, and dual-use systems that combine solar or wind with grazing or small-scale farming. Holistic land-use guidelines must integrate environmental protections, maintain agricultural viability, and secure local community consent, ensuring renewable targets are met without undermining food security or biodiversity.
18. RBMPs	**Integrate RBMPs with sector-specific water assessments:** Current RBMPs lack enforceable, sector-specific targets tied to water stress. To close this gap, future RBMP updates should explicitly integrate cross-policy measures (such as the CAP's irrigation standards or EU industrial water-efficiency directives) so that scenario analysis can be grounded in real, enforceable measures. Without such linkages, neither NCs nor RBMPs can meaningfully project how policy reforms might reshape water demand or supply.
19. Cross-sectoral, Policy	**a)** **NECPs & CAP:** Embed CAP-funded rural development schemes within NECP frameworks. Tie farm subsidies to verifiable carbon targets, so that CAP payments reward energy- and environmental-friendly practices. The use of cross-sectoral scientific modelling tools is highly recommended. **b)** **NECPs & land-use planning:** Require each NECP to include a dedicated land-use chapter that sets binding urbanization boundaries aligned with CAP and national land-use policies, accounting for land requirements for renewables expansion, ensuring sustainable land use changes and consistent development. **c)** **Adopt a WEF Nexus in NECPs, CAP, and RBMPs**: Current water-scarcity hotspots should be prioritized for integrated planning of energy infrastructure, and avoidance of water-intensive energy projects and land-uses. **d)** **Cross-policy monitoring and enforcement:** Create a joint "Nexus Monitoring Committee" coordinating NECP, CAP, and RBMP updates, with common modelling tasks and planning horizons. This body would audit progress on water, land, and emissions targets in tandem and recommend mid-course corrections. **e)** **Unified Data Portal:** Develop a unified data portal where NECPs, CAP implementation reports, and RBMP status updates are published in a standardized format, enabling transparent tracking of how water availability, agricultural practices, and energy investments interact.
20. Equity considerations	Western and Northern European countries tend to set more ambitious net-zero goals, relying on robust technological readiness, secure grid infrastructure, and mature supply chains. In contrast, Southern and Eastern Member States often lack these advantages, making it harder for them to commit to or achieve equally stringent goals without additional support.

[6] The European Commission's Assessment of the NECPs itself discusses how several Member States use the NECPs as funding tools, especially those eligible for EU Cohesion Policy and Just Transition Fund support, which often requires detailed project pipelines and cost-benefit justifications. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0564

	a) <u>Targeted EU Funding:</u> Allocate a dedicated share of the EU's Just Transition and Recovery Funds to upgrade grids, storage, and renewable manufacturing in Southern and Eastern Member States, enabling them to build the infrastructure that underpins deeper decarbonization. **b) <u>Technology transfers:</u>** Establish pan-European purchasing consortia for solar panels, electrolyzers, and other clean-energy technologies, enabling poorer countries to benefit from bulk-purchase discounts and shared R&D. **c) <u>Capacity-building:</u>** Create specialized training and technical assistance centers funded by wealthier Member States or EU programs, to provide expertise in project development, permitting, and grid integration for renewables in lagging regions, supported by monitoring and accountability mechanisms. **d) <u>Cross-border renewable projects:</u>** Launch EU co-financing for interconnection projects and shared renewable installations (e.g., offshore wind farms serving neighboring grids), ensuring less-resourced nations gain access to low-carbon electricity without bearing the full infrastructure cost alone.

7. The role of finance and the P2R Adaptation Finance Catalogue

A crucial step in the realization of net-zero solutions is to be aware of the financial resources, and use them properly, or be able to request and manage the increased needs. In this last section, we mention a key tool to support such efforts, and explain its usefulness.

Implementing innovative solutions for decarbonization pathways and climate resilience requires, perhaps predominantly, financial resources. The double externalities associated with environmental actions and innovation render the market mechanisms inefficient and the traditional financial sources and instruments, in many cases, obsolete (Popp et al., 2010; Prasad et al., 2022). According to the IPCC 6th Assessment Report (2023) "*If climate goals are to be achieved, both adaptation and mitigation financing would need to increase many-fold. There is sufficient global capital to close the global investment gaps but there are barriers to redirect capital to climate action. Enhancing technology innovation systems is key to accelerate the widespread adoption of technologies and practices*".

Delivering the targets enshrined in NECPs and climate/land policies across the world is contingent on scaling up climate finance, despite the recent progress. According to CPI (2025) global climate finance reached an all-time high of 1.9 tr. USD in 2023, with mitigation finance flows doubling their 2018-22 average. Nonetheless, this development is lopsided, as it is concentrated in a handful of economies and sectors. Furthermore, adaptation finance represents less than 5% of global finance flows for the climate, with national and regional budgets being the main source for the crucial aspect of building environmental and socioeconomic resilience at the local level. The global adaptation finance gap is estimated at 215-387 bil. USD each year, whereas in Europe – the fastest warming continent- the gap is estimated annually at 18-64 bil. € (UNEP, 2024; World Bank, 2024).

