~~v~~GCAM-Europe v7.2.0: Enhancing Policy-Relevant Climate Modelling Through Spatial and Sectoral Detail

Jon Sampedro[1,2], Russell Horowitz[1], Clàudia Rodés-Bachs[1], Konstantinos Koasidis[3], Dirk-Jan Van de Ven[1]

[1] Basque Center for Climate Change, Sede Building 1, 1st floor, Scientific Campus of the University of the Basque Country, Leioa, 48940, Spain
[2] IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain.
[3] National Technical University of Athens, Athens, Greece

Correspondence to: Jon Sampedro (jon.sampedro@bc3research.org) and Dirk-Jan Van de Ven (dj.vandeven@bc3research.org)

Abstract.

Integrated Assessment Models (IAMs) serve as critical instruments for scenario-based analysis and have been instrumental in informing environmental policy at both global and regional scales. However, their limited geographical and sectoral scope constrains their ability to evaluate comprehensive policy packages such as the European Union's Fit-for-55. GCAM-Europe, an expansion of the well-stablished Global Change Analysis Model (GCAM) addresses this gap by explicitly representing energy, land use, agriculture, water, and emissions systems for European Member States and key non-EU countries. Operating within a global framework, the model enables integrated assessment of policy impacts both across and within European regions, while also capturing spillover effects in other regions in the world. As an open-access and continuously evolving platform, it provides a valuable tool for European researchers, policymakers, and stakeholders to design, test, and evaluate climate and environmental strategies that support a just and effective climate transition.

1. Introduction

Integrated assessment models (IAMs) are "*simplified representations of complex physical and social systems, focusing on the interaction between economy, society and the environment*" (IAMC, 2022). Over the past four decades, IAMs have played an ~~relevant~~ important role in shaping environmental policy and advancing research at both global and regional levels (Weyant, 2017). In recent years, the number of IAM-related publications addressing climate change has grown exponentially, and IAMs have become integral to the development of recent ~~IPCC~~ reports from the Intergovernmental Panel on Climate Change (IPCC; IPCC, 2022), supporting scenario analysis, mitigation strategies, and long-term climate projections (Fisher-Vanden and Weyant, 2020). Notably, from the hundreds of scenarios included in the early IPCC reports (van Beek et al., 2020) ~~(van Beek et al., 2020)~~, the contribution of Working Group III in the recent Six Assessment Report (AR6) of IPCC featured a little more than 1,200 scenarios, and almost thrice as many submissions (Kikstra et al., 2022) .~~(Kikstra et al., 2022).~~

Among the models inter alia underpinning IPCC reports, ~~T~~the Global Change Analysis Model (GCAM) is a well-reputed multisector IAM developed and maintained at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (Calvin et al., 2019; JGCRI, 2025). The model is designed to explore the interdependencies between the energy, agriculture, forestry and land use (AFOLU), water, and climate systems in 32 geopolitical regions across the globe. It enables the analysis of alternative "what-if" type scenarios through a unified computational platform, with projections extending up to the year 2100. GCAM ~~is a fully open-access community model that~~ has been used in major cross-regional analyses, including the IPCC reports (IPCC, 2022), the development of the Shared Socioeconomic Pathways (Calvin et al., 2017), or the recent Scenario Model Intercomparison Project for CMIP7 (van Vuuren et al., 2025). A key advantage of GCAM is that it is a fully open-source and accessible model supported by an active and widespread community of practice. Although the IAM community has recently made progress in releasing the source code of many emblematic models, the reliance on proprietary support software remains a core limitation, particularly in the case of optimisation models. By adopting a price-clearing, recursive-dynamic, partial-equilibrium solution mechanism, GCAM has positioned itself among the few models that can be freely used by any potential user without the need for proprietary software (see Table S1). This openness has fostered a strong community that ensures continuous maintenance, updates, and expansions.

~~Nevertheless~~ Despite their usefulness in climate science, IAMs have also faced significant criticisms (Ackerman et al., 2009)~~. (Ackerman et al., 2009).~~ One common criticism is on the spatial granularity represented~~,~~. GCAM and other existing IAMs are limited to assess comprehensive packages like the EU's Fit-for-55 or the Inflation Reduction Act (IRA). Global models often lack the geographic and sectoral detail needed to capture national and regional differences, while national models typically miss cross-border interactions and wider economic dynamics (Anderson and Jewell, 2019; Brutschin et al., 2021; Keppo et al., 2021). In fact, out of the 13 models with at least one scenario in IPCC AR6 (Sognnaes and Peters, 2025),

~~(Sognnaes and Peters, 2025),~~ only two global models featured a disaggregated representation of all EU member states (see Table S1), namely POLES (Criqui et al., 2015)~~, (Criqui et al., 2015),~~ a closed-source energy system model, and GEM-E3 (Capros et al., 2013) ~~(Capros et al., 2013)~~ a general equilibrium model, relying on the proprietary Global Trade Analysis Project (GTAP) database (Aguiar et al., 2022)~~. (Aguilar et al., 2022).~~ On the other hand, regional bottom-up models with a detailed representation of the EU, like EU-TIMES (Gago~~AGO~~ et al., 2013)~~, (Joint Research Centre, 2013),~~ often lack the ability to capture global trends along with the regional dynamics. Additionally, IAMs generally focus on identifying "least-cost" pathways to emission reduction targets (van de Ven et al., 2023)~~(van de Ven et al., 2023)~~, which involves applying a uniform carbon price across all regions and sectors, with little attention to feasibility (Bertram et al., 2024) or non-emission outcomes (Geels et al., 2016). As a result, these models often produce scenarios that diverge significantly from national political realities, such as over-reliance on negative emissions technologies (NETs) (Lamb et al., 2024) and on land removals (Dooley et al., 2024), or unrealistic policy assumptions (Gambhir et al., 2019)~~(Gambhir et al., 2019)~~. In addition, in terms of sectoral and technological granularity, IAMs often fail to adequately represent the diversity of household behaviour and consumption, which critically limits their ability to assess inequality impacts and the broader social and distributional consequences of climate transitions, which are essential to ensure no one is left behind in the shift to a low-carbon future (Emmerling et al., 2024; Low et al., 2025). These~~is~~ limitations of IAMs underscore~~s~~ the critical need to develop new, and refine existing, IAMs (Braunreiter et al., 2021; Koasidis et al., 2023; Skea et al., 2021). Particularly, enhancing the geographical resolution of IAMs is essential to accurately represent the heterogeneity of socio-economic systems, institutional capacities, and political contexts at the national level. Such granularity enables more detailed, bottom-up climate policy modelling within a global context and beyond stylized assumptions like uniform carbon pricing, thereby improving the feasibility, relevance, and robustness of projected outcomes.

The GCAM community has already developed several regional versions of the models for different regions over the world that include the USA (GCAM-USA; (Binsted et al., 2022), China (GCAM-China; CGS, 2025), Korea (GCAM-Korea; Jeon et al., 2021), Middle East (GCAM-KSA), South America (GCAM-LAC), Canada (GCAM-Canada) or India (GCAM-India). These regional versions ~~are~~ have been proven to be better suited for modelling bottom-up environmental policies and assessing their system-wide implications at both national and subnational scales. Therefore, they have garnered significant interest from a diverse array of stakeholders. For instance, GCAM-USA has been widely employed to evaluate the impacts of existing climate policies at the national and state levels (Bistline et al., 2025; Zhao et al., 2024), with its outputs informing both academic research and decision-making in policy and industry. Similarly, the recent launch event for the latest version of GCAM-China drew considerable attention, with nearly 200 participants attending in person and over 10,000 viewers joining online. However, neither the GCAM nor the broader IAM community has so far managed to deliver a European version of a core global model, with full member state granularity that is open source and freely accessible, despite the EU's historical international climate leadership (Oberthür and Dupont, 2021)~~. (Oberthür and Dupont, 2021).~~ Within this ~~framework~~context, we ~~are confident that~~present GCAM-Europe, ~~will serve as~~ a powerful tool for in-depth analysis of

European climate policy at the member state level, ~~and will receive strong interest from key stakeholders involved in the climate transition~~which,~~.~~ ~~In addition,~~ unlike existing regional versions of GCAM, ~~GCAM-Europe~~ explicitly represents land use, agriculture, water resources, and energy extraction at the subregional level. This constitutes a significant contribution to the European IAM community, enabling more precise assessments of resource dynamics and policy impacts across diverse European contexts, with the potential to receive strong interest from key stakeholders involved in the climate transition of the EU and globally.

2. Model description

GCAM-Europe's geographical disaggregation is highly-detailed for the European continent. While core GCAM divides the European continent into five different regions, namely EU-12, EU-15, Europe Eastern, Europe-non-EU, and European Free Trade Association (EFTA), in GCAM-Europe all European countries are disaggregated into individual model regions (Figure 1)~~(Figure 1)~~ for the energy-economy system. These include the 27 Member States of the European Union (EU) and additional key non-EU countries (e.g., Switzerland or the United Kingdom). In terms of land-use and water systems, GCAM-Europe disaggregates 119 land regions, which result from the interactions between geopolitical regions (countries) with the hydrologic basins. Having this level of detail enables us to explore the country-level effects of European policy packages or transformational strategies, as well as the potential international effects (e.g., carbon leakages).

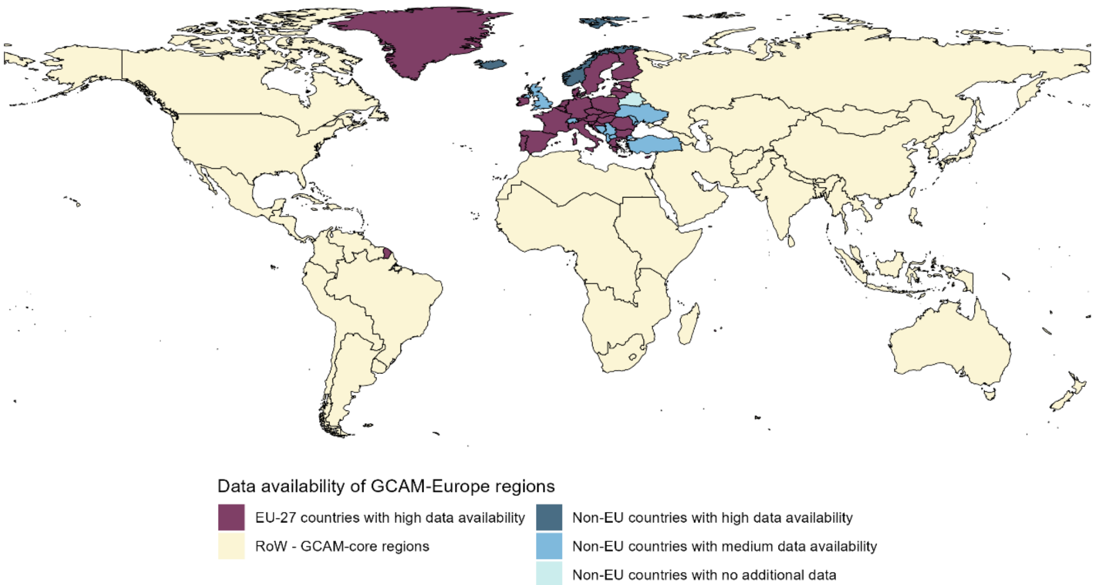
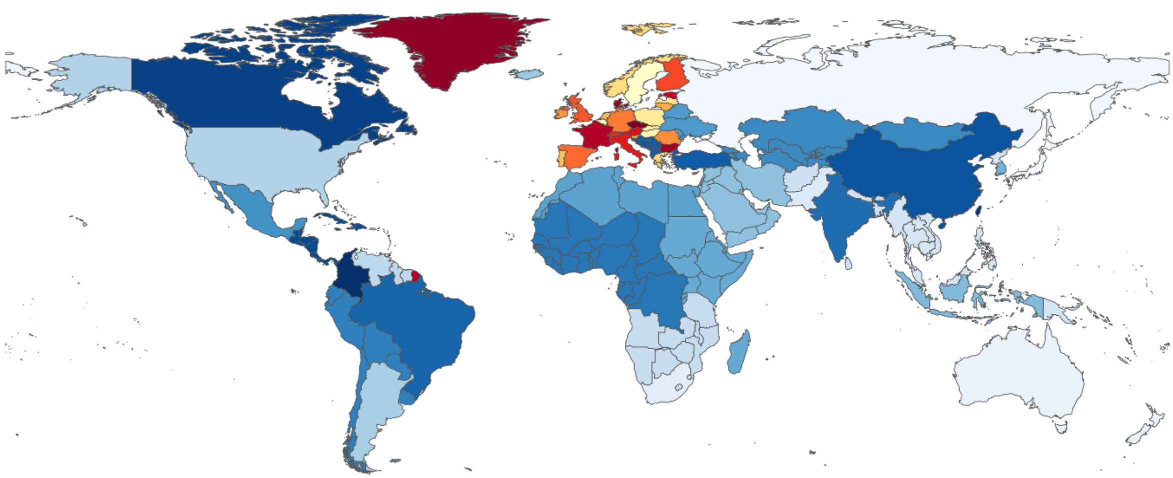


Figure 1: Regional disaggregation in GCAM-Europe. Purple and blue areas indicate regional groups that are explicitly disaggregated in this model, while yellow areas represent regional groups from the original model.



~~**Figure 1: Regional disaggregation in GCAM-Europe.** Yellow-to-red colours represent the regional groups that are explicitly disaggregated for this model. White-to-blue regions represent model regional groups that were part of the original model.~~

GCAM-Europe replaces the default (international) data sources for all newly defined European countries with Europe-specific data, such as energy statistics from Eurostat (Eurostat, 2025a), whenever available. If certain countries lack coverage in these European datasets, alternative sources are used, most commonly reverting to the default GCAM data, such as IEA energy statistics (IEA 2022). Population projections are also replaced by specific data from the EU Ageing Report 2024 (European Commission, 2024), ensuring consistency with official demographic and economic outlooks.

Beyond the regional disaggregation and data replacement, GCAM-Europe includes additional features compared to the core version, including the enhanced representation of electricity grids and regional trade, as well as demand segments, which allows to have more sectoral detail in the power sector. In final energy demand, predominantly in building energy demand, new demand categories are included as well as new technologies like heat pumps. Although limited data availability at the global scale constrains the level of sectoral detail in the core model, particularly in areas such as buildings, greater regional data availability allows for more granular sectoral representation in regional model versions like GCAM-Europe and GCAM-USA.

~~, driven by high data availability for European countries.~~

With its higher regional disaggregation (from 32 to 66 regions) and the additional layers of complexity (e.g., electricity grid regions or expanded household technologies), GCAM-Europe requires substantially more input data for setup and a larger number of markets and equations to solve at each time step. This added complexity makes the model considerably more memory intensive: it consumes roughly 50% more RAM than the core version and increases system-wide committed memory. As a result, GCAM-Europe requires the page file, which reduces CPU efficiency and slows computation. In practice, a full simulation run (e.g., the Reference scenario to 2100) takes about three times longer to complete. To run GCAM-Europe efficiently, systems with at least 128 GB of RAM and high memory bandwidth are advisable, together with SSD (NVMe) storage to reduce paging overhead, since memory capacity and bandwidth remain the critical constraints.

~~Finally, we would like to note that, as part of the model development process, we conducted a validation exercise to assess the model's accuracy and consistency. This exercise involved comparing the results from the first modelling period (2020) with observed data across multiple sectors, including energy and emissions. The analysis provided an important check on the model's ability to reproduce observed trends and sectoral dynamics, thereby strengthening confidence in its subsequent projections. The complete set of validation results and comparisons is provided as Supplementary Material.~~

~~To run GCAM-Europe efficiently, systems with at least 128 GB of RAM and high memory bandwidth are advisable, together with SSD (NVMe) storage to reduce paging overhead, since memory capacity and bandwidth remain the critical constraints.~~

2.1 Power system

The electricity system in GCAM-Europe is modelled as an interconnected system structured around grid regions, load segments, and inter-segment storage. Like in other regional GCAM versions (e.g., GCAM-USA), the electricity system in GCAM-Europe is subdivided into several "grid-regions", in which all electricity supply and demand can flow unrestricted, while electricity trade between grid-regions is relatively more constrained. Figure 2~~Figure 2~~ shows the grid region structure for GCAM-Europe, which we have designed largely following the seven "wholesale regions" as defined in the quarterly European electricity market reports, and an additional region joining together the electricity grid of Moldova and Ukraine. This leaves 3 remaining European countries without being integrated in larger grid regions: Belarus, Iceland and Turkey. The ~~national grids of Belarus and Iceland~~electricity grids of these countries are represented as~~ will act as~~ standalone grids without interconnection, as real-world interconnection with other European countries is inexisting (Iceland) or insignificant (Belarus and Turkey). ~~For Turkey, grid interconnection with the rest of Europe is represented.~~

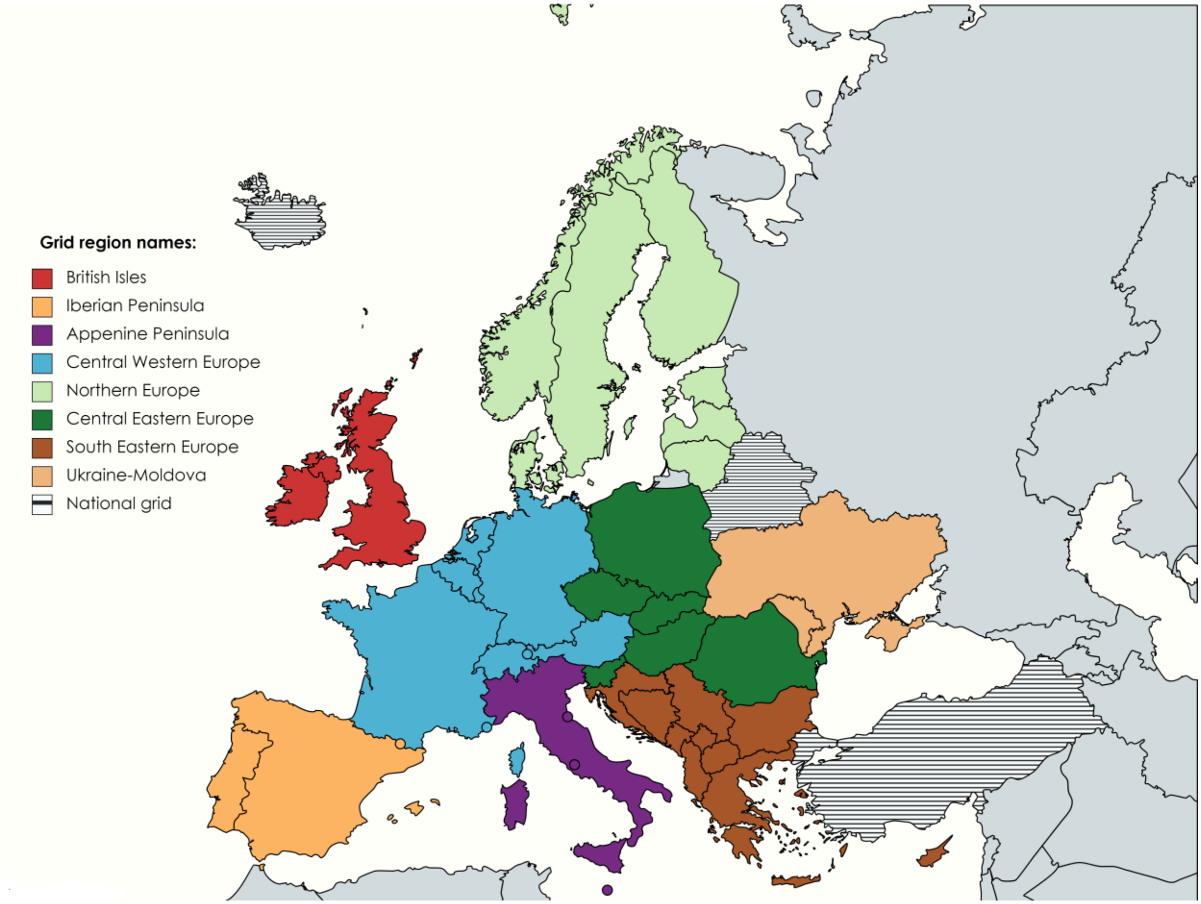
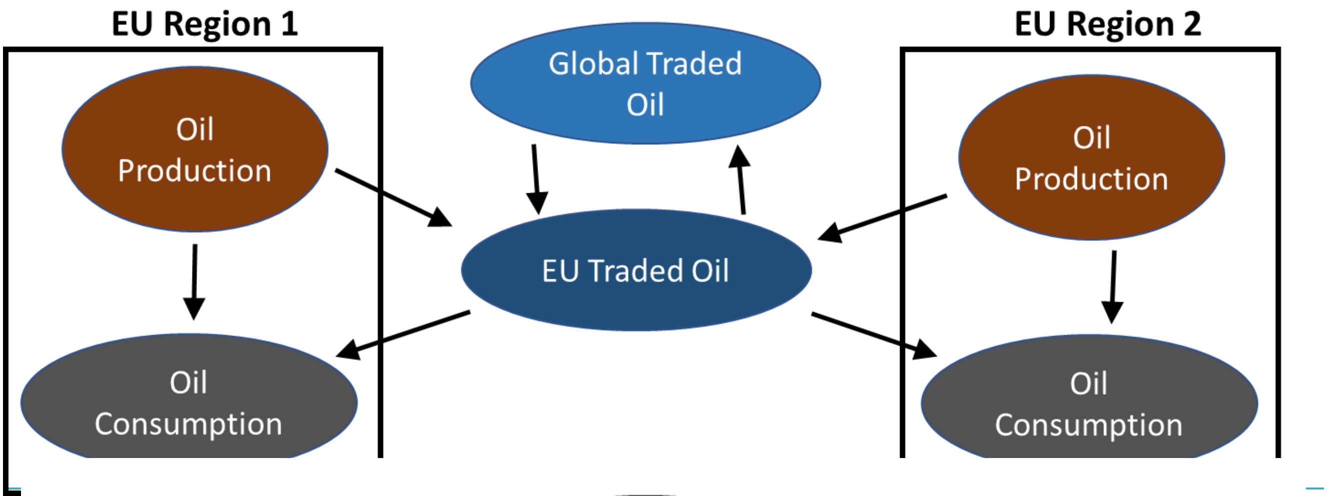


Figure 2: Electricity grid regions GCAM-Europe

The representation of the electricity system is based on the “National trends” scenario of the “Ten-Year Network Development Plans” (TYNDP) 2024 process by the European Network of Transmission System Operators for Electricity (ENTSO-E). This scenario serves as a reference for grid investment planning and electricity demand projections across Europe (ENTSOE, 2024). Load segmentation is derived using data from the openTEPES electricity model (Ramos et al., 2022), resulting in four distinct load segments: base load, intermediate, subpeak, and peak. This segmentation captures temporal variations in electricity demand and supply with greater accuracy and supports detailed analysis of storage technologies and their role in balancing the grid across time periods and regions. Each grid region and load segment operates its own electricity market, with prices typically lowest during off-peak periods and highest during peak demand. These price dynamics can incentivize investment in storage technologies, while regional price differences may encourage cross-border electricity trade.