A material aspect for regions and cities in building resilience through sound adaptation actions is the strong barriers associated with adaptation finance, both at accessing and leveraging financial resources.

Adaptation projects often do not yield tangible revenue streams (rather alleviate future costs), have highly uncertain outcomes and are local and/or context- specific in most cases. Combined with knowledge and awareness limits prevalent in regional and municipal authorities, this results in substantial under-financing and heavy reliance on public or EU sources. Having said that, diversifying financial sources and instruments is paramount for cities and regions striving to meet climate targets, both in adaptation and mitigation. Diversification of climate finance portfolios helps to unlock new capital and identify significant opportunities for public authorities, private enterprises and individuals. Nonetheless, stakeholders and policymakers are quite often overwhelmed with the bulk of uncollated information and data on the issue of financial sources and instruments and struggle to evaluate the most suitable options for their case.

A valuable tool in the case for diversifying adaptation finance options for cities and regions in Europe (and beyond) is the *P2R Catalogue for Adaptation Finance.* The Pathways2Resilience (P2R) project is an EU-funded initiative under Horizon Europe's Adaptation Mission, designed to support over 100 European regions in co-developing pathways towards climate resilience. In this process, it is developing a comprehensive catalogue of finance mechanisms, sources, and best practices. This catalogue aims to:

(i) raise awareness of the full range of adaptation finance available to regions,

(ii) support a shift to financing action by providing the data needed for regions to efficiently make decisions and develop Adaptation Investment Plans, and

(iii) increase the speed and efficiency of adaptation project development and reduce costs. The P2R catalogue contains a **nested taxonomy of 55 sources**, including public, private, and third-sector entities (Figure 17), and 61 financial instruments, classified by financial strategy and including traditional and innovative options (Figure 18).

It provides detailed, practice-oriented information on aspects like scalability, resource requirements, advantages and drawbacks, and relevance to specific Key Community Systems, enabling regions to select the most appropriate options and overcome barriers to accessing finance.

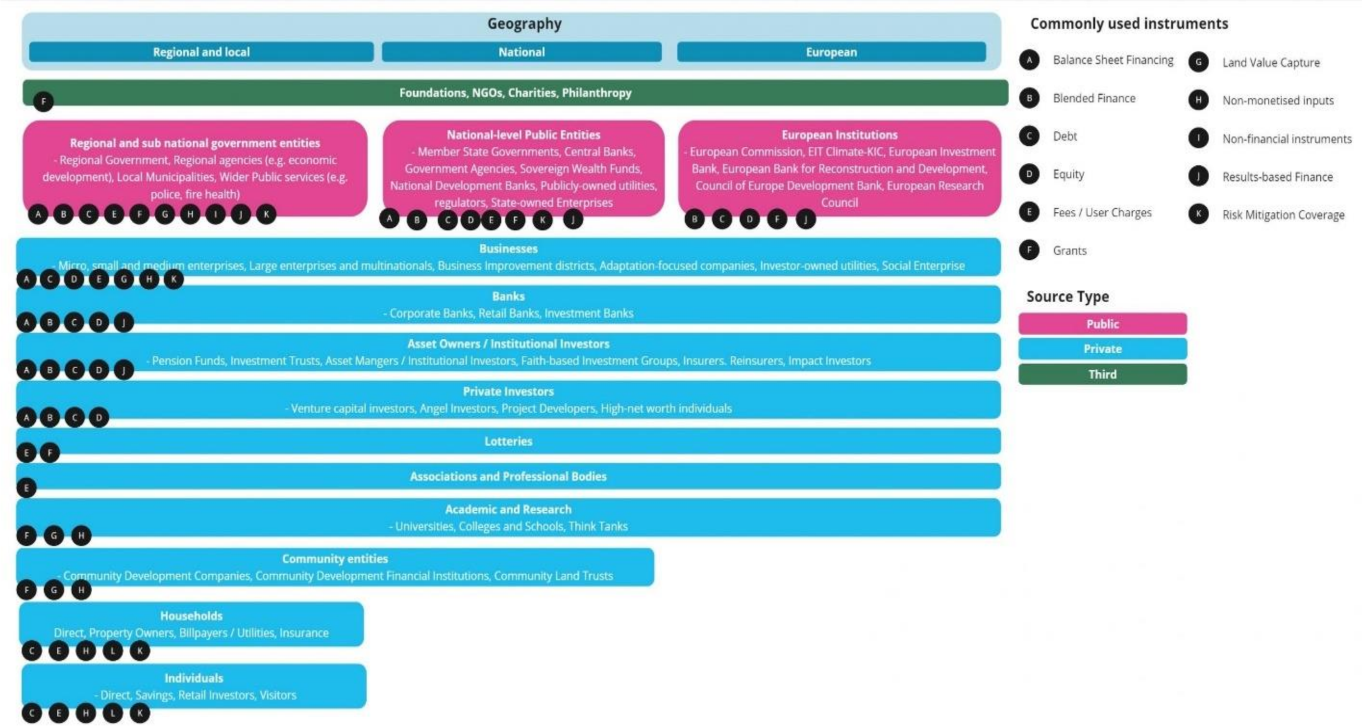


Figure 17. Sources for Regional Adaptation Finance.

The catalogue is available to all stakeholders in the P2R webpage: https://www.pathways2resilience.eu/finance-catalogues.

It has the form of a simple spreadsheet and offers a set of 169 case studies from across the globe to help regions and cities assess the replicability and efficiency of financial strategies mapped to local contexts. The process is enhanced for P2R participating regions through a bold capacity building program including guidance documents, an online toolbox and dedicated training sessions. Throughout this process, stakeholders are encouraged to document existing financial sources and instruments and browse through the catalogue for potential new mechanisms. In the final step towards developing finance adaptation pathways and bankable adaptation projects, regions outline the structural barriers that stifle diversification towards specific sources and instruments, as well as the tangible policy and structural changes that would help address them.

Figure 18: Instruments for Regional Adaptation Finance.

Despite the emphasis of Pathways2Resilience on scaling up finance for adaptation in Europe, the financial catalogue is a source for generic sources and instruments to fund climate projects, including adaptation. It is common knowledge that financing mitigation is much more straightforward as mitigation projects (e.g. renewable energy) have succinct revenue streams and more *conventional* business plans. Nonetheless, the finance gap persists in mitigation as well, and this warrants flexibility in the range of financial mechanisms available to national and regional authorities and private stakeholders. To this end, tools like the P2R catalogue can catalyze both adaptation and mitigation actions and underpin the policy recommendations outlined in Table 3.

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Annex

Table A1. The summary for the NECPs assessment and comparison

Country	Final/Draft (F/D) - Publication date	Plan-ning Horizon	Status of long-term strategy (LTS)	Fuel-focused (supply) / Consumption-focused (demand) / Balanced	Level of detail on achieving net-zero target	Reduction in GHG emissions target for 2030 (%)	GHG emissions target for 2050	Renewable energy share in total energy consumption by 2030 (%)	Renewable energy share in total energy consumption by 2050 (%)	Renewable energy share in total electricity generation in 2050 (%)	Total energy consumption in 2050	Account for reliance on imports (Y/N, quantity)	Export targets by 2050
Alb	F - 31 October 2024	2050	embedded in the NECP	Imports in fossils, exports in electricity	Very detailed	10.21	2.2 Mt CO2-eq. (excluding LULUCF)	59.4	73	93	111.7 PJ	600 ktoe=7 TWh in Fossils (oil+NG)	570 ktoe in Electricity
Aus	F - 20 December 2024	2050	currently updating the 2019 LST	balanced	Moderately detailed	48 compared to 2005	24,9 Mt CO2-eq. (excluding LULUCF)	56.8			884 PJ (data reported also per sector)	Y (1 TWh in 2050)	
Bosnia & Herz	D - 30 June 2023	2050	December 2020	consumption - focused	Little detail	53% compared to 2014	80% compared to 1990, 4.19 Mt	28	43	85	129 PJ	Y (12 TWh in fossils)	–
Bel	D - 4 December 2023	2050	March 2020		Little detail	15 compared to 2005	85% compared to 1990	22.6	56.6				
Bul	F - 15 January 2025	2050	submitted in 2022	balanced	Very detailed	10 compared to 2005	climate neutrality	34.96	85.50 (4 893 ktoe)	60 (80303 GWh)	6 544 ktoe (data reported also per sector)	Y (4.9% in 2050)	6010 GWh
Swi	F(Long-Term Climate strategy and Supplement) - 27 January 2021 and 29 January 2025	2050		balanced	Moderately detailed	65 compared to 1990 in 2035	net zero emissions			45,000GWh		N	
Cyp	F - 20 December 2024	2030	September 2022	balanced	Moderately detailed	32 compared to 2005	zero emissions	33.2	95		1996 ktoe		