2.2. Commodity trade structure

GCAM-Europe incorporates a trade structure that reflects the European Economic Area (EEA) and the internal free-trade market among EU member states, Norway, and Iceland (Figure 3)(Figure 3). By default, commodity trade in GCAM, including energy, food, and selected industrial commodities such as steel and ammonia, is governed by Armington trade specifications (Armington, 1969; Zhao et al., 2022)(Armington, 1969; Zhao et al, 2022), which define the substitutability between domestically produced and imported goods, both at the international level and within individual regions. Armington trade elasticities are commodity-specific and determined by literature (Hertel et al., 2007) (Hertel et al, 2007) and hindcasting experiments (Zhao et al., 2021). (Zhao et al, 2021). In GCAM-Europe, EEA countries are treated as a single trading block in relation to other GCAM regions in the international market, including the newly separated United Kingdom. Within the EEA, intra-regional trade is modelled with an additional layer of Armington specifications to capture trade flows among member countries. While international trade costs and Armington elasticities between the EEA block and non-EEA regions remain the same as in the default GCAM framework, trade within the EEA is assigned lower costs and friction (e.g. higher elasticities), reflecting reduced trade barriers within the internal markets. For those commodities where trade costs apply, a rule of thumb is applied, determining intra-EEA trade (e.g. between France and Germany) to cost 1/3rd of extra-EEA (e.g. between France and USA), reflecting closer distances and lower administrative costs. In terms of trade elasticity, intra-EEA crop trade is assumed to be frictionless, having EEA-wide crop commodity markets rather than national markets. Intra-EEA trade for other commodities (animal, energy and industrial commodities) is assumed to occur with very low friction (logit of –12). Given the dual role of international trade in either hindering mitigation through emission displacement (Peters and Hertwich, 2008) (Peters and Hertwich, 2008) or enabling it when trade measures effectively support collective climate action (Farrokhi and Lashkaripour, 2025; Jakob, 2021), (Jakob, 2021; Farrokhi and Lashkaripour, 2025)Beyond improved trade realism, this enhanced structure offers an improved trade realism that facilitates the representation of shared trade policies across the EU and EEA, such as the Carbon Border Adjustment Mechanism (CBAM), enabling more nuanced and policy-relevant modelling in future analyses.



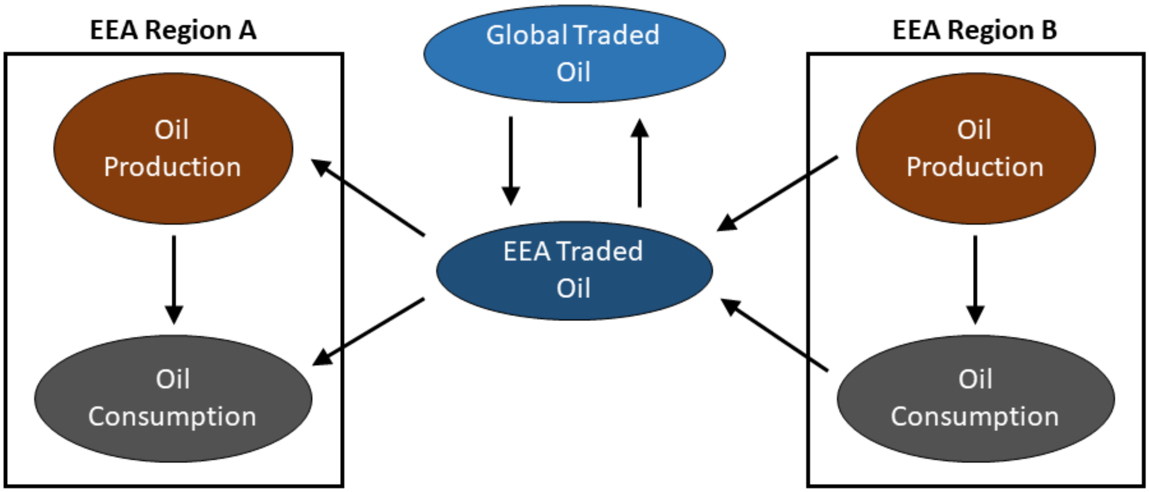


Figure 3: Updated trade structure in GCAM-Europe

Figure 3: Updated trade structure in GCAM-Europe

2.3 Sectoral and technological coverage in the buildings sector

Leveraging the richer and more detailed data available for European countries, the model has been expanded across multiple dimensions with a particular emphasis on building energy demand. The core GCAM version disaggregates residential energy consumption into cooling, heating and non-thermal (e.g., appliances) services. In GCAM-Europe, following the categorization in Eurostat (Eurostat, 2025b), we introduce new demand categories, namely hot water, cooking, and various household appliances, enabling more accurate and granular modelling of household energy consumption patterns.

In addition, GCAM-Europe includes a detailed representation of heat pump technologies, which are not explicitly modelled in the core version of GCAM. The model distinguishes between several types of systems: air-source heat pumps that extract energy from the outside air ("air-air"), water-source heat pumps that extracts heat from the outside air and transfers it to a water-based heating system ("air-water"), and ground-source heat pumps that draw energy from the ground (“geo-water”). GCAM-Europe also incorporates solar thermal technologies for both space and water heating, providing a more comprehensive view of low-carbon heating solutions.

In terms of household structure, GCAM-Europe includes consumer heterogeneity in the residential energy sector in the form of income deciles, which is aligned with the current structure in the core version of the model. To implement the multiple consumer groups, we adopt the core GCAM approach by applying the corresponding demand functions, calibrated to average income data, to estimate consumption levels for each income decile within a region. Because the aggregation of decile-level estimates does not necessarily match with the observed national (or regional) consumption, a bias-correction term is introduced, defined as the difference between the estimated aggregate and the observed value. The details of this implementation in core GCAM are documented in (Sampedro et al., (2024) Sampedro et al. (2024). As a next step, we plan to enhance this representation by integrating empirical data from national Household Budget Surveys (HBS) (Eurostat, 2025c), which are available for all EU member states (see *Discussion*). This improvement will allow for a more realistic calibration of household energy consumption and expenditure patterns, thereby increasing the accuracy and policy relevance of model outputs (see *Discussion and Conclusion*). Despite these advancements, the current representation cannot capture all relevant dynamics. Key drivers like insulation levels and natural ventilation are omitted, and behavioural or urban policies, such as energy-saving awareness campaigns, cannot be explicitly modelled. Linking with more detailed building-specific tools would enable the analysis of such comprehensive policies (Burleyson et al., 2020).

3. Results

3.1. Socioeconomics

The socioeconomic projections in GCAM-Europe are aligned with the moderate demographic and economic growth defined in the SSP2 narrative (O'Neill et al., 2014), which is the same assumption in the baseline scenario of the core version of the model ("GCAM-Core-v7p2"). However, the population trajectories for different countries in GCAM-Europe have been updated using EU-specific information from the EU Ageing Report 2024 (European Commission, 2024). This results in higher population projections at European level, compared to the core. Figure 4 ~~Figure 4~~ shows that European population peaks and start declining at the middle of the century. However, in the core model, population accounts for 685M and 632M people in 2050 and 2100, respectively, while these values represent 696M and 649M in the GCAM-Europe baseline. In terms of GDP, GCAM-Europe does not include any update, and the projections are completely aligned with the moderate economic growth in the core model (Fig S1). In principle, it is possible to adapt socioeconomic assumptions to other SSPs. However, the EU Ageing Report 2024 provides only one baseline demographic projection that is generally more consistent with SSP2, and not a range of alternative scenarios like the SSPs. Opting for different SSP socio-economic assumptions, might entail avoiding the adaptation to EU-specific data, and reverting to the native SSP population data at the national level. Additionally, fully harmonising a model to different SSP storylines would require not just adapting socio-economic but also techno-economic assumptions and scenario drivers both at the global level (core) and the EU part.

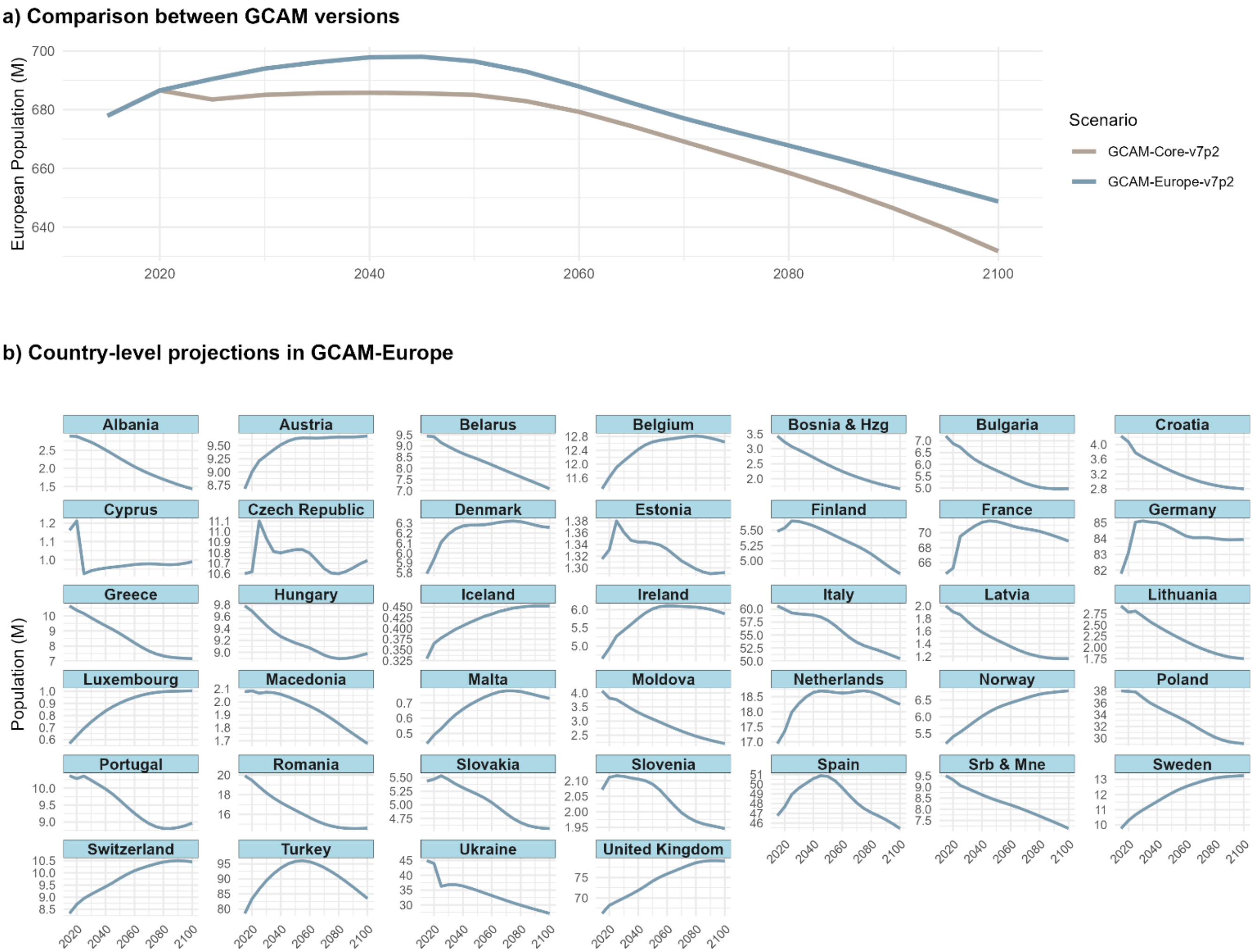


Figure 4: Population by period, region, and scenario (Million). Panel A compares population projections between the GCAM-Europe and the core baseline scenarios. Panel B shows population by European country in the GCAM-Europe baseline.

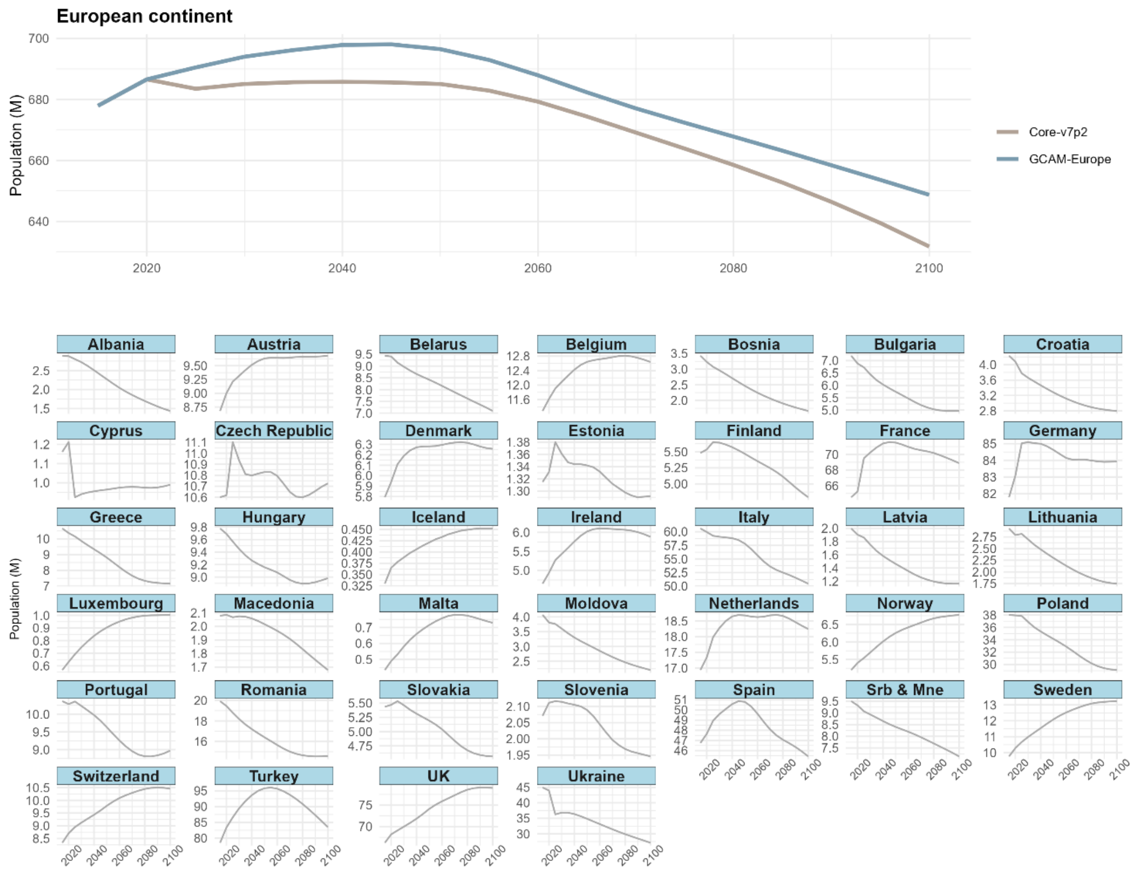
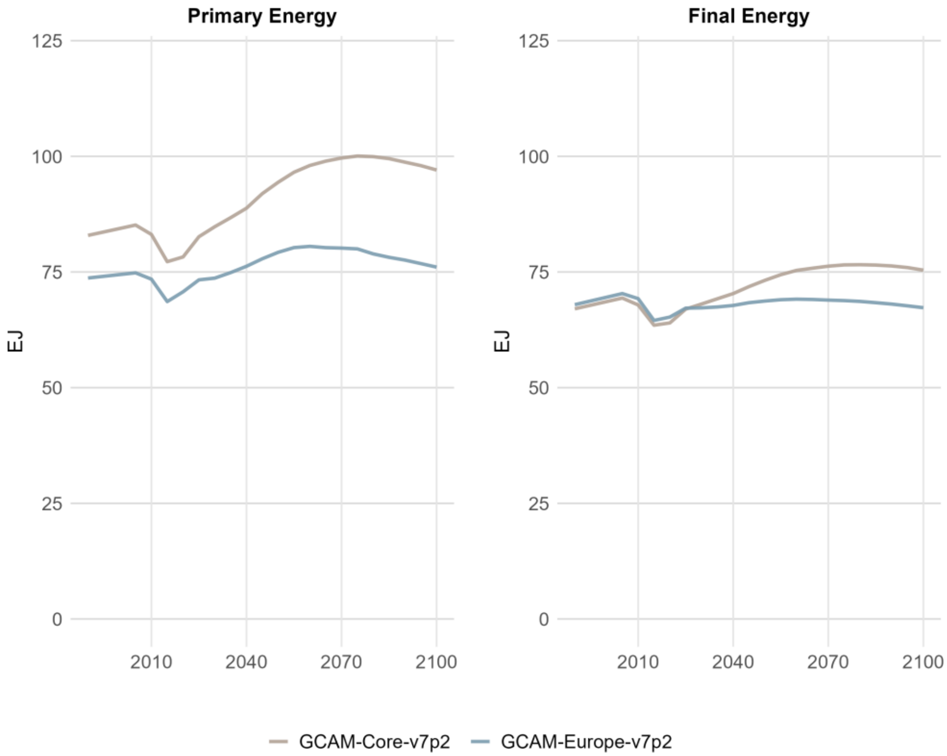


Figure 4: Population by period, region, and scenario (Million).

The upper panel Panel A compares population projections between the GCAM-Europe and the core baseline scenarios. The lower panePanel B l shows population by European country in the GCAM-Europe baseline.

3.2. Energy

In the GCAM-Europe baseline scenario, energy consumption gradually increases over time, peaking in the last quarter of the century, in line with socioeconomic trends and influenced by the adoption of more efficient technologies across end-use sectors. Primary energy consumption in Europe increases from 76 EJ in 2015 to 90 EJ in 2070, and then slightly declines to 87 EJ by the end of the century. Total final energy consumption shows a similar trend, increasing from 65 EJ in 2015 to 69 EJ in 2070, and then decreasing to 67 EJ by 2100. These trends in both primary and final energy consumption are consistent with the projections in the core version of the model. However, the implementation of new features, such as the grid regions and load segments in the power system, as well as the highly-efficient heat pump technologies implies that the values in the GCAM-Europe baseline are lower than in the core GCAM model (Figure 5~~Figure 5~~). In the core version, primary energy in Europe increases to 100 EJ in 2070 and declines to 97 EJ in 2100. Likewise, final energy achieves around 77 EJ and 75 EJ in 2050 and 2100 respectively, which are higher than the values in the GCAM-Europe baseline.