Cze	F - 20 December 2024	2050	December 2019	fuel-focused	Very detailed	68.4 compared to 1990	96% reduction compared to 1990 (7.98 Mt CO2ek)	30	65	52	Graph 117	Y (hydrogen imports 36.7 TWh in 2050)	2.8 TWh (2043-2047)
Ger	F - 29 August 2024	2050	February 2019	balanced	Little detail	55 compared to 1990	GHG neutrality by 2045 - total GHG emissions with LULUCF 153 Mt CO2-eq.	41	88.8 (green hydrogen imports) 80.5 (hydrogen imports from exclusively non-renewable sources)		6,238 PJ (data reported also per sector)	Y (38.7% - 31311 MW in 2050)	28368 MW
Den	F - 1 July 2024	2040	December 2019	balanced	Moderately detailed	70 compared to 1990	110 compared to 1990	60 for EU target of 45%	2653,7ktoe in 2040 (82,3%)		17798 ktoe in 2040	Y (1969ktoe in 2040)	160 PJ
Est	D - 17 August 2023	2050	April 2017	fuel-focused	Little detail		95% reduction compared to 1990	65				Y	
Gre	F - 7 January 2025	2050	2019	Fuel-focused	Very detailed	58% reduction compared to 1990	98% reduction compared to 1990	43	95.8	100.8	13412 ktoe	Y (very detailed for all fuels)	424 ktoe in electricity
Spn	F - 26 September 2024	2030	December 2020	balanced	descriptive	55 compared to 2005	climate neutrality (at least 90% reduction compared to 1990)	48 (37.295ktoe)		100			
Fin	F - 1 July 2024	2040	April 2020	consumption - focused	Little detail	50 compared to 2005		62	464ktoe in 2040		21927ktoe in 2040	Y (4300GWh electricity in 2040)	
Fra	F- 10 July 2024	2030	March 2020	consumption - focused	descriptive	50 compared to 1990	net zero emissions		No estimated share of renewable beyond 2030.		decrease by 50 % compared to 2012		
Cro	D - 4 July 2023	2050	June 2021	fuel-focused	descriptive	50.2 compared to 2005	9 Mt CO2	42.5	65%	93	6334 ktoe	Y, fossils	
Hun	F - 16 October 2024	2050	updated 2021	balanced	Very detailed	50 compared to 1990 (47,5 Mt CO2e)	climate neutrality	30	62	32 TWh		Y	
Ire	F - 22 July 2024	2050	updated in 2024	balanced	Moderately detailed	42 compared to 2005	net zero emissions	43			11,541 ktoe	Y (60% in 2040)	
Ita	F - 1 July 2024	2050	February 2021	balanced	descriptive	43 compared to 2005	85 Mt CO2	38.7	42.3	69	95400	Y(54% in 2040)	
Lit	F - 7 October 2024	2040	update in 2021	consumption - focused	descriptive	≥70 compared to 1990	100	55	95			Y	43.000 tonnes of

													green hydrogen
Lux	F - 24 July 2024	2040	November 2021	balanced	Moderately detailed	55 compared to 2005	climate neutrality	37			29 168GWh in 2040	Y (60,7% electricity dependancy in 2040)	
Latvia	F - 15 July 2024	2040	2019	balanced	Little detail	65 compared to 1990	climate neutrality	62	82,7 (2040)		3331 ktoe (2040)	Y (19,6% in 2040)	
Mont	D - December 5th, 2024	2050	embedded in the NECP	consumption - focused	Very detailed	27 compared to 2022	0.40 Mt CO2	39.17	50.7	100	614 ktoe	Y (fossils)	n
North Mac	F - 31 May 2022	2050	embedded in the NECP	consumption - focused	Very detailed	51 % compared to 1990	3.3 MtCO2	35	57.2	95.9	2517 ktoe	Y (fossils + 8% electricity)	N
Mal	F - 7 January 2025	2040	October 2021	consumption - focused	Moderately detailed		carbon neutrality	24.5				Y in 2030	
Neth	F - 26 June 2024	2050	December 2019	balanced	Little detail	46-57 compared to 1990	95% reduction	30.5			55046 ktoe	Y (72% in 2040)	
Nor	F - 8 January 2021	NECP 2030, long-term strategy (LTS): 2050	October 2020	emissions focused	descriptive	50-55 compared to 1990 (Norway's target of being climate neutral from 2030 onwards)	90-95 reduction compared to 1990					N	
Pol	D - 5 March 2024	2030	not submitted	balanced	Little detail	35 compared to 1990		29.8				Y (2030)	
Port	F - 10 December 2024	2040 NECP, 2050 LTS	June 2019	fuel-focused	Moderately detailed	43	carbon neutrality (2045)	51	88	100		65% in 2030	
Rom	F - 16 October 2024	2050	embeded to NECP	fuel-focused	Moderately detailed	85% compared to 1990	13.8	36.2	86.1	86.9	16512	Y (Renewables)	NG+ oil products = 82%
Ser	F- 25 July 2024	2050	embeded to NECP	balanced	Moderately detailed	33.3 compared to 1990	13.2	33.6	64.53	90.6	9537 ltoe	Y (35%)	Oil products
Swe	F- 1 July 2024	2040	December 2019	consumption - focused	Little detail	50 compared to 2005		67				Y	
Slovn	F- 7 January 2025	2040	March 2020	balanced	Moderately detailed	35-45 compared to 2005	0 (Figure 83)	33 (with a view to significantly increasing the share of RES by 2040 (and 2050) at the next update of the NECPs)				Y	

Slovk	D- 6 September 2023	2040		Demand	descriptive	~55% compared to 1990	16.25	not available data	32.7	no data for electricity generation	6910 (estimated)	Y(fossils)	–
UK	F - 31 January 2020	2030	Energy and emissions projections 2023 to 2050 report (December 2024)	balanced	descriptive		net zero emissions	22-29				Y in 2050	

Table A2. The biofuel production potential (min-max), and the demand for biofuels use under the NC scenario. In case of excess production potential, we assume that this amount can be exported (black font, last column); otherwise it needs to be imported (red font, last column).