Primary Energy
Final Energy
EJ
125
100
75
50
25
0
2010
2040
2070
2100
GCAM-Core-v7p2
GCAM-Europe-v7p2

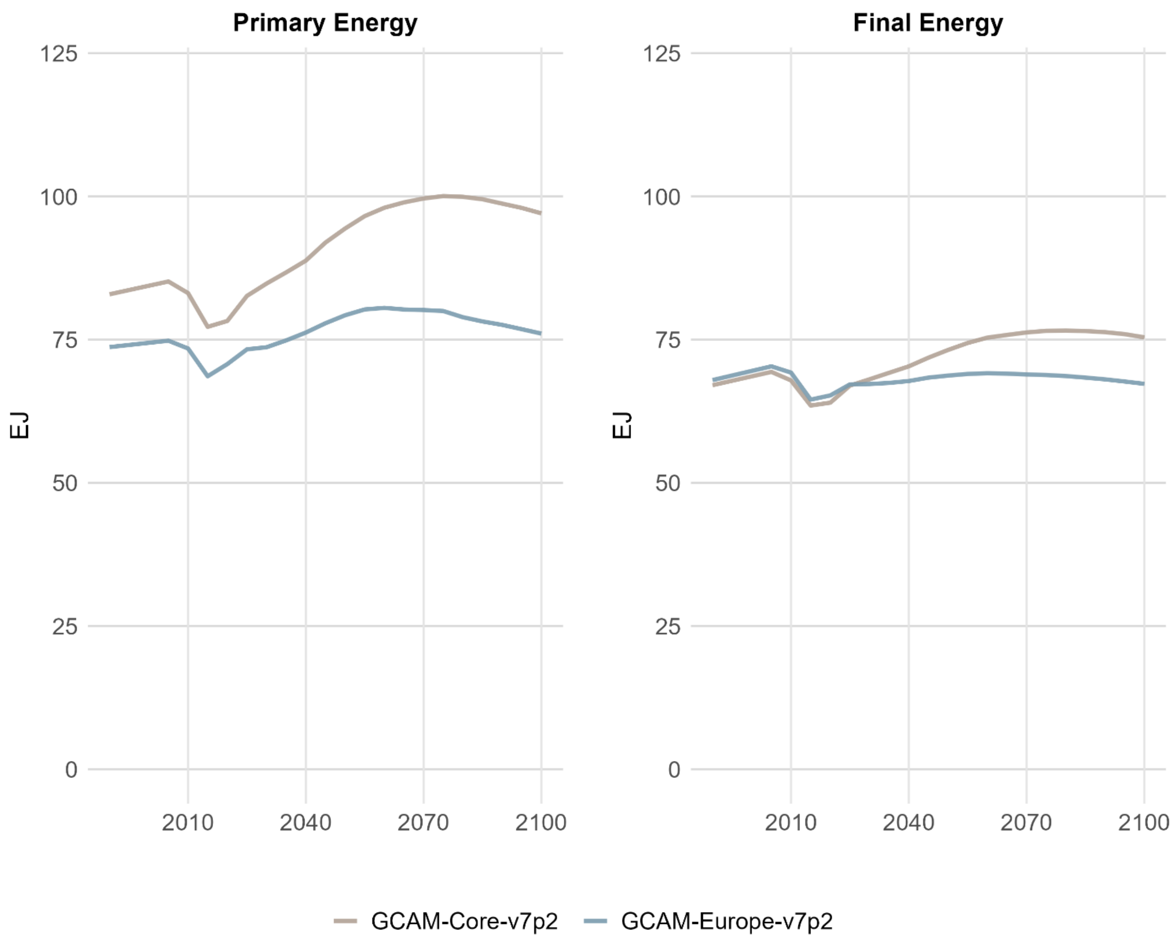


Figure 5: Primary energy (left) and final energy (right) in Europe by period and scenario (EJ).

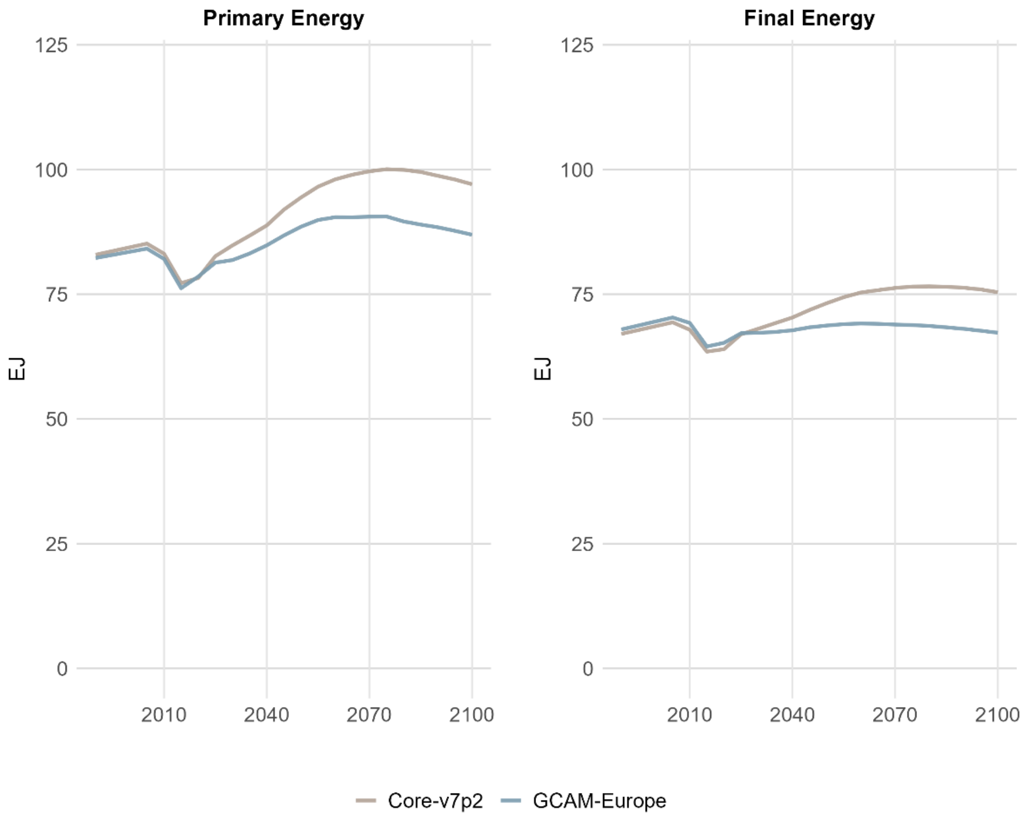
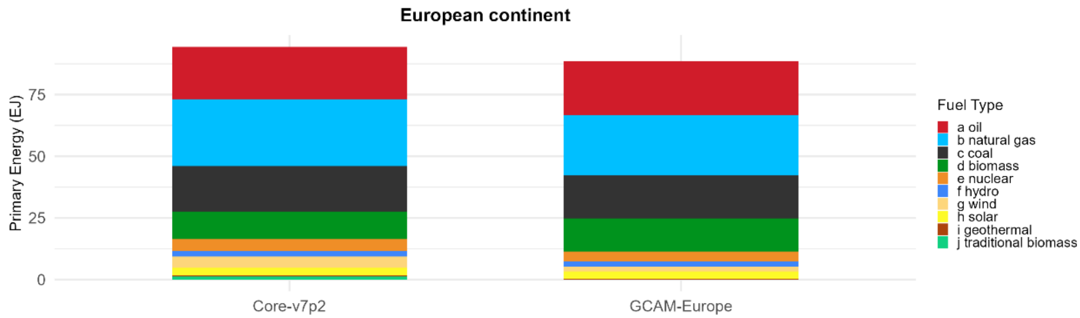
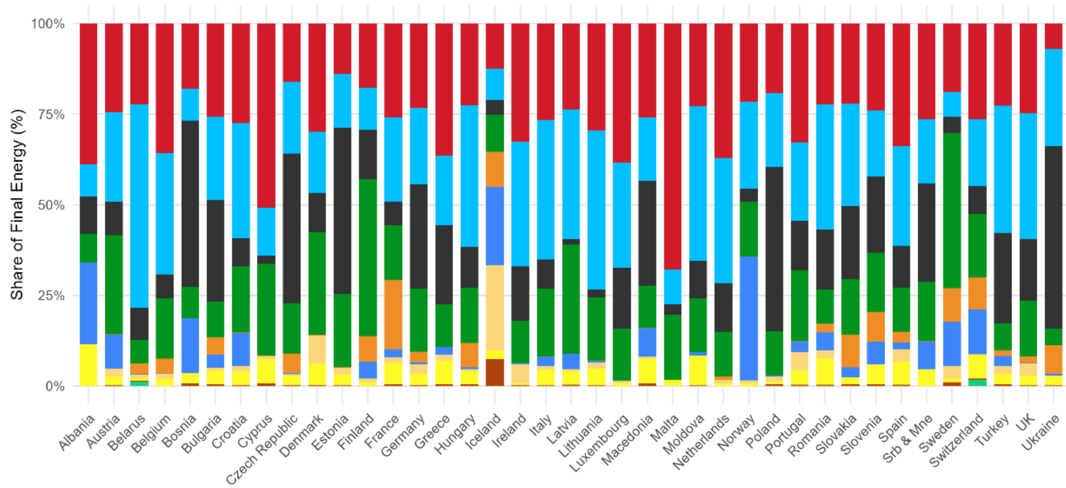


Figure 5: Primary energy (left) and final energy (right) in Europe by period and scenario (EJ).

Fossil fuels are the main source of primary energy during the entire time horizon in the GCAM-Europe baseline scenario. However, the share of renewable energy gradually increases as technological advancements reduce costs and therefore increase their competitiveness. In 2015, fossil fuels represent around 80% of total primary energy at European level and by 2050 this share is reduced to around 70%. This share is similar to the value observed in the core GCAM version. However, there are some differences across fuels. In GCAM-Europe there is a higher penetration of biomass technologies, reaching about 13 EJ in 2050 and comprising 15% of the primary energy mix. This value is smaller in GCAM core, as in the same period biomass consumption accounts for 11 EJ (12% of the mix). Contrarily, the baseline scenario in GCAM-Europe shows a more pessimistic penetration of wind energy. In 2050, wind power achieves 1.8 EJ, representing around 2% of the primary energy mix. In the core model, these values rise to 4.5 EJ and 4%, respectively. A comparison of primary energy across scenarios in 2050 is presented in- Figure 6Figure 6.


European continent
Primary Energy (EJ)
0
25
50
75
Core-v7p2
GCAM-Europe
Fuel Type
a oil
b natural gas
c coal
d biomass
e nuclear
f hydro
g wind
h solar
i geothermal
j traditional biomass


Share of Final Energy (%)
0%
25%
50%
75%
100%
Albania
Austria
Belarus
Belgium
Bosnia
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
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Switzerland
Turkey
UK
Ukraine

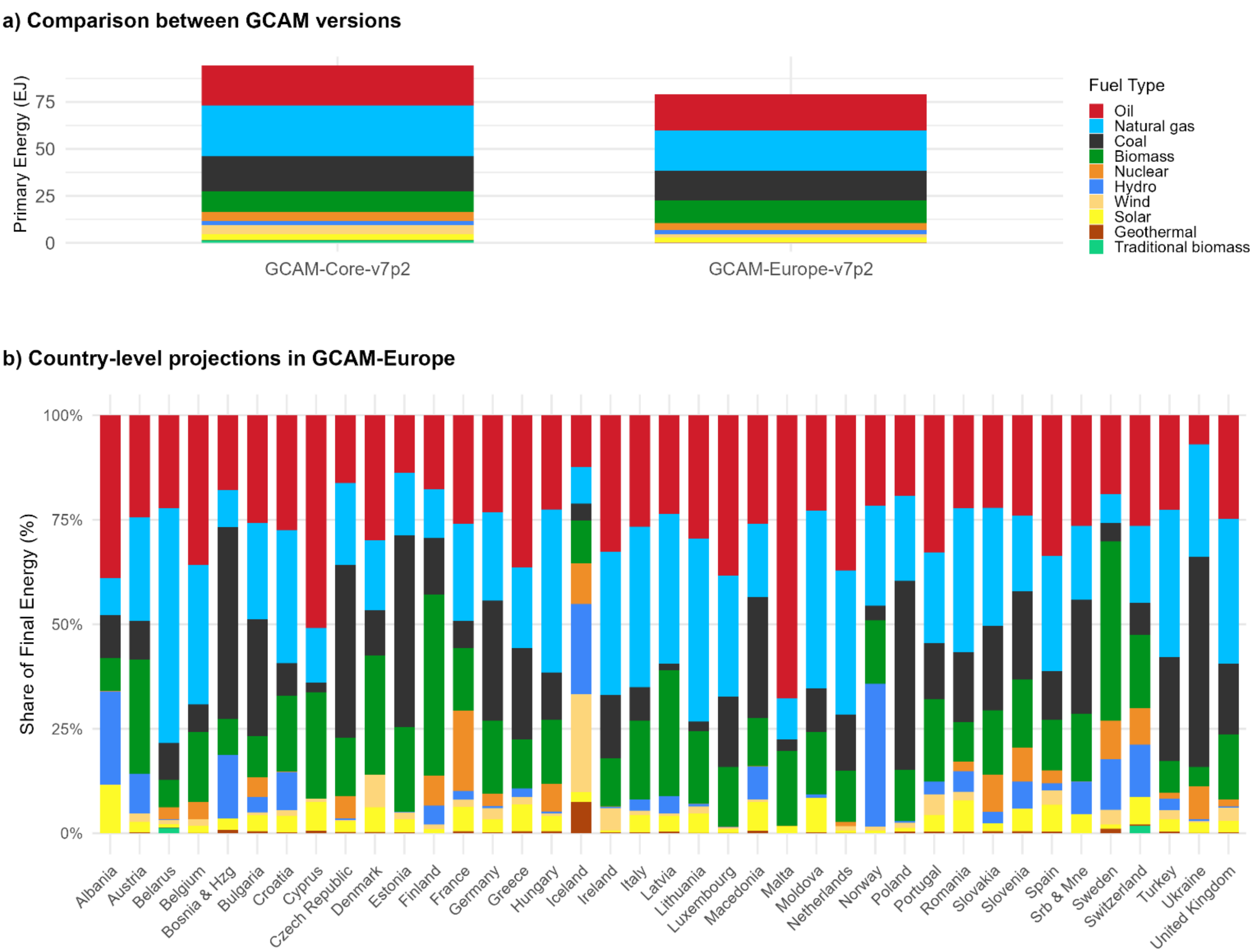


Figure 6: Primary energy consumption in 2050 by scenario, region, and fuel (EJ).

~~**Figure 6: Primary energy consumption in 2050 by scenario, region, and fuel (EJ).**~~ ~~The upper panel~~ Panel A shows total primary energy for the European continent (EJ). Panel B ~~The lower panel~~ shows the share of different fuels in each country's primary energy mix (%) in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S2. Total primary energy by European country is shown in the Supplementary Information (SI) Fig S3.

~~Total primary energy by European country is shown in the Supplementary Information (SI) Fig S32.~~

~~T~~Total final energy shows similar trends and differences across scenarios and fuels (Fig S4~~3~~). Focusing on final energy by sector, industry is projected to be the most energy-intensive sector during the entire time horizon. Industrial energy demand increases from 24 EJ in 2015 to 30 EJ by 2070, driven by growing industrial activity associated with the projected population growth and economic expansion. Then, it slightly declines by the end of the century to 28 EJ. Energy consumption for the transportation sector shows a moderate and steady increase throughout the entire time horizon, with the associated energy consumption rising from 19 EJ in 2015 to 22 EJ by 2100. This rise is primarily driven by growing demand for freight transportation services. On the contrary, the building sector presents a decrease over time in energy consumption from 21 EJ in 2015 to 16 EJ in 2100. This is largely due to most European households approaching energy satiation levels, meaning that rising incomes no longer lead to increased demand for thermal services such as heating and cooling. As residential demand for energy services stabilizes, the growing adoption of efficient heat pump technologies (Fig S54), which become increasingly competitive in the near future, directly contributes to the overall decline in energy use within the sector. There are some differences when comparing these trends with the GCAM core baseline scenario. Energy demand in the transportation sector is slightly higher in the GCAM-Europe baseline, whereas demand in both the industrial and building sectors is higher in the core scenario. The disparity is especially pronounced in the building sector, considering that the core version does not explicitly model the highly efficient heat pump technologies. This information for a representative year (2050) is summarized in Figure 7Figure 7.

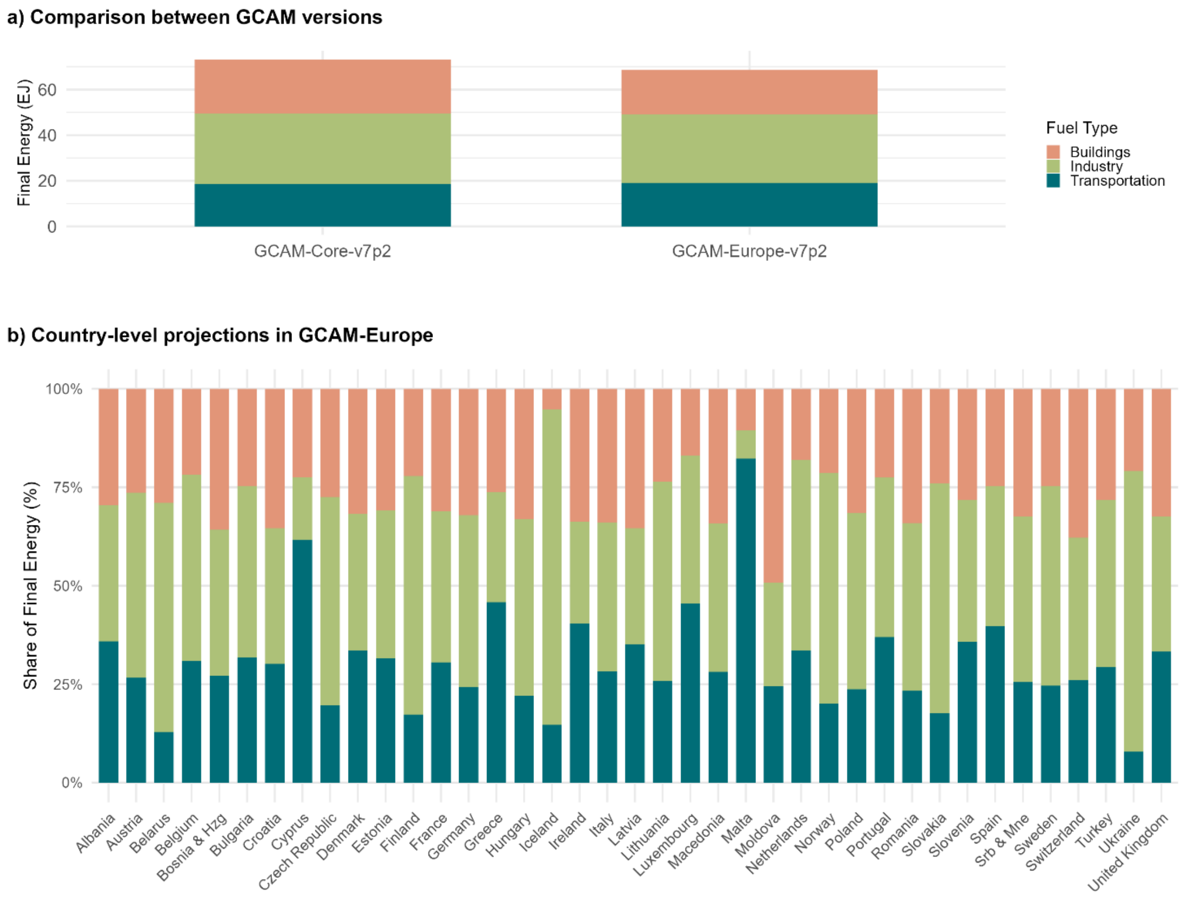
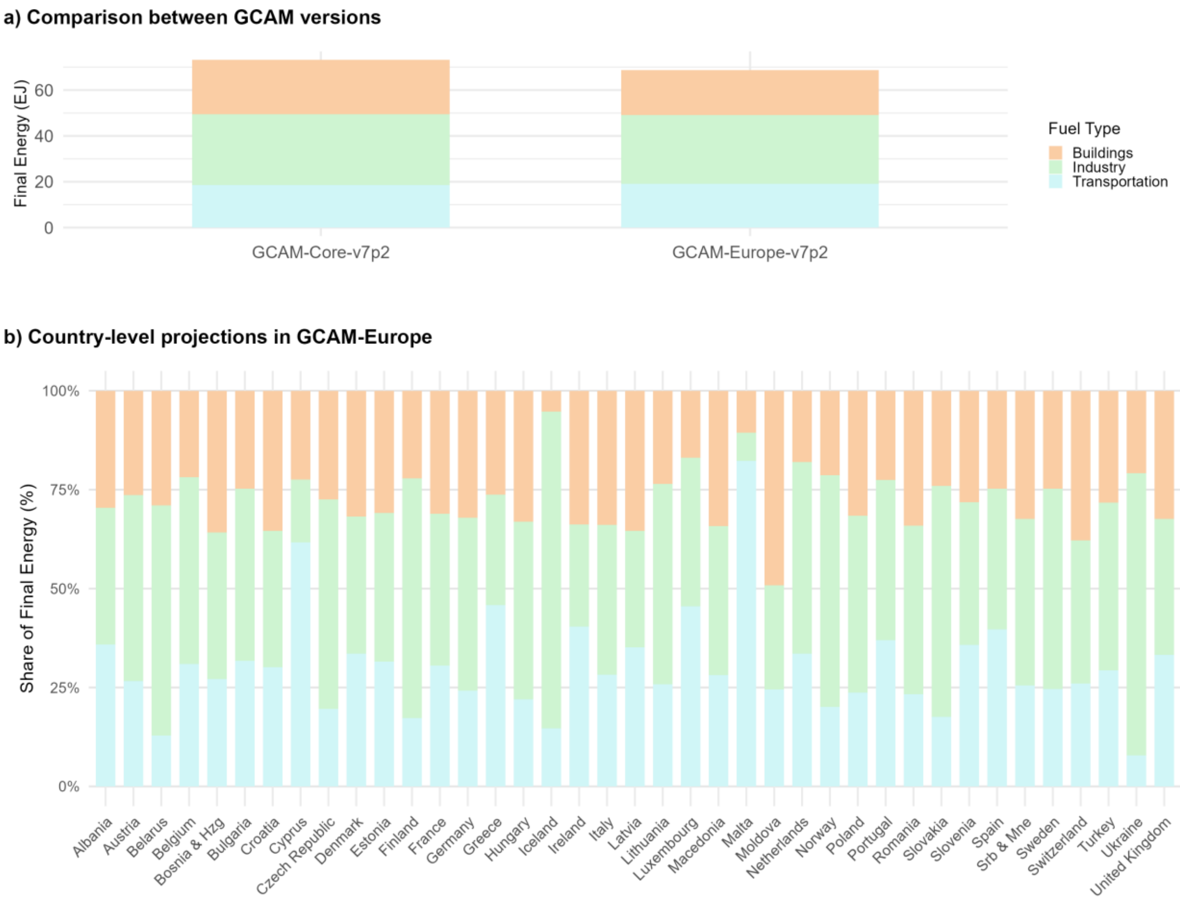