COUNTRY	Biofuel Demand for Consumption, NC, 2050 (ktoe)					Biofuel Demand for Energy Transformation, NC, 2050 (ktoe)	BiofuelGCH - Production Potential (min-max), 2050 (ktoe)	Comments [Black = potential for exports, Red = need for imports]
	Industry	Transportation	Services	Residential	Agriculture			
Alb	0.0	22.0	0.0	0.0	50.0	0.0	No Data	-
Aus	158.8	1133.4	1.0	0.0	6.6	0.0	641-1010	Slow increase in biofuels demand by 2050, which cannot be covered from the potential domestic production - need to import ~500ktoe.
Bosn-Hrz	0.0	0.0	0.0	0.0	10.8	0.0	No Data	-
Belg	601.9	1300.0	0.0	1.1	130.0	15.9	234-369	Small increase in biofuels demand by 2050, which cannot be covered from the potential domestic production - need to import ~1800ktoe.
Bulg	0.0	123.0	0.0	0.0	15.2	0.0	848-1336	Moderate increase in biofuels demand by 2050. Domestic production can fully cover all (small) uses, and even export ~900ktoe.
Swi	107.5	650.0	0.0	0.0	0.0	0.0	No Data	-
Cyp	0.5	11.9	0.1	0.0	8.5	0.0	478-750	Small increase in biofuels demand by 2050. Domestic production can fully cover all (small) uses, and even export ~480ktoe.

Cze	147.5	935.9	0.0	0.0	39.1	0.0	602-949	Moderate increase in biofuels demand by 2050, which cannot be covered from the potential domestic production - need to import ~370ktoe.
Germ	64.3	2058.8	8.3	1.9	850.3	18.2	144-358	Can fully cover all uses, except for transportation & agriculture - need to import ~ 3000ktoe. Same pattern for the period 2022-2050.
Den	250.0	164.3	0.0	0.0	20.0	0.0	241-381	After 2035 can cover all uses, and gradually export up to 145ktoe. Increasing biofuel production potential from 2030-2050.
Est	0.0	34.1	0.0	0.0	0.0	0.0	345-544	Small increase in biofuels demand by 2050. Domestic production can fully cover all (small) uses, and even export ~350ktoe.
Sp	214.6	2962.4	1.0	527.0	67.7	0.6	831-1618	High demand for biofuels, which cannot be covered from the potential domestic production - need to import ~2500ktoe. After 2025 the biofuels demand sharply increases.
Fin	1289.8	1242.0	10.0	50.0	0.0	0.0	271-416	High demand for biofuels, which cannot be covered from the potential domestic production - need to import ~2200ktoe. After 2025 the biofuels demand sharply increases.

Fra	86.0	3697.0	17.0	0.0	258.0	43.6	3440-5297	Can fully cover all uses, and even export from 60-1912ktoe in 2025 up to 74-1933ktoe in 2050.
Gre	0.0	770.3	0.0	0.0	0.0	0.0	268-519	Gradual large increase in biofuel demand, which cannot be covered from the potential domestic production, especially after 2035 - need to import ~300ktoe.
Cro	0.2	17.7	0.0	0.0	19.5	0.0	432-681	Small increase in biofuels demand by 2050. Domestic production can fully cover all (small) uses, and even export ~460ktoe.
Hung	0.0	250.8	0.0	0.0	0.0	0.0	711-1120	Moderate increase in biofuels demand by 2050. Domestic production can fully cover the use, and even export ~540ktoe.
Ire	0.0	293.0	0.0	0.0	37.4	0.0	20-34	Gradual large increase in biofuel demand, which cannot be covered from the potential domestic production - need to import ~200ktoe.
Ita	40.0	4000.0	20.0	0.0	80.0	806.1	2302-3628	Gradual increase in biofuel demand, which cannot be covered from the potential domestic production - need to import ~1950ktoe.
Lith	0.0	160.0	0.0	0.0	0.0	0.0	499-786	Gradual increase in biofuel demand by 2050. Domestic production can fully cover all (small) uses, and even export ~400ktoe.

Lux	0.0	300.0	0.0	0.0	0.0	0.0	20-31	Small increase in biofuels demand by 2050. Need to import ~270ktoe.
Lat	0.0	31.0	0.0	0.0	5.0	0.0	493-778	Moderate increase in biofuel demand by 2050. Domestic production can fully cover all (small) uses, and even export ~550ktoe.
Mont	0.0	3000.0	0.0	0.0	2000.0	0.0	No Data	-
North Mac.	0.0	64.0	0.0	0.0	10.0	0.0	No Data	-
Malt	0.0	20.0	0.0	0.0	1.0	0.0	2.4-3.8	Small increase in biofuels demand by 2050. Need to import ~18ktoe.
Neth	100.0	1300.0	20.0	10.0	80.0	0.0	317-500	Moderate increase in biofuel demand by 2050, which cannot be covered from the potential domestic production - need to import ~1110ktoe.
Nor	77.4	584.7	17.2	0.0	4.0	25.2	11-18.4	Sharp increase in biofuel demand after 2025, which cannot be covered from the potential domestic production - need to import ~400ktoe in 2025 up to ~695ktoe in 2050.
Pol	20.0	1589.0	30.0	30.0	200.0	0.0	1064-1665	Gradual increase in biofuels demand by 2040. There is potential to marginally cover the demand.
Port	11.4	351.6	0.0	0.0	1.0	0.0	700-1103	Moderate increase in biofuel demand by 2050. Domestic production can fully cover all uses, and even export ~530ktoe.