Figure 7: Final energy consumption in 2050 by scenario region, and fuel (EJ). Panel A shows total final energy for the European continent (EJ). Panel B shows the weight of different sectors in each country's final energy consumption (%) in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S6. Total final energy by European country is shown in the Supplementary Information (SI) Fig S7.


a) Comparison between GCAM versions
Final Energy (EJ)
0
20
40
60
GCAM-Core-v7p2
GCAM-Europe-v7p2
Fuel Type
Buildings
Industry
Transportation
b) Country-level projections in GCAM-Europe
Share of Final Energy (%)
0%
25%
50%
75%
100%
Albania
Austria
Belarus
Belgium
Bosnia & Hzg
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
Turkey
Ukraine
United Kingdom

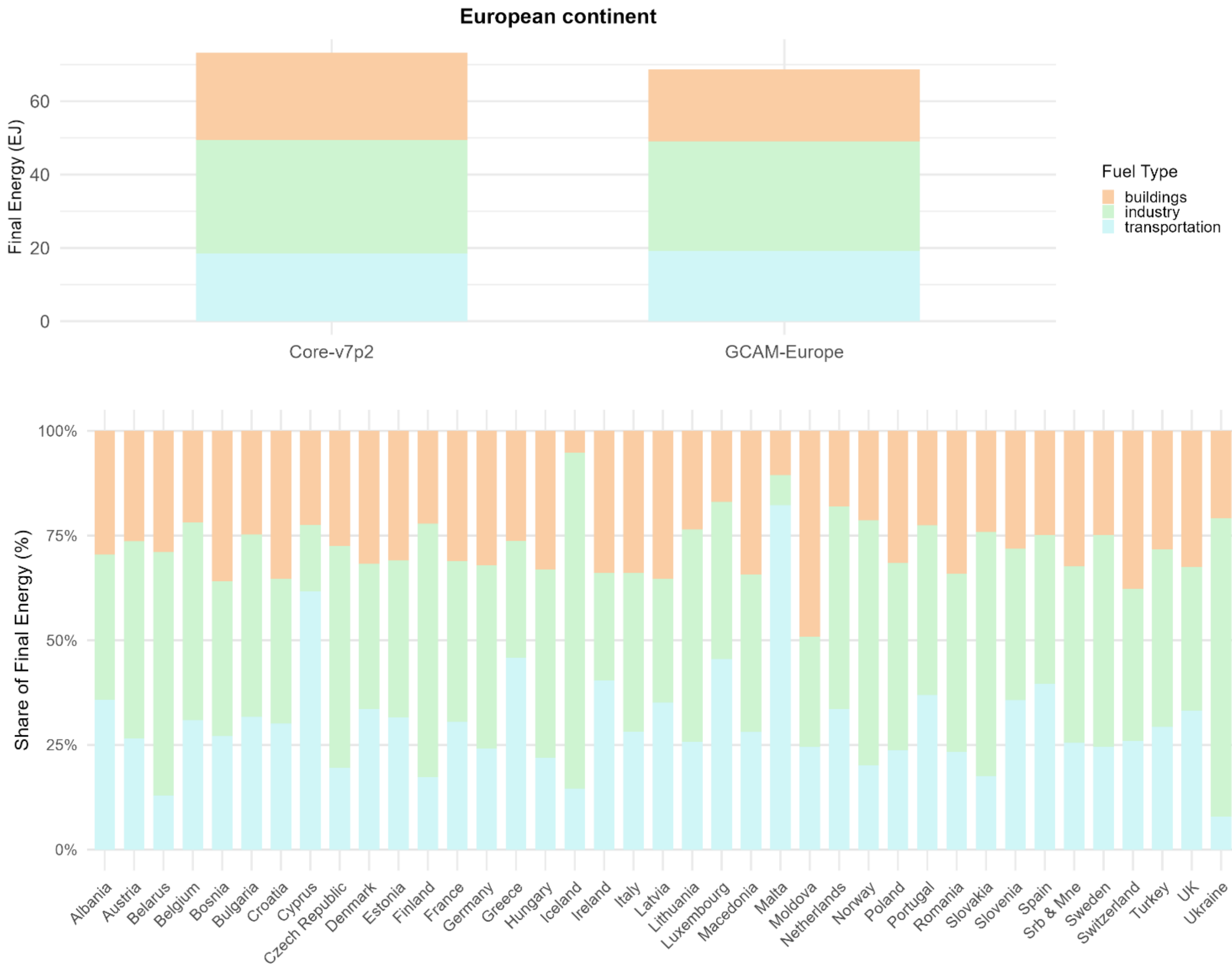


Figure 7: Final energy consumption in 2050 by scenario region, and fuel (EJ). The upper panelPanel A shows total final energy for the European continent (EJ). The lower panelPanel B shows the weight of different sectors in each country's final energy consumption (%) in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S62. Total final energy by European country is shown in the Supplementary Information (SI) Fig S75.

Focusing on the power sector, electricity production in the GCAM-Europe baseline scenario shows ana steady increase during the entire century, from around 14 EJ generated in 2015 to 24 EJ in 2100. However, this growth is smaller than the one in the core baseline, which exceeds the 29 EJ of electricity generation by 2100 (Fig S86). The notable differences between the core and GCAM-Europe are driven by variations in total final energy demand, as well as differences in the representation of the power system.

The share of fossil fuel in total electricity generation is almost similar in the two model versions. We see that in the two scenarios coal and gas still represent around 20% and 15% of the European electricity mix by 2050. However, notable differences emerge between GCAM-Europe and the core model version in the deployment of renewable energy sources within the electricity sector, largely driven by the load segments, inter-segment storage, and grid regions included in GCAM-Europe. For example, grid storage represents around 6% of the electricity mix by 2050 in the GCAM-Europe baseline, which is not represented in the core. Likewise, there are large differences in wind power generation. While it represents around 18% of the total electricity mix in 2050 in the core, this share decreases to 7% in the GCAM-Europe baseline. The share of total solar power is also similar across scenarios, but there are some technological differences. In GCAM-Europe there is a higher penetration of distributed rooftop photovoltaics, while centralised photovoltaics power sources are the main solar energy source in the core. Nuclear energy is also relatively similar in the two scenarios, accounting for around 18% of the European electricity mix by 2050.

There are also large differences across European regions, with different countries showing completely different electricity mixes, depending on their access to alternative energy sources (Figure 8)~~(. Figure 8).~~ By 2050, some regions are projected to rely almost entirely on renewable energy (e.g., Switzerland). In contrast, fossil fuels are expected to continue playing a major role in other countries, particularly in Eastern Europe (e.g., Bosnia). We also observe notable differences across electricity system segments, with intermittent technologies playing an increasingly important role in baseload generation, while fossil fuels remain dominant during peak and sub-peak demand periods.

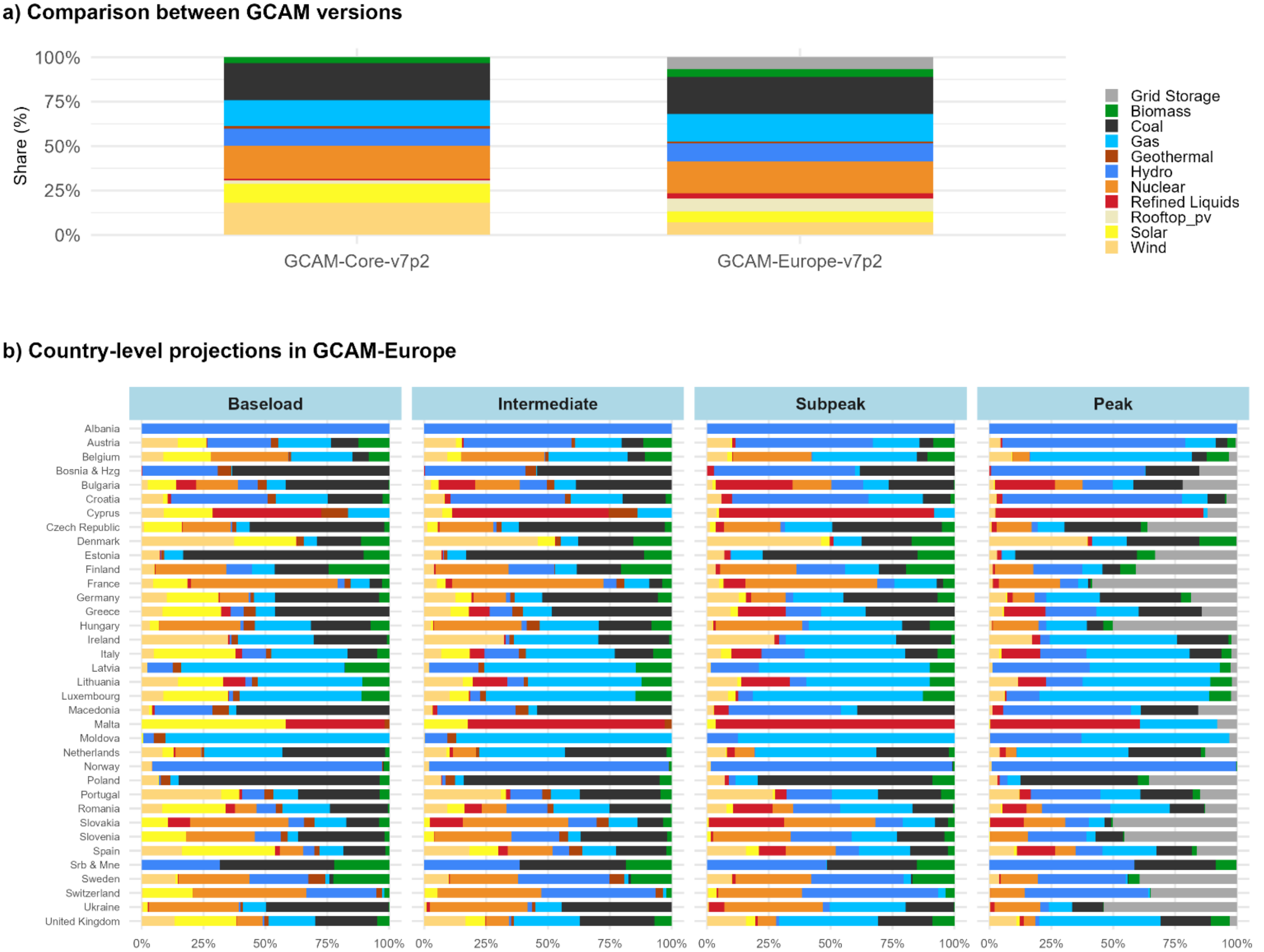
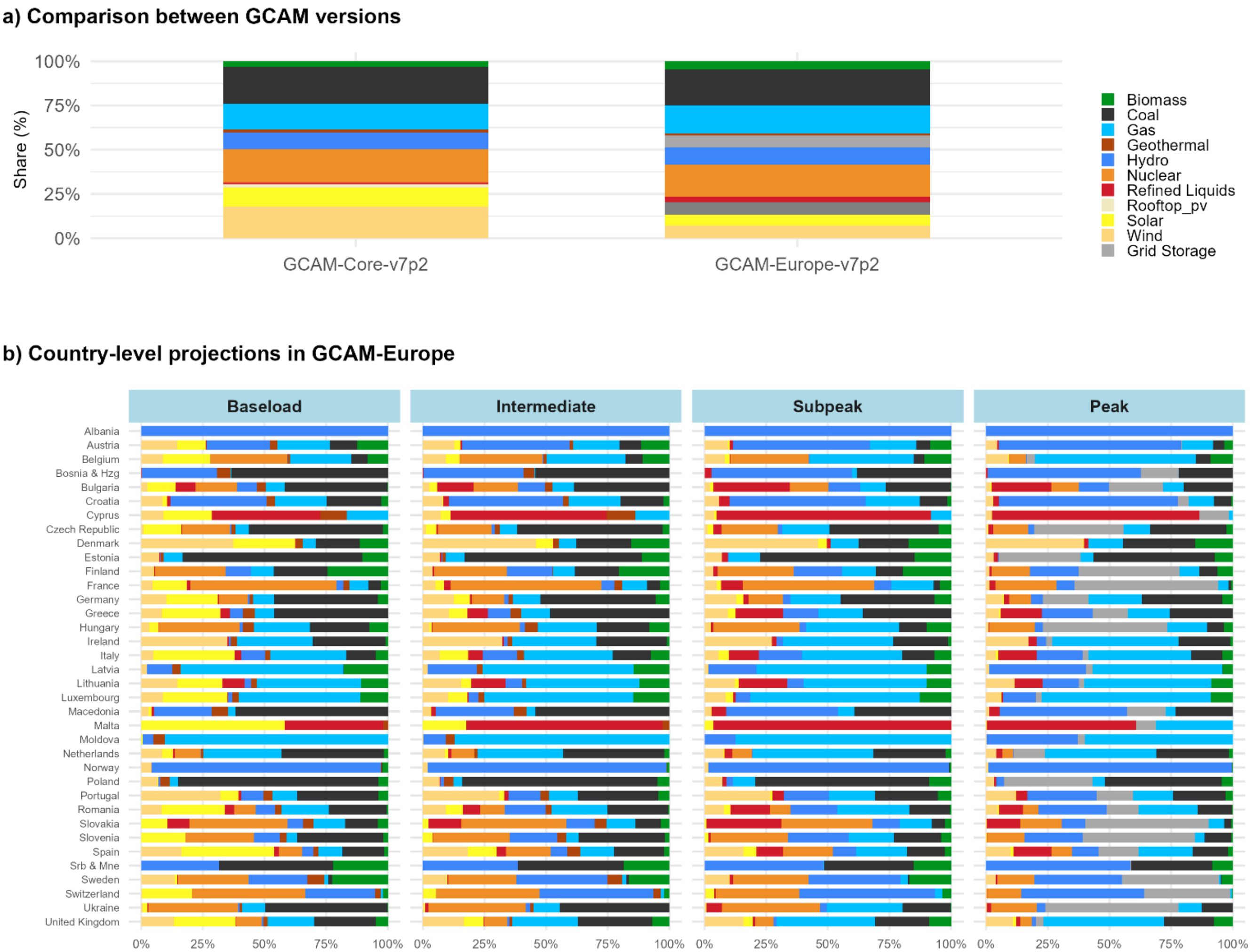


Figure 8: Electricity generation in 2050 by scenario region, and source (EJ). Panel A shows the total electricity mix for the European continent (%). Panel B shows the weight of different sources in each country's final electricity mix (%) in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S9. Total electricity generation by European country is shown in Fig S10. Belarus, Iceland and Turkey are not included as they are not connected to the European grid regions.



a) Comparison between GCAM versions
100%
75%
50%
25%
0%
Share (%)
GCAM-Core-v7p2
GCAM-Europe-v7p2
Biomass
Coal
Gas
Geothermal
Hydro
Nuclear
Refined Liquids
Rooftop_pv
Solar
Wind
Grid Storage
b) Country-level projections in GCAM-Europe
Baseload
Intermediate
Subpeak
Peak
Albania
Austria
Belgium
Bosnia & Hzg
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
Ukraine
United Kingdom
0%
25%
50%
75%
100%