Rom	0.0	739.1	0.0	0.0	11.0	0.0	1821-2870	Moderate increase in biofuel demand by 2050. Domestic production can fully cover all uses, and even export ~1250ktoe.
Serb	0.0	40.0	0.0	0.0	0.0	0.0	No Data	-
Swe	859.8	1074.8	59.1	104.3	51.6	0.0	99-139	Gradual increase in biofuel demand after 2025, which cannot be covered from the potential domestic production - need to import ~2030ktoe. Same pattern over the 2025-2050 period.
Slov	0.0	86.0	0.0	0.0	0.0	0.0	155-244	Moderate increase in biofuel demand by 2050. Domestic production can fully cover the use, and even export ~110ktoe.
Slvk	0.0	86.0	0.0	0.0	1.0	0.0	375-590	Moderate increase in biofuel demand by 2050. Domestic production can fully cover the uses, and even export ~300ktoe.
UK	67.1	7325.7	0	0	20	0	No Data	-

Table A3. The existing capacity (2022 data) and the NECP-projected requirements in solar and wind energy, in MW.

Country	Solar capacity, 2022	Wind capacity, 2022	NECP-proj. Solar, 2050	NECP-proj. Wind, 2050	Comments
Alb	0	0	1700	350	Target year: 2050.
Aus	2500	3500	-	-	There is no info in the NECP. But the expected electricity generation from SolarPV=35 TWh and from onshore Wind=27TWh in 2050.
Bel	4788	2787	39200	9000	Target year: 2050.
Bosn	0	135	1492	600	Target year: 2030. But they expect electricity generation from Solar PV = 1.3 TWh and from onshore Wind = 3.6 TWh in 2050.
Bulg	1726	705	13660	5450	Target year: 2050.
Cro	96	925	1800	2064	Target year: 2040.
Cyp	424	158	3934	1466	The NECP does not provide this info. However, Cyprus used only solar and onshore wind in 2022, and the goal is to rely mostly on these two technologies in the long run. These values were estimated based on the electricity needs as of 2050, with the 2022 shares.
Cze	2053	339	26100	5500	Target year: 2050.
Den	1536	4644	34921	5325	Target year: 2040.
Est	370	326	1000	3124	Target year: 2030.
Fin	7	3184	15	3500	Target year: 2050. There is no info in the NECP, values based on the current trends.
Fra	13154	19516	75000-100000	40000-45000	Target year: 2035.
Ger	57744	55289	350000	182400	Target year: 2050, combination of sources.
Gre	5430	4702	35051	13000	Target year: 2050.
Hung	2524	323	12400	3000	Target year: 2050.
Ire	0	1919	12000	10000	Target year: 2050.
Ita	5137	10658	245000	51000	Target year: 2050.
Lat	14	87	2000	2110	Target year: 2040.
Lith	259	671	3109	4516	Target year: 2040.
Lux	258	167	1236	453	Target year: 2040.
Malt	222	0	350	0	Target year: 2050.
Mont	0	118	1589	263	Target year: 2030.
Neth	14911	5310	42580	5522	Target year: 2040.
North.Mc	22	37	2100	900	Target year: 2050.
Nor	0	5105	10100	17700	Target year: 2050.
Pol	6664	7950	46293	25816	Target year: 2040.

Port	1032	5328	26000	13000	Target year: 2050. Half of the projected Solar PV installed capacity will be decentralized.
Rom	1160	2957	16960	23777	Target year: 2050.
Serb	3	533	17500	8000	Target year: 2050.
Slov	549	4	7000	4900	Target year: 2040.
Slvk	459	3	8000	500	Target year: 2040.
Sp	14640	18523	57000	59000	Target year: 2030.
Swe	0	12100	33000	32000	Target year: 2050. The NECP has no information. The values were retrieved from the Swedish Energy Authority. Considerable investment in offshore wind power is also expected.
Swi	0	12100	-	-	These countries provide only data for electricity generation from Renewables as a whole, but we do not know the future share of wind and solar.
UK	0	0	-	-	

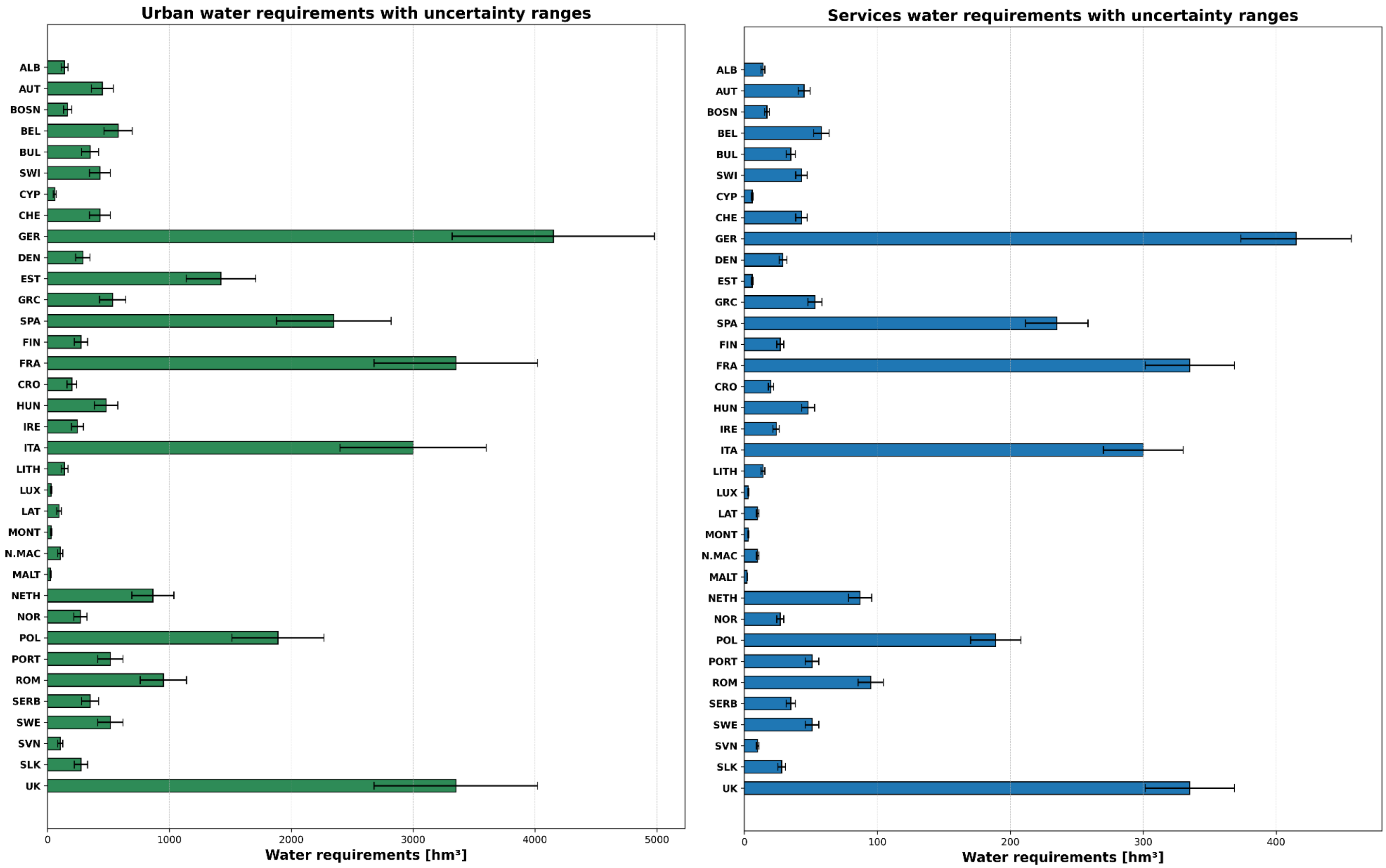

Figure A1. The average urban and services water demand with their min-max uncertainty ranges.