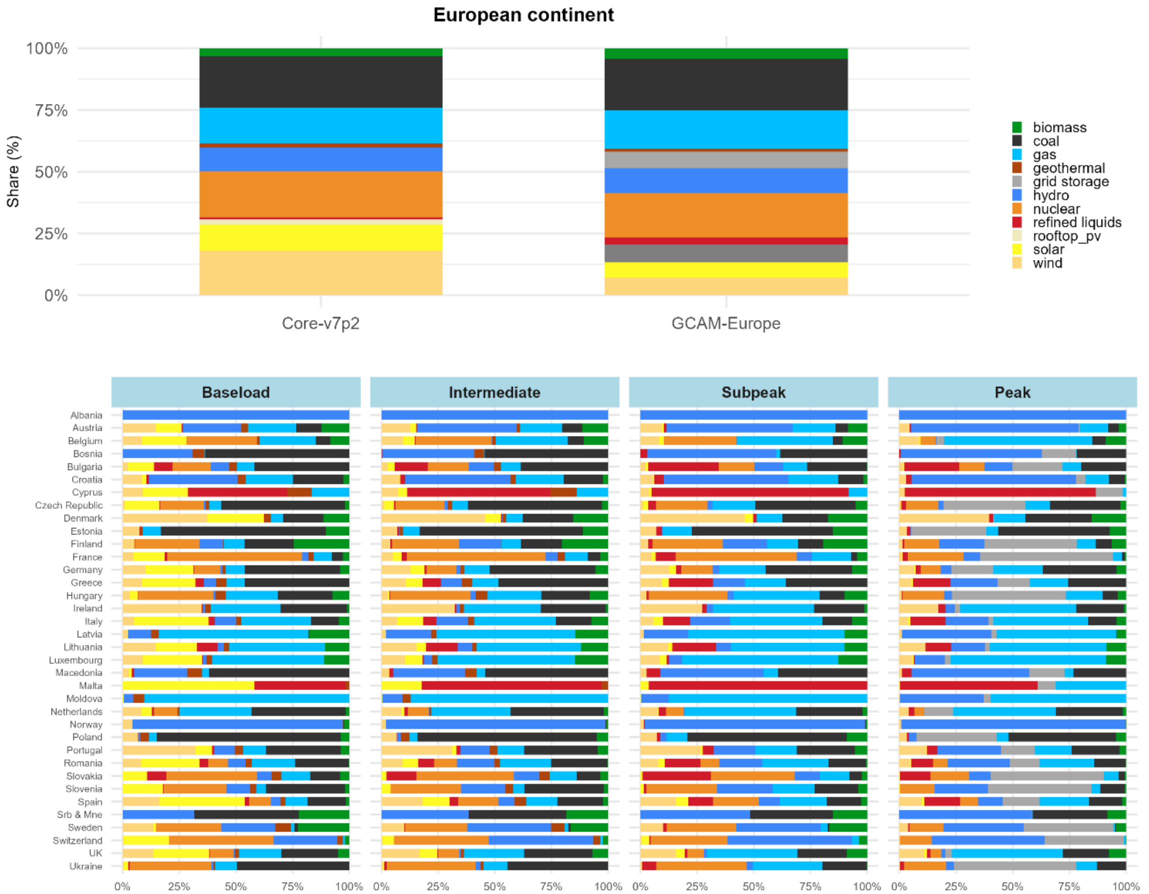
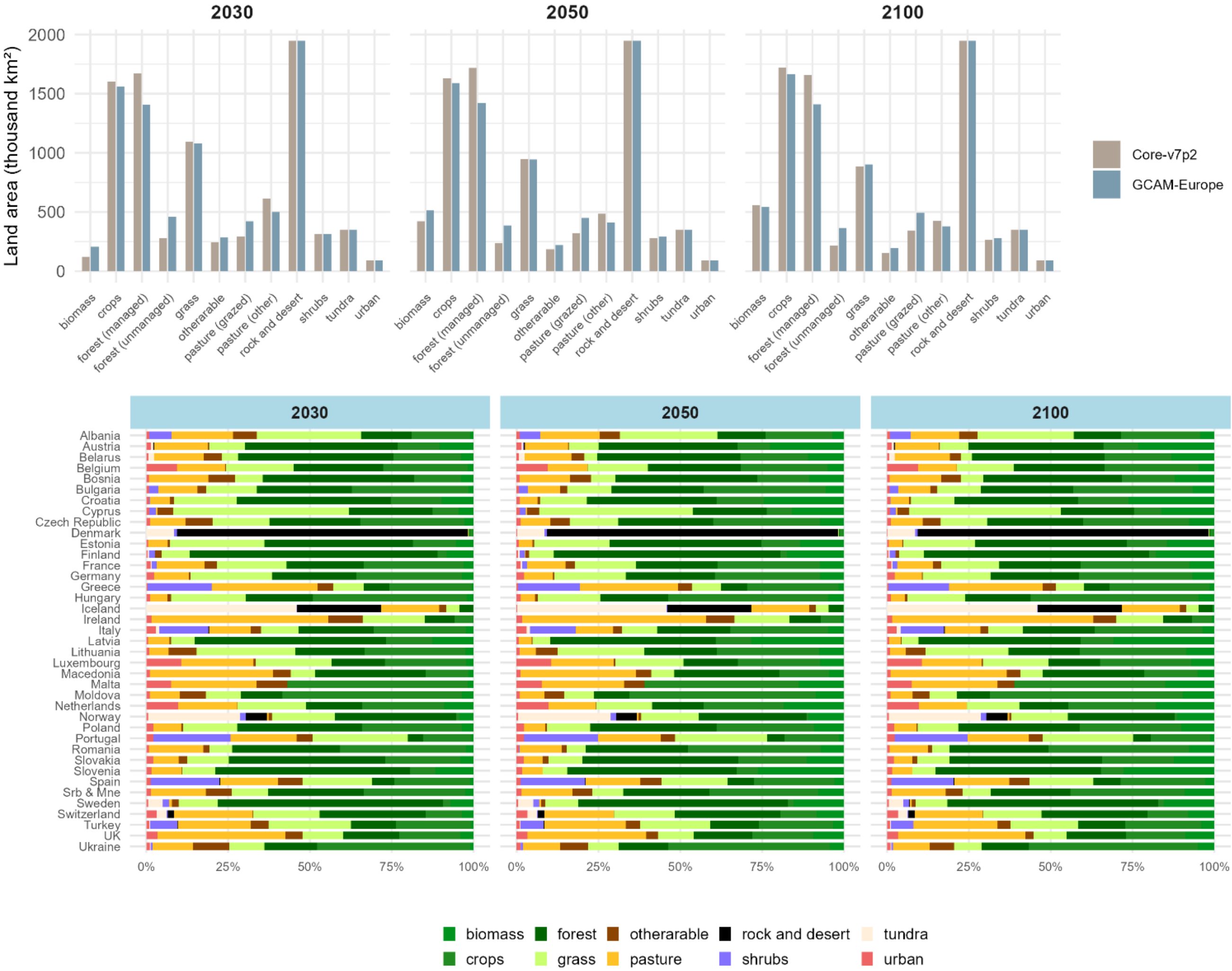


Figure 8: Electricity generation in 2050 by scenario region, and source (EJ). The upper panelPanel A shows the total electricity mix for the European continent (%). Panel B The lower panel shows the weight of different sources in each country's final electricity mix (%) in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig STotal9. Total electricity generation by European country is shown in the Supplementary Information (SI) Fig S107. Belarus, Iceland and Turkey are not included as they are not connected to the European grid regions.

3.3. Land and water

The higher disaggregation and new features incorporated into GCAM-Europe have some direct and indirect impacts on the distribution of land compared to the core version of the model (Figure 9). In GCAM, there are some land types that are exogenously defined and do not compete with other land types. These include the urban, tundra and “rock and dessert” categories, which are therefore identical in the two scenarios. Some natural land types, such as shrubs or grass, also show minor variations between GCAM-Europe and the core. The most significant differences are found in the distribution of pasturelands and forests. GCAM-Europe projects a larger share of grazed pastures, reaching up to 490 thousand km2 by the end of the century, which is substantially higher than the 344 thousand km2 projected by the core model. In contrast, the area of non-grazed (“other”) pastures is notably larger in the core version of the model, especially in the near term, with projections of 611 thousand km2 in 2030 compared to 499 thousand km2 in GCAM-Europe. A similar dynamic is observed in the distribution of forestland. The core model has more land allocated for managed forest, representing up to 1720 thousand km2 in 2050, higher than the 1420 thousand km2 in GCAM-Europe. However, the share of natural (unmanaged) forest is larger in the GCAM-Europe baseline. These differences are driven by the use of assumed yields in combination with observed national outputs of forest and animal products to define the relative share of managed pasture and forest relative to all pasture and forest (Zhao and Wise, 2023n.d.)(Zhao & Wise, 2023). Real-world deviations from the assumed yields can lead to under- or overestimation of “managed land”, and by aggregating many regions, such under or overestimations can persist throughout the whole region. Having separated all countries however, the estimated area of “managed land” on aggregate are likely more accurate, as the impact of potential yield deviations are limited to each individual country. Land distribution varies significantly across European countries. While cropland and forests represent the majority of land use in many regions, pasture is particularly prominent in some areas, such as the United Kingdom. In Scandinavian countries, such as Denmark, tundra and "rock and desert" areas also account for a notable portion of the total land area (Figure 9Figure 9).


2030
2050
2100
Land area (thousand km²)
0
500
1000
1500
2000
biomass
crops
forest (managed)
forest (unmanaged)
grass
otherarable
pasture (grazed)
pasture (other)
rock and desert
shrubs
tundra
urban
Core-v7p2
GCAM-Europe
Albania
Austria
Belarus
Belgium
Bosnia
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
Turkey
UK
Ukraine
0%
25%
50%
75%
100%
biomass
forest
otherarable
rock and desert
tundra
crops
grass
pasture
shrubs
urban

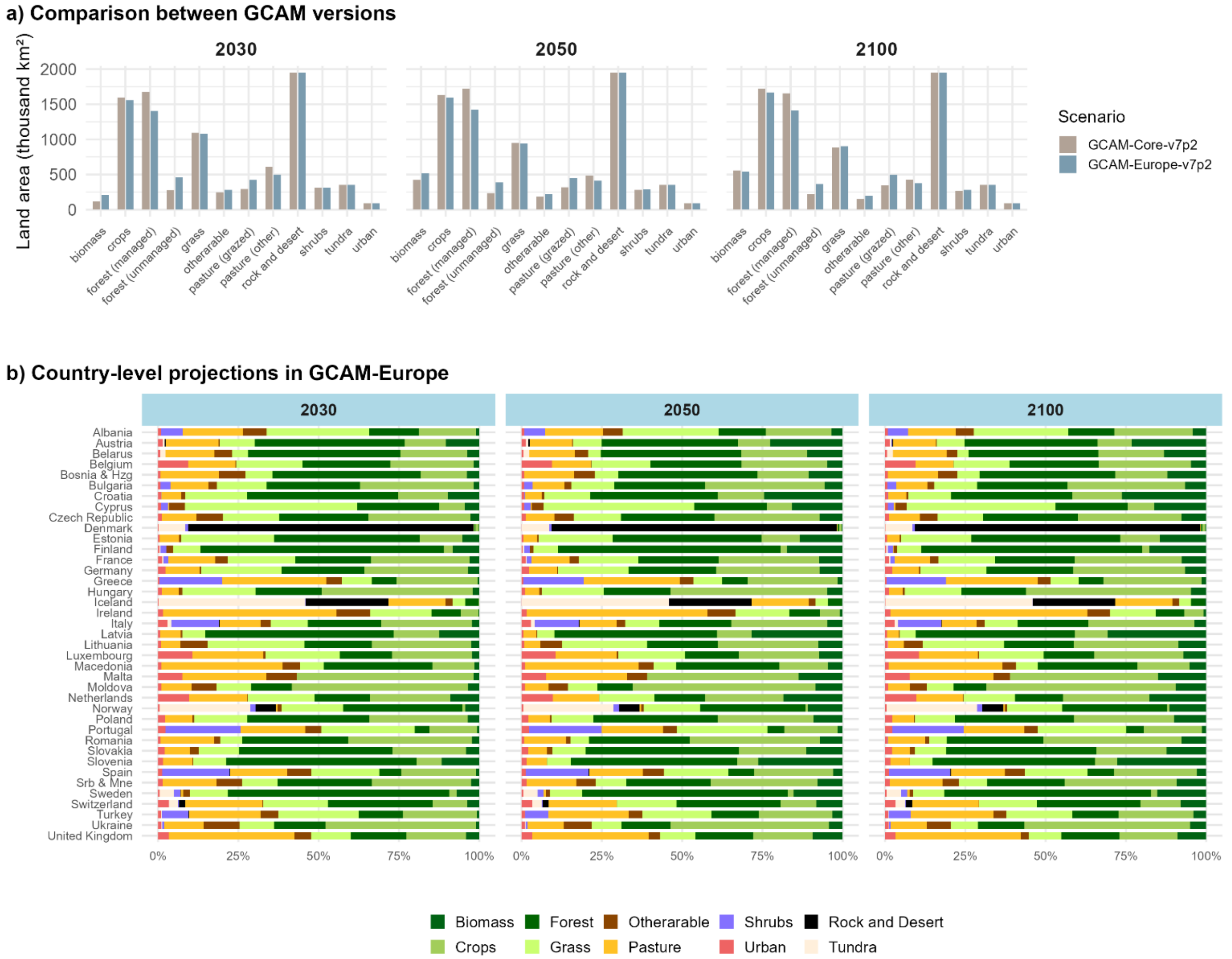


Figure 9: Land allocation by scenario, region, period and type.

Figure 9: Land allocation by scenario, region, period and type. The upper panelPanel A shows the total land area for the European continent by scenario, period and land type. The lower panel Panel B shows the weight of different land types in each country for different time periods (%) in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S11.

Total water withdrawals for the European continent in GCAM-Europe show a moderate and steady increase over time, rising from 330 km³ in 2020 to 380 km³ in 2085, followed by a slight decline to 365 km³ by 2100 (Figure 10Figure 10). The figure also shows how the projected differences in energy mix and land allocation between GCAM-Europe and the core model also result in changes to water systems, with GCAM-Europe showing a slightly higher water withdrawal volume by the end of the century. Water withdrawal levels vary across European countries, with some countries such as Germany, France, and

Turkey recording notably higher volumes. While certain countries, like France, exhibit an upward trend in water withdrawals, the overall growth across most of Europe remains relatively moderate. In fact, some countries, such as Poland, show a decline in their water withdrawal volumes over time. On top of water withdrawal projections presented in Figure 10, the current structure of GCAM-Europe enables analyzing multiple aspects of water-energy interactions, such as inter alia water implications of CO_2 emission reductions (e.g., increased water use from shift to low-carbon technologies), and co-benefits from energy–carbon–water nexus policies (Li et al., 2020; Srinivasan et al., 2018)(Srinivasan et al., 2018; Li et al., 2020).


a) European continent
Water use (km3)
300
200
100
0
2010
2040
2070
2100
Scenario
GCAM-Core-v7p2
GCAM-Europe-v7p2
b) Indiviual countries
Water use (km3)
40
20
0
Albania
Austria
Belarus
Belgium
Bosnia & Hzg
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
Turkey
Ukraine
United Kingdom
2020
2040
2060
2080
2100

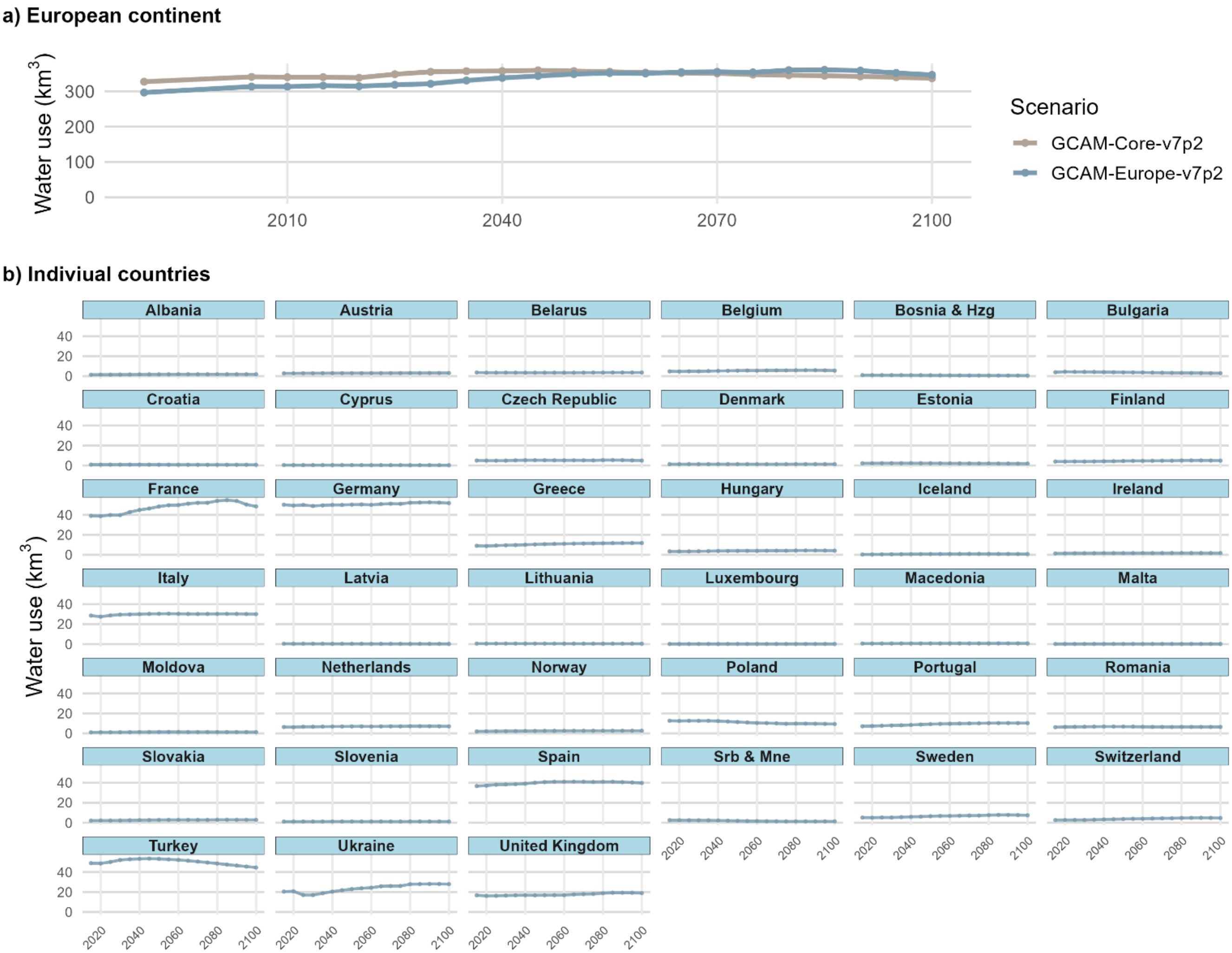
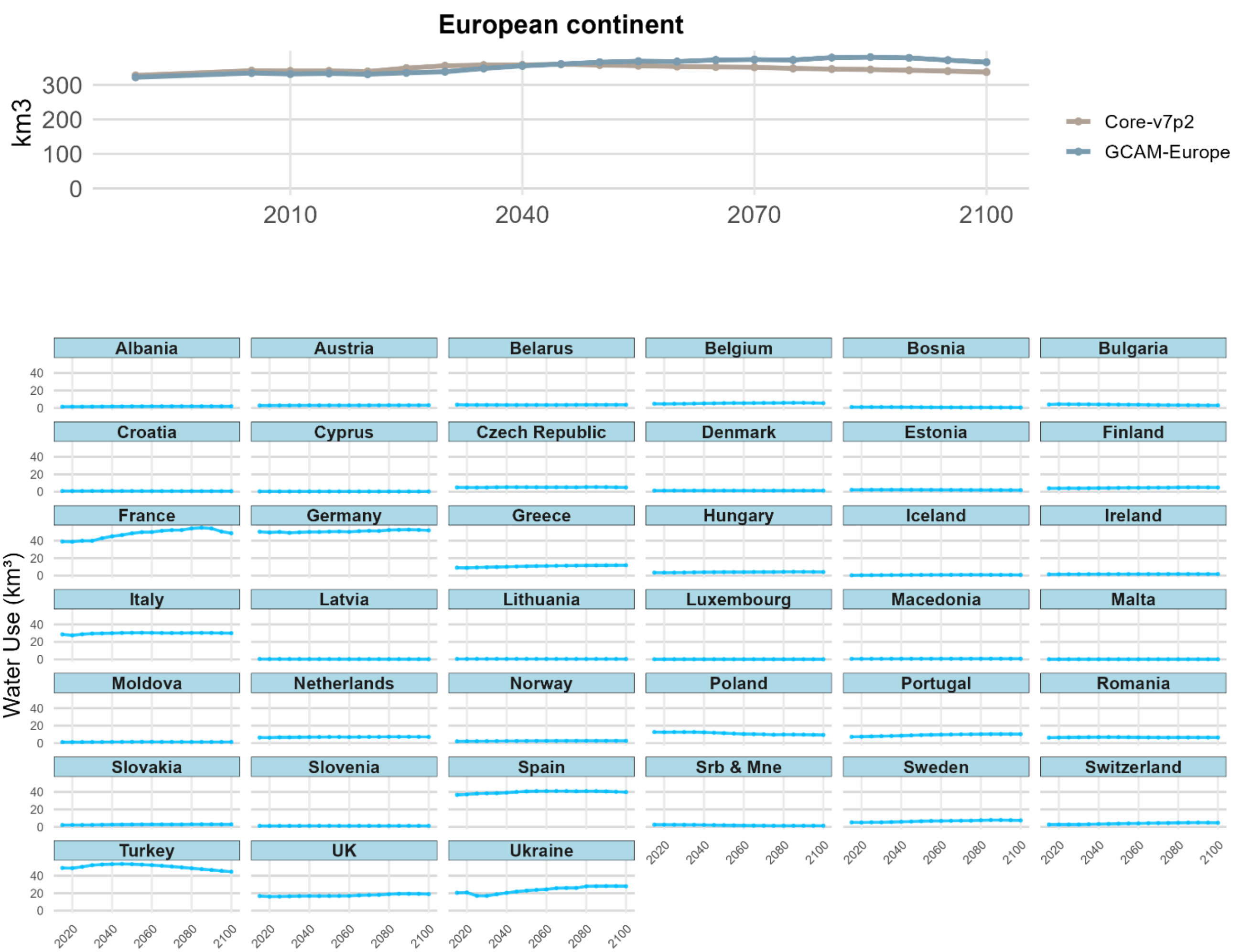


Figure 10: Water withdrawals by scenario, region, and period (km3).

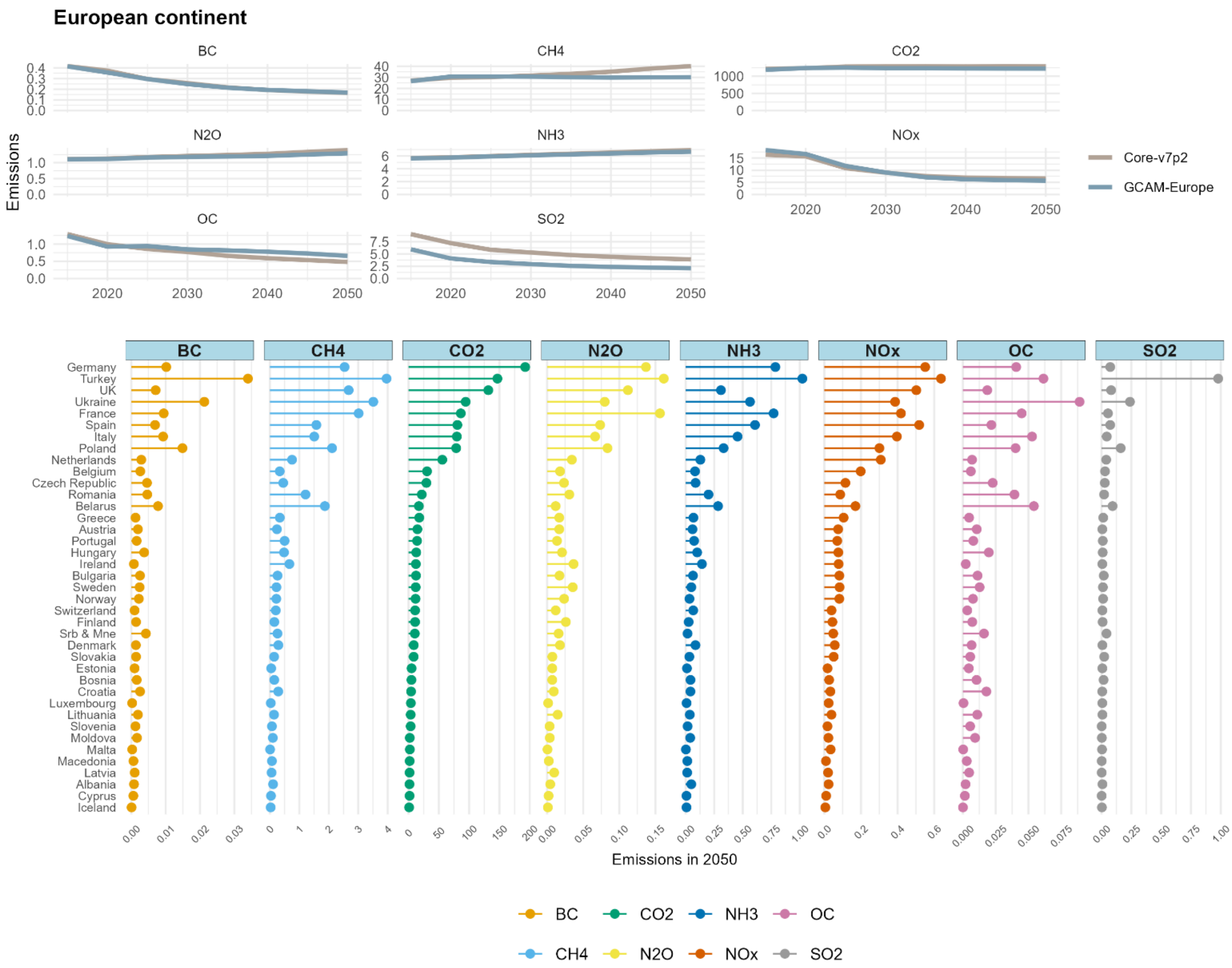


~~**Figure 10 Water withdrawals by scenario, region, and period (km3).**~~ ~~The upper panel~~ Panel A shows total water withdrawals for the European continent by scenario and period. Panel B ~~The lower panel~~ shows water withdrawals by period and country in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S12.

3.4. Emissions

Future emission projections of greenhouse gases and air pollutants in GCAM-Europe substantially varies across regions and species (Figure 11~~Figure 11~~). Total carbon dioxide (CO2) emissions remain relatively constant at European level, slightly rising from 1178 MTC in 2015 to 1220 MTC in 2100. Detailed CO2 emission projections for different European countries are provided in the SI (Fig S13~~S8~~). Similar trends can be observed in the emissions of other greenhouse gases such as methane (CH4) and nitrogen dioxide (N2O). In contrast, emissions of air pollutants generally decrease over time, with the exception of ammonia (NH3), which increases due to rising livestock production. These decreasing trends in air pollutants are driven by assumed reductions in emission factors (EFs) over time resulting from technological advancements and stricter air quality regulations. There are also some differences across GCAM-Europe and the core model, particularly in terms CH4 and sulphur dioxide (SO2) emissions. The divergence in CH4 emissions are associated with changes in livestock. For example, methane emissions attributable to the production of beef account for 6.5 Tg and 5 Tg in the core and GCAM-Europe baselines, respectively in 2100. The differences in SO2 emissions are mainly driven by the lower final energy consumption in the GCAM-Europe baseline.

Figure 11 ~~Figure 11~~ also highlights significant differences in GHG and air pollutant emissions across European countries, with certain nations emerging as major contributors for specific species. Germany leads emissions of CO2 with nearly 192.5 MTC in 2050, followed closely by Turkey (146.7 MTC), the UK (131.7 MTC), and France (86.3 MTC), reflecting their larger energy demands. CH4 emissions are highest in Turkey (3.96 Tg in 2050), Ukraine (3.51 Tg), and France (3.01 Tg), which is directly related to the size of their of agricultural and waste sectors. In the case of NH3, primarily linked to livestock and fertilizer use, Turkey, Germany, and France show the largest emissions with values in 2050 accounting for above 0.7 Tg. For nitrous oxide (N2O), emissions are more evenly spread, but Turkey, France, and Germany remain the top contributors. Nitrogen oxides (NO_x), mainly from combustion processes, show the highest emissions in Turkey, Germany, and Spain, each exceeding 0.5 Tg in 2050. Emissions of primary particulate matter (PM2.5), namely black carbon (BC) and organic carbon (OC), have their highest emissions in Germany, Poland, and Turkey (BC), and Belarus, Italy, and Ukraine (OC). Finally, sulphur dioxide (SO2) emissions, linked to fossil fuel combustion, are highest in Turkey, followed by far by Ukraine, and Poland, highlighting continued reliance on sulphur-intensive energy sources in these regions.



European continent
BC
CH4
CO2
N2O
NH3
NOx
OC
SO2
Emissions
Core-v7p2
GCAM-Europe
2020
2030
2040
2050
Germany
Turkey
UK
Ukraine
France
Spain
Italy
Poland
Netherlands
Belgium
Czech Republic
Romania
Belarus
Greece
Austria
Portugal
Hungary
Ireland
Bulgaria
Sweden
Norway
Switzerland
Finland
Srb & Mne
Denmark
Slovakia
Estonia
Bosnia
Croatia
Luxembourg
Lithuania
Slovenia
Moldova
Malta
Macedonia
Latvia
Albania
Cyprus
Iceland
Emissions in 2050

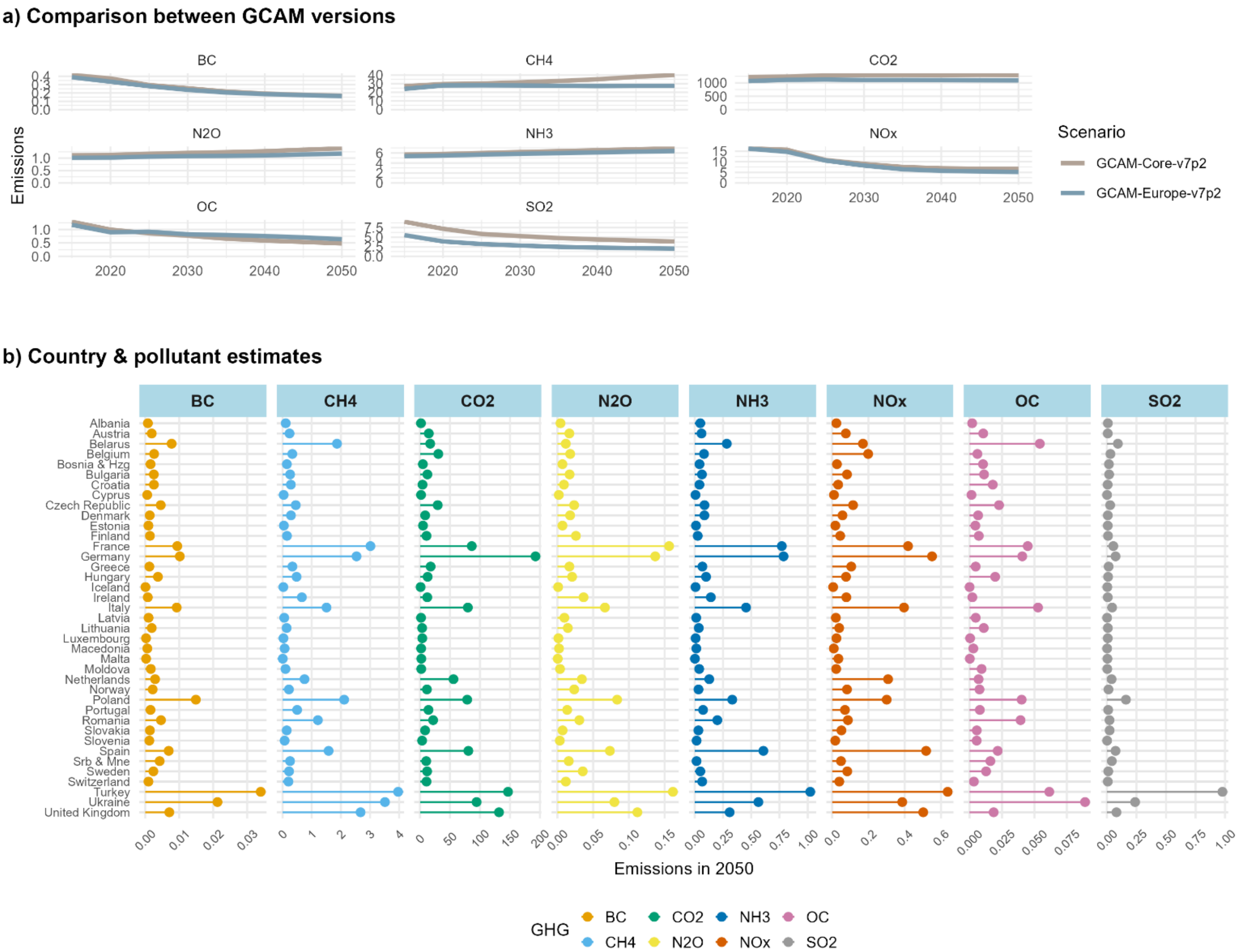


Figure 11: GHG and air pollutant emissions by scenario, region, period and specie.

Figure 11: GHG and air pollutant emissions by scenario, region, period and specie. The upper panelPanel A shows total emissions for the European continent by scenario, period and specie (MTC and Tg). PanelThe lower panel B shows emissions by period, country and specie for 2050 in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S14.

3.5. Trade dynamics

The implementation of the double-Armington structure to represent trade dynamics in GCAM-Europe changes the relation between domestic versus ~~imported~~ traded commodities in the different European countries, both within EEA countries and internationally (Figure 12~~Figure 12~~). Taking 2050 as a reference year, we observed several differences across trade commodities. For fossil fuels, both scenarios project strong dependence on international crude oil imports (around 19 EJ in 2050), with minimal intra-EEA trade, a pattern also observed for coal. In contrast, the explicit representation of intra-EEA markets in GCAM-Europe increases natural gas trade within Europe. In 2050, intra-EEA gas imports reach 8 EJ, exceeding total international imports (7.5 EJ).

Biomass production rises in GCAM-Europe relative to the core model (17 EJ versus 15 EJ), consistent with recent estimates of European biomass potential (Ruiz et al., 2019). Although intra-EEA biomass trade exists, it remains limited compared to international exchanges. At the country level, Scandinavian nations are major biomass exporters, with Sweden exporting about 1.6 EJ in 2050. Germany is the largest importer (1.2 EJ), nearly matching its domestic production. Iron and steel production and trade also expand under the double-Armington structure, with the largest flows involving Ukraine, Germany, and Turkey. A similar trend is observed for livestock, where intra-EEA trade intensifies, particularly among Germany, France, and the Netherlands.

~~For crude oil, both scenarios project heavy reliance on imports, but in GCAM-Europe this dependence is slightly increased (20.22 EJ imported versus 18.62 EJ in the core). In the case of solid fuels such as coal and biomass, domestic production continues to exceed imports in both scenarios; however, the structural shift in GCAM-Europe results in increased reliance on imports and a corresponding decline in domestic output. By 2050, imports of biomass and coal are projected to rise to 4.63 EJ and 8.61 EJ, respectively, under GCAM-Europe, both noticeably higher than the 2.53 EJ and 7.20 EJ observed in the core scenario. Natural gas shows a decline in both domestic production and imports in GCAM-Europe compared to the core, driven by the reduced demand for gas-based energy technologies projected in this scenario. In the case of crops, the model assumes a "single European market" for agricultural commodity trade, which results in only minor differences between scenarios in the balance between domestic production and imports. GCAM-Europe projects a modest increase in domestic crop production (1,450 Mt compared to 1,395 Mt in the core) alongside a slight reduction in imports (398 Mt versus 418 Mt) by 2050. The double Armington structure implemented in GCAM-Europe has a pronounced impact on the import patterns of several key commodities, including iron and steel, ammonia, and livestock. In the GCAM-Europe baseline for 2050, imports of these commodities rise significantly, reaching 129 Mt for iron and steel, 12 Mt for ammonia, and 45 Mt for livestock,~~

~~substantially higher than the corresponding values in the core scenario, which account for 69 Mt, 6 Mt, and 13 Mt, respectively. In contrast, domestic production of these same commodities is lower in the GCAM-Europe baseline: iron and steel production decreases from 116 Mt in the core to 80 Mt, ammonia declines from 18 Mt to 16 Mt, and livestock production decreases from 273 Mt to 244 Mt.~~

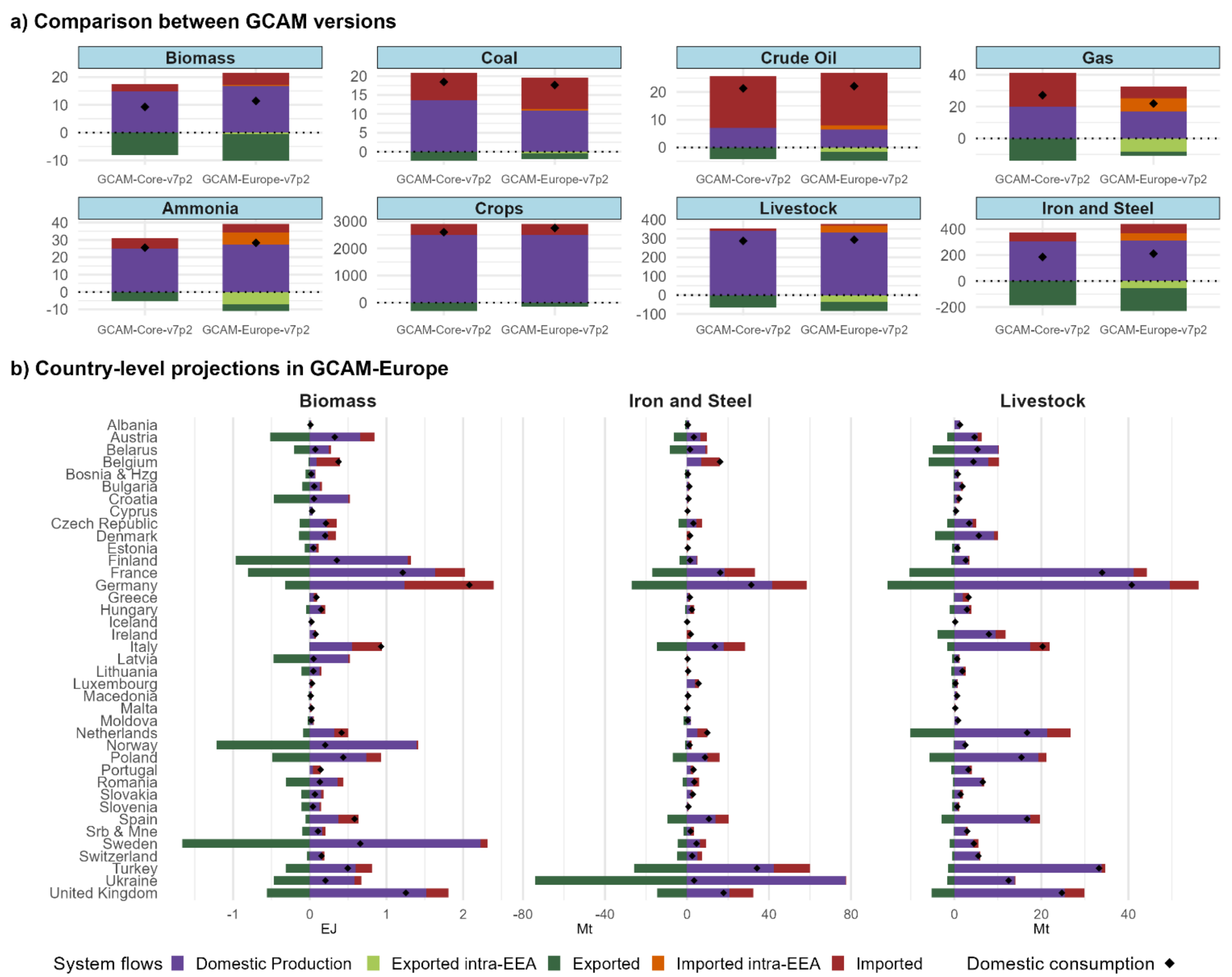
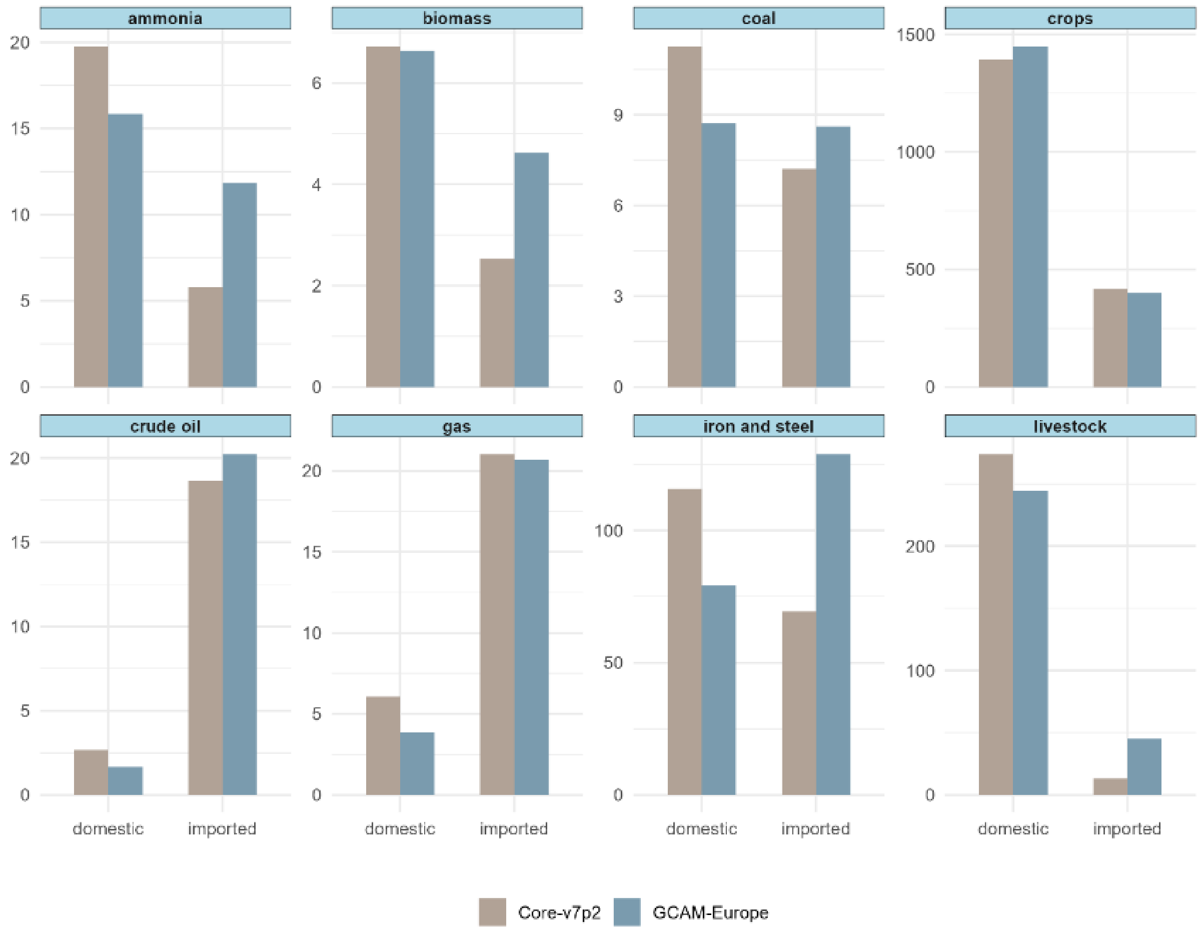
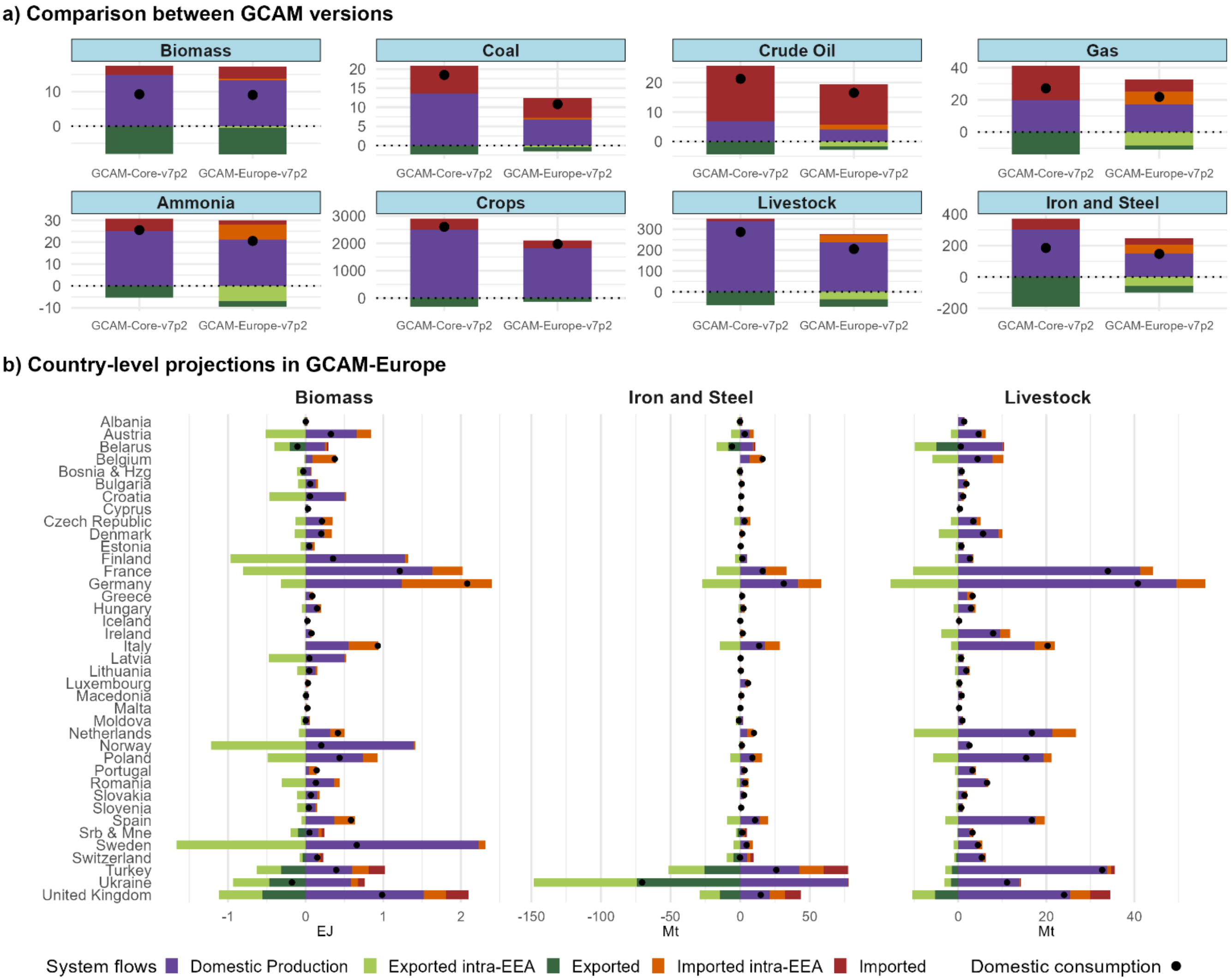