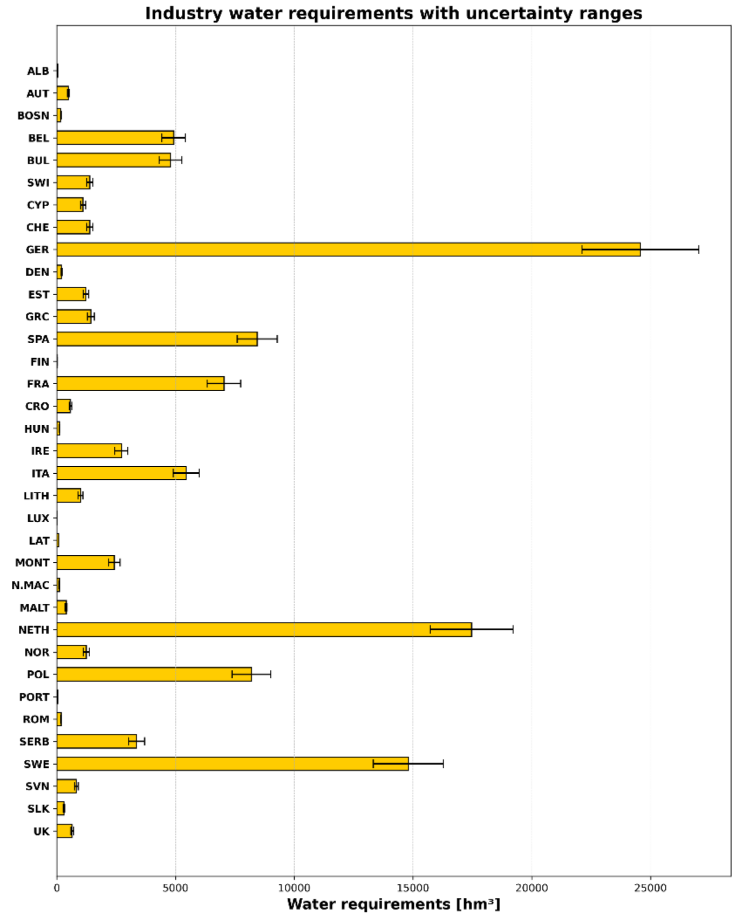

Figure A2. The average industrial water demand with its min-max uncertainty ranges.

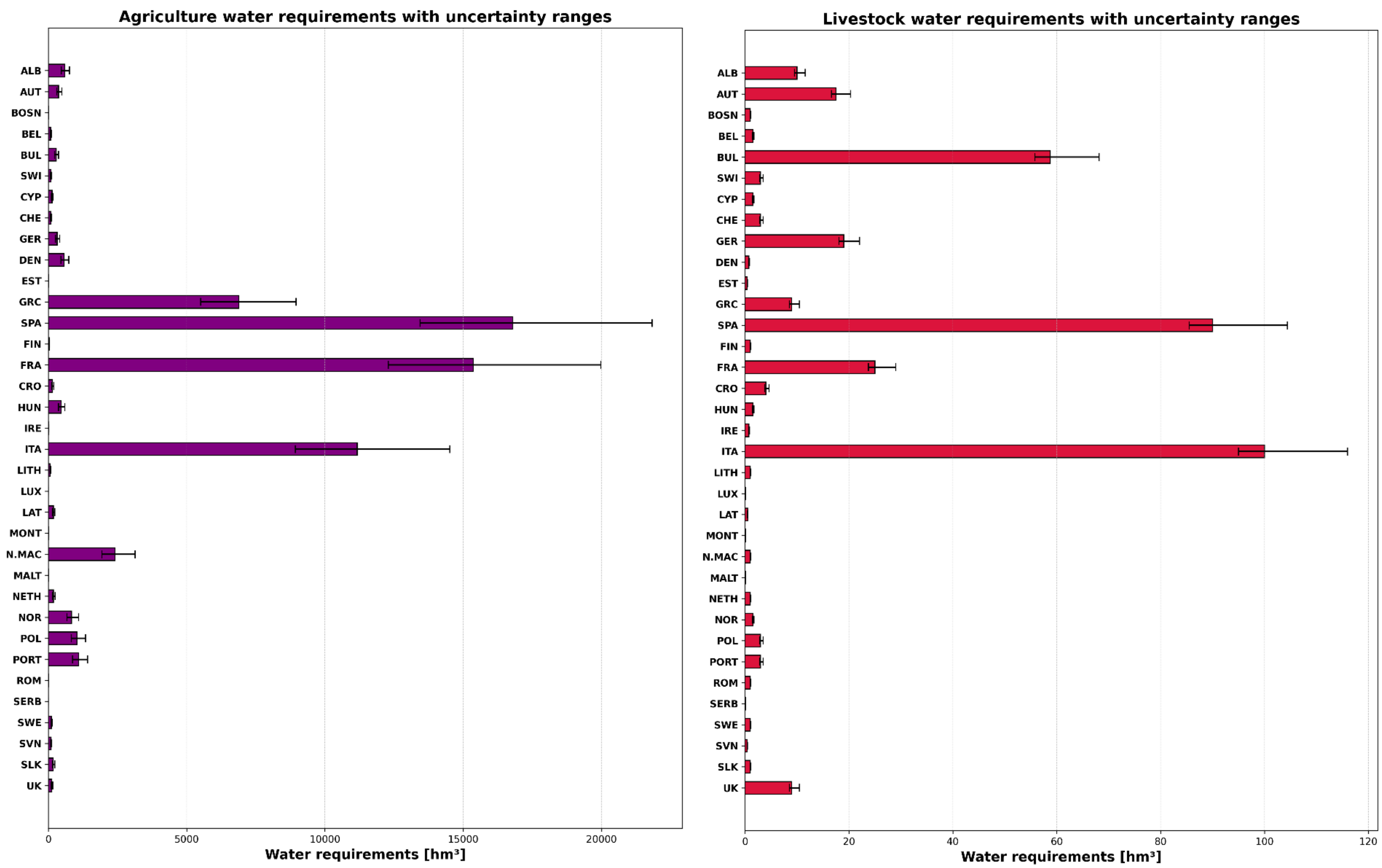

Figure A3. The average agricultural and livestock water demand with their min-max uncertainty ranges.