Figure 12: Domestic production and trade dynamics in 2050 by scenario and commodity (EJ or Mt). Panel A shows total emissions for the European continent by scenario, period and specie (MTC and Tg). Panel B shows emissions by period, country and specie for 2050 in the GCAM-Europe baseline. A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S15. Panel B does not disaggregate intra and extra EEA trade.


ammonia
biomass
coal
crops
crude oil
gas
iron and steel
livestock
20
15
10
5
0
6
4
2
0
9
6
3
0
1500
1000
500
0
20
15
10
5
0
20
15
10
5
0
100
50
0
200
100
0
domestic
imported
domestic
imported
domestic
imported
domestic
imported
Core-v7p2
GCAM-Europe

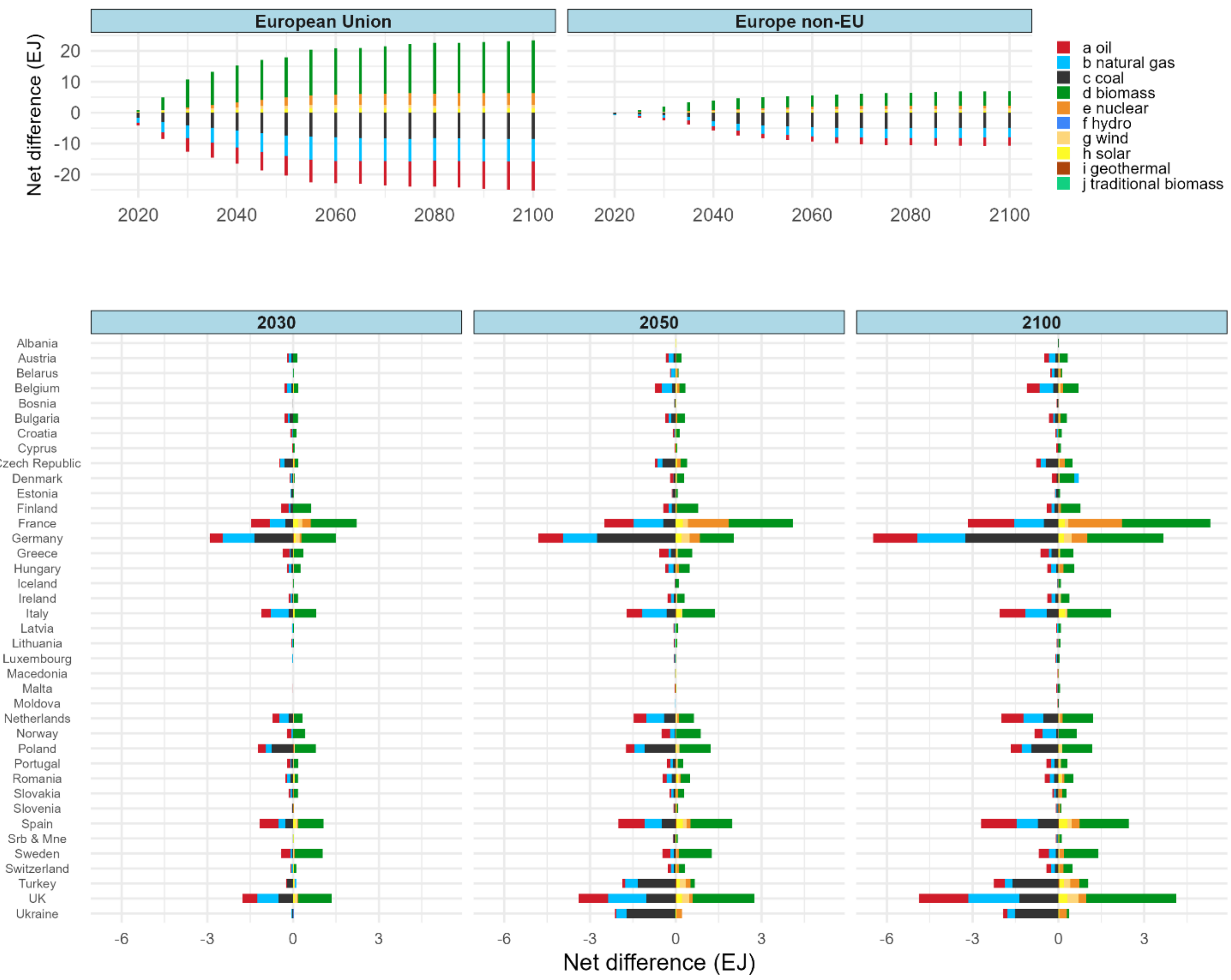


~~**Figure 12: Domestic production and imports in 2050 by scenario and commodity (Mt and EJ).** A comparison between GCAM-Europe and the GCAM core for the five core European regions is provided in Fig S15.~~

4. Implementation of a climate policy

The aim of this section is to see how GCAM-Europe responds to the implementation of an ambitious climate policy and analyse the main resulting changes in terms of energy system and emission pathways. The "policy" scenario includes a CO2 emission constraint for EU-27 compatible with the Nationally Determined Contribution (NDC) in 2030 and the 2050 Net-Zero target (van de Ven et al., 2023). Since the purpose of this exercise is to test the responsiveness of the model to a stylised definition of climate policy, targets are achieved through an economy-wide carbon price that guarantees the achievement of the beforementioned targets. Similarly, ~~I~~it also introduces a carbon tax for other European and global regions, consistent with their respective NDCs and long-term climate goals.

The policy has a direct impact on primary energy consumption at European level, affecting both total energy demand and the composition of the energy mix (Figure 13~~Figure 13~~). At EU level, there is a rapid and pronounced decrease of fossil fuel demand in the policy scenario, which produces several co-benefits in terms of air quality or energy security. C~~In the policy scenario, c~~oal, gas, and oil consumption decrease by 7.4, 6.6, and 6.4 EJ, respectively, in 2050, and by 8.5, 7.3, and 9.4 EJ in 2100, compared to the baseline. The reduced fossil fuels demand primarily offset by biomass, nuclear and other renewable energy sources, such as wind or solar. At the EU level, biomass use rises by 13 EJ in 2050 and 17 EJ in 2100 in the policy scenario compared to the baseline. Nuclear energy also sees an increase of approximately 2.6 EJ in 2050 and 3.8 EJ in 2100. Solar and wind energy together contribute an additional 2.2 EJ in 2050 and 2.4 EJ in 2100 relative to the baseline. Whereas in the no-policy scenario in Section 3 the share of RES in primary energy consumption was limited, the share of RES in electricity generation was more substantial, reflecting the existing economic competitiveness of renewables. The implementation of even a stylized policy, however, was able to produce system-wide changes that increased the penetration of RES in the overall energy mix. The non-EU European regions show similar trends, with biomass and other renewable energy sources consistently replacing fossil fuel demand throughout the entire century in the policy scenario. While all European countries show a consistent decline in fossil fuel demand, the choice of (non-emitting) replacement technologies varies by country (Figure 13~~Figure 13~~). This variation is influenced by country-specific factors such as current and projected costs of resources and technologies, as well as historical preferences for certain energy carriers. For example, nuclear energy is expected to play a major role in France due to its existing nuclear infrastructure. In contrast, countries like the UK are projected to see a large share of wind power in their primary energy mix.


European Union
Europe non-EU
Net difference (EJ)
20
10
0
-10
-20
2020
2040
2060
2080
2100
a oil
b natural gas
c coal
d biomass
e nuclear
f hydro
g wind
h solar
i geothermal
j traditional biomass
2030
2050
2100
Albania
Austria
Belarus
Belgium
Bosnia
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
Turkey
UK
Ukraine
-6
-3
0
3
Net difference (EJ)

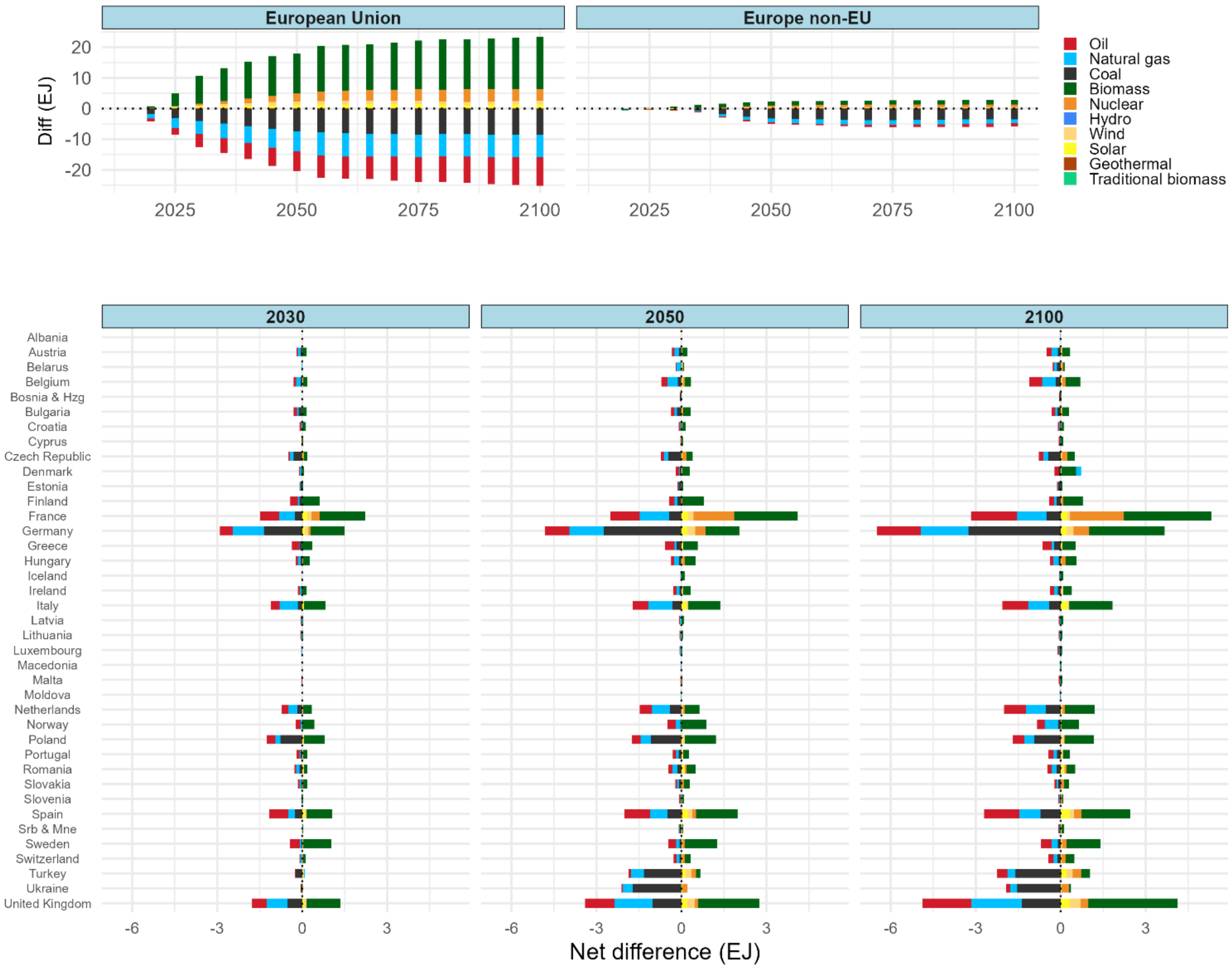
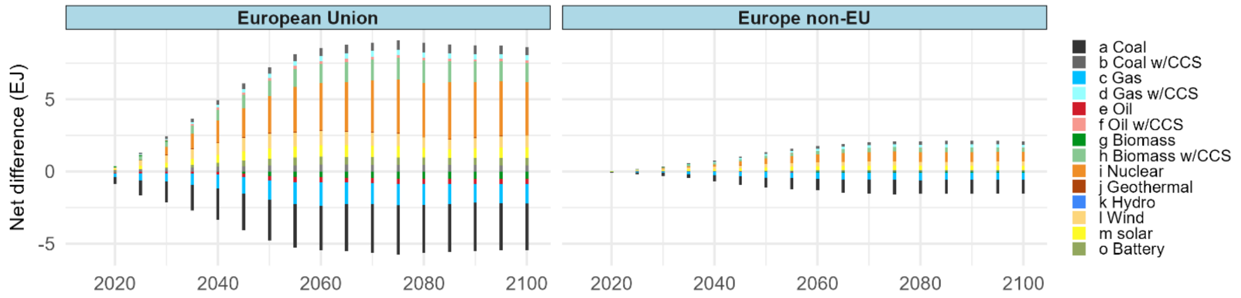
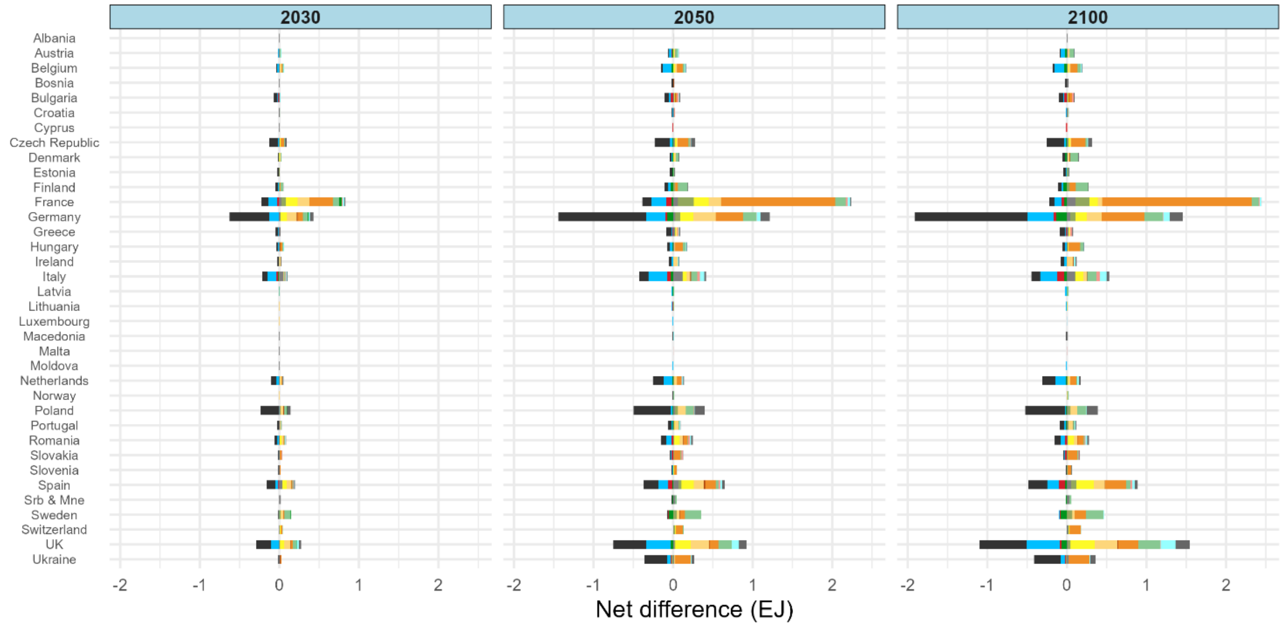


Figure 13: Difference in primary energy demand between the policy and the baseline scenarios by period, region, and fuel. The upper panel shows absolute differences (Policy - Baseline) in primary energy for the entire EU and non-EU regions by period, region and fuel (EJ). The lower panel shows the country level differences by period and fuel (EJ).

~~**Figure 13: Difference in primary energy demand between the policy and the baseline scenarios by period, region, and fuel.** The upper panel shows absolute differences (*Policy - Baseline*) in primary energy for the entire EU and non-EU regions by period, region and fuel (EJ). The lower panel shows the country level differences by period and fuel (EJ).~~

The power sector shows similar trends, with non-emitting technologies replacing fossil fuels in the electricity mix under the policy scenario, both in the EU and other European regions~~.~~ (Figure 14~~Figure 14~~). However, in this sector, nuclear energy is projected to be the main substitute, with an increase of 2.5 EJ in 2050 and 3.7 EJ in 2100 under the policy scenario compared to the baseline. This significant growth is primarily driven by expected nuclear deployment in Germany and France. In the case of Germany, this result seems counterintuitive, given the country's long-standing effort to phase-out nuclear energy as part of the *Energiewende* strategy (Rogge and Johnstone, 2017)~~(Rogge and Johnstone, 2017)~~. However, the policy scenario implemented here is fairly stylized in the sense that it applies an EU-wide target, with the model then freely making decisions based on a cost-optimal basis. This is an important insight both in terms of transparency and prospect capabilities of the model. First, even a version of the model without member state–level spatial granularity might yield similar aggregate EU results, while concealing an underlying regional allocation that would, in practice, be politically unrealistic. By transparently providing the unconstrained tendencies and model fingerprints (Dekker et al., 2023)~~(Dekker et al., 2023)~~ of the newly developed model, future users are informed on appropriate assumptions needed and consequently develop more realistic scenarios. Second, it also highlights the importance of region-specific modelling, since applying national-based constraints and targets per country would improve the policy-realism of the scenarios compared to the aggregated cost-optimal ones. Other countries, such as Spain and the UK, are projected to see a larger increase in solar and wind power, which become the primary substitutes for reduced fossil fuel use. Notably, several countries show some deployment of carbon capture and storage (CCS) technologies, particularly in combination with biomass (i.e., BECCS). However, the projected contribution of CCS to the electricity mix remains limited and does not constitute a significant share in any European country. Finally, Figure 14 ~~Figure 14~~ illustrates an overall increase in total electricity consumption at both the EU and non-EU levels, with particularly notable growth in certain countries, such as France or Spain.


European Union
Europe non-EU
Net difference (EJ)
5
0
-5
2020
2040
2060
2080
2100
a Coal
b Coal w/CCS
c Gas
d Gas w/CCS
e Oil
f Oil w/CCS
g Biomass
h Biomass w/CCS
i Nuclear
j Geothermal
k Hydro
l Wind
m solar
o Battery


2030
2050
2100
Albania
Austria
Belgium
Bosnia
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
UK
Ukraine
-2
-1
0
1
2
Net difference (EJ)

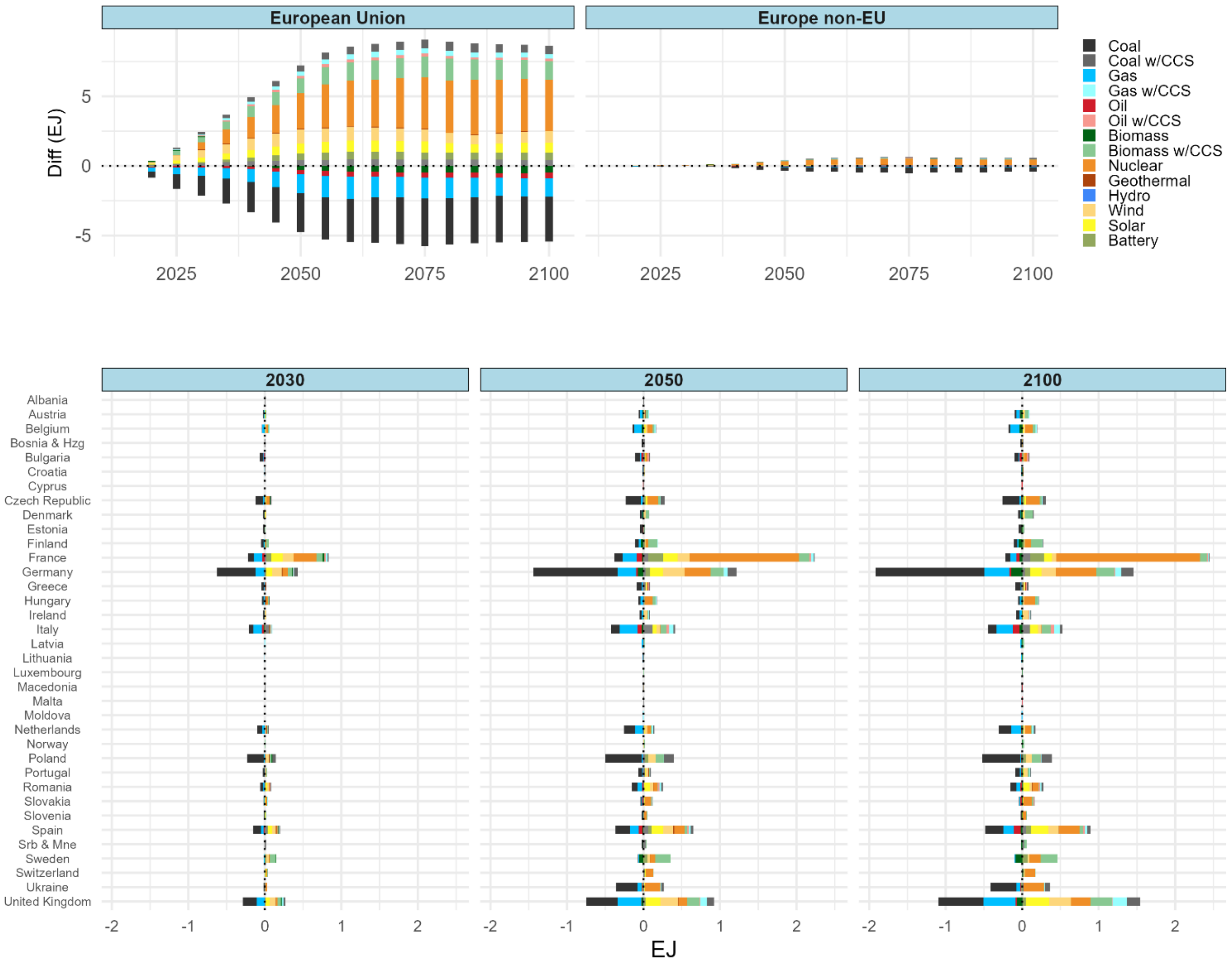


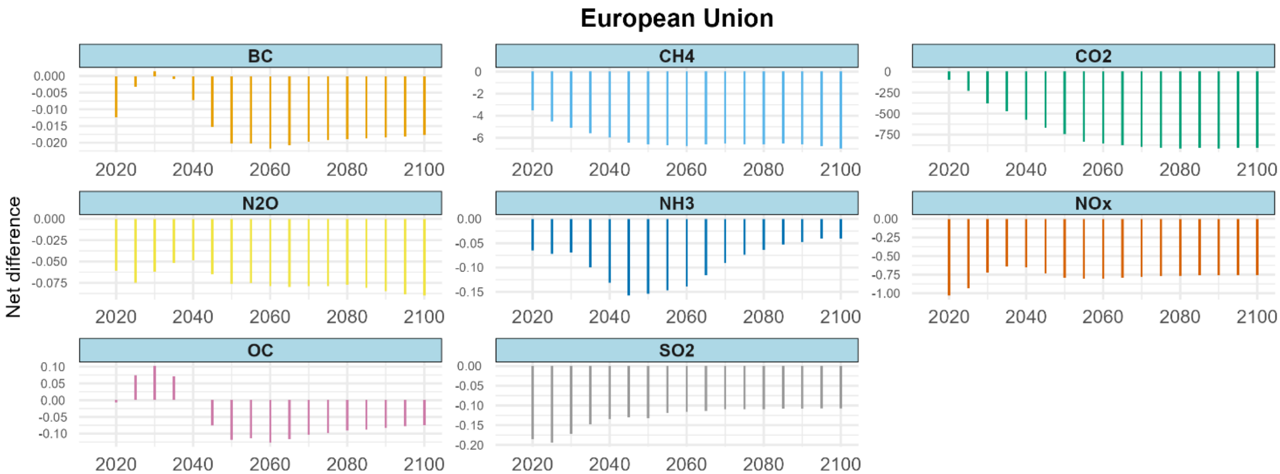
Figure 14: Difference in electricity demand between the policy and the baseline scenarios by period, region, and technology. The upper panel shows absolute differences (Policy - Baseline) in electricity generation for the entire EU and non-EU regions by period, region and technology (EJ). The lower panel shows the country level differences by period and technology (EJ). Belarus, Iceland and Turkey are not included as they are not connected to the European grid regions.

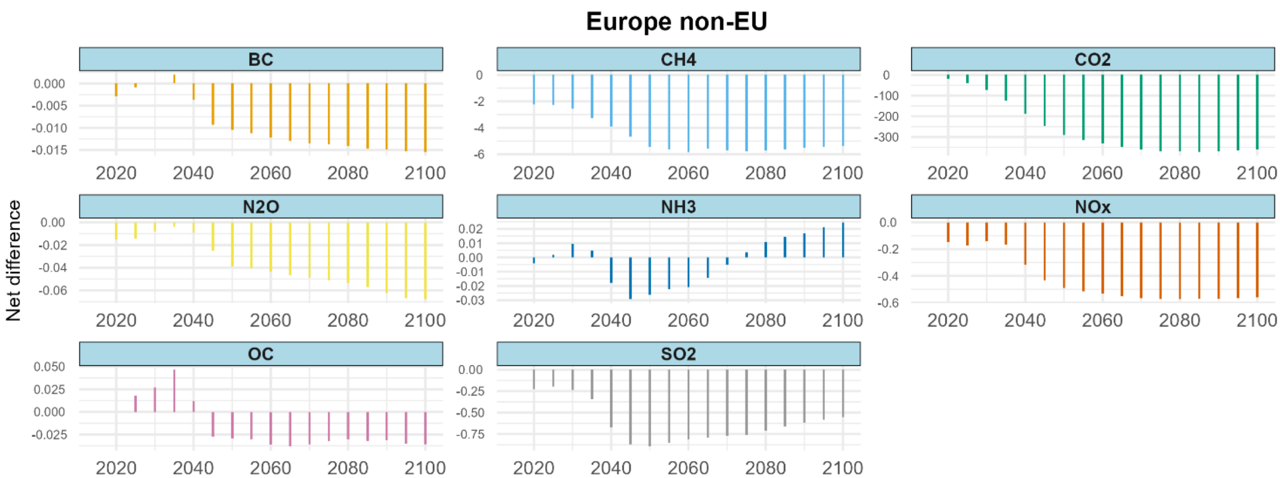
~~**Figure 14: Difference in electricity demand between the policy and the baseline scenarios by period, region, and technology.** The upper panel shows absolute differences (*Policy - Baseline*) in electricity generation for the entire EU and non-EU regions by period, region and technology (EJ). The lower panel shows the country level differences by period and technology (EJ). Belarus, Iceland and Turkey are not included as they are not connected to the European grid regions.~~

Projected changes in the total energy demand and the composition of the energy mix will have direct implications for the emission of GHG and air pollutants (Figure 15 Figure 15 and Figure 16Figure 16). CO2 emissions decline substantially by the end of the century, driven by reduced fossil fuel demand in both the EU bloc and the non-EU European region. Under the policy scenario, emissions in these regions decrease by 910 MTC and 362 MTC, respectively by 2100. This reduction is particularly pronounced in several Scandinavian countries such as Denmark, Sweden, and Finland, where CO2 emissions in the policy scenario fall by more than 250% by 2100, compared to the baseline. Significant reductions are also observed in other greenhouse gases (GHGs) as a result of the implementation of the policy. For example, methane emissions decrease by 7.0 Tg in the EU and 5.4 Tg in non-EU European regions by the end of the century. The most pronounced methane reductions are observed in Cyprus and Hungary, with decreases of over 60% by 2100.

Most air pollutants show a decreasing trend in the policy scenario compared to the baseline over the entire century. Nitrogen oxides (NOx), highly related to the combustion of the fossil fuels, particularly in the transportation sector, show a steady decrease at both EU and European non-EU region. By the end of the century, countries such as the Czech Republic and the UK reduce their NO_x emissions by more than 50%. Similarly, SO2$_2$ emissions, primarily associated with coal use, also decline across Europe over the entire time horizon. In some Eastern European countries, where coal dependency is high in the baseline scenario, SO2$_2$ emissions decrease by more than 70% by 2100 when the climate policy is implemented. However, the trends for other pollutants varies over time. The large-scale deployment of biomass technologies in the near term leads to an increase in certain biomass-related emissions, such as organic carbon (OC), by 2030. In some South-Eastern European countries, such as Bulgaria, Romania, or Italy, OC emissions rise by more than 50% by 2030. This could contribute to localized air pollution issues, highlighting the importance of integrating air quality and public health considerations into climate policy design (Vandyck et al., 2021).

While this analysis shows the model response to a stylised representation of climate policy, through an economy-wide carbon price for the entire EU-27, the model also allows for the assessment of a more sophisticated set of real-world energy and climate policies, including the combination of national (e.g. energy efficiency and renewable energy targets) and EU-wide (e.g. vehicle efficiency standards, the EU emission trading system) policies, as well as index decomposition analyses to shed light on the impact of each modelled policy (Riemer et al., 2023). (Riemer et al., 2023). A recent application of the model reflecting the EU Fit-for-55 policy program, including the country-specific National Energy and Climate Plans (Frilingou et al., 2025)(Frilingou et al., 2025), alleviates this model capacity, and verifies its usefulness for assessing geographically explicit implications (Rodés-Bachs et al., 2025) (Rodes-Bachs et al, 2025). These more detailed policy scenarios can also be reproduced directly through the open model release of GCAM-Europe v7.2. Given the model´s capabilities, policy assessment could be further extended to assess trade policies such as CBAM, the impact of specific behavioural and technological assumptions, and policies or impacts along the climate-land-energy-water nexus (IAEAnternational Atomic Energy Agency, 2024) (IAEA, 2024).


European Union
BC
CH4
CO2
N2O
NH3
NOx
OC
SO2
Net difference
2020 2040 2060 2080 2100


Europe non-EU
BC
CH4
CO2
N2O
NH3
NOx
OC
SO2
Net difference
2020 2040 2060 2080 2100

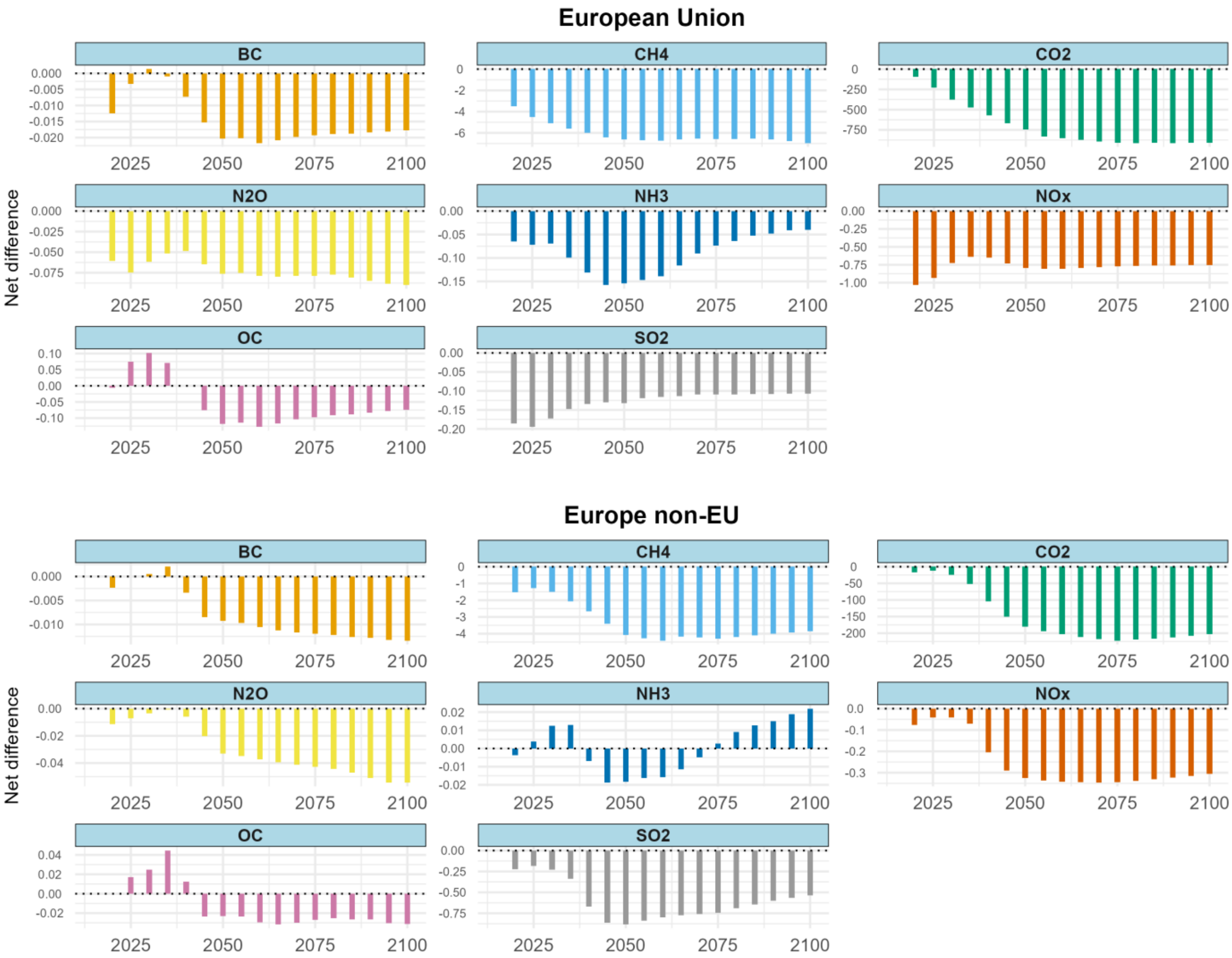
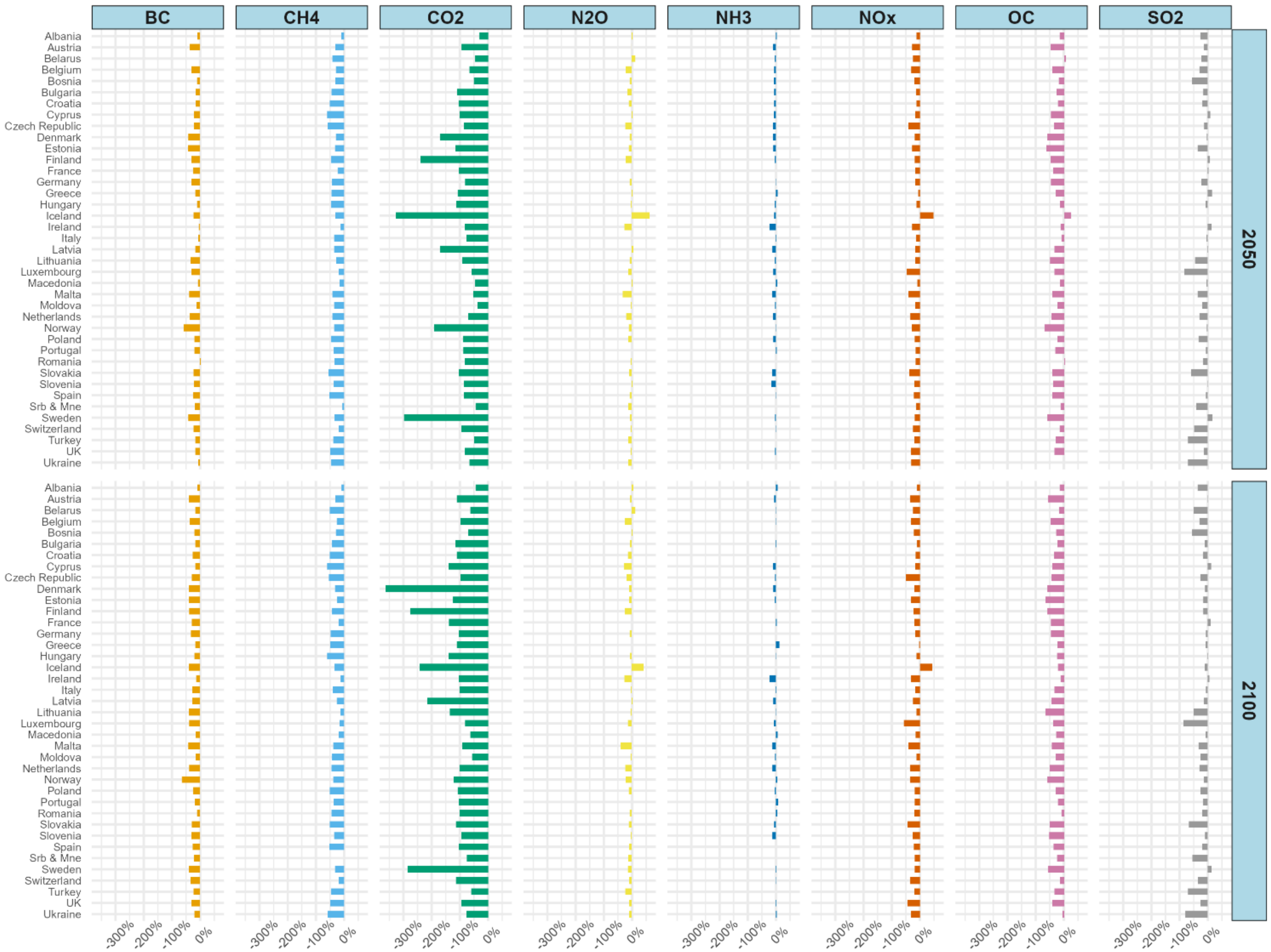


Figure 15: Differences in GHG and air pollutant emissions between the policy and the baseline scenarios by period, region, and specie (MTC and Tg).

~~Figure 15: Differences in GHG and air pollutant emissions between the policy and the baseline scenarios by period, region, and specie (MTC and Tg).~~



BC
CH4
CO2
N2O
NH3
NOx
OC
SO2
2050
2100
Albania
Austria
Belarus
Belgium
Bosnia
Bulgaria
Croatia
Cyprus
Czech Republic
Denmark
Estonia
Finland
France
Germany
Greece
Hungary
Iceland
Ireland
Italy
Latvia
Lithuania
Luxembourg
Macedonia
Malta
Moldova
Netherlands
Norway
Poland
Portugal
Romania
Slovakia
Slovenia
Spain
Srb & Mne
Sweden
Switzerland
Turkey
UK
Ukraine
-300%
-200%
-100%
0%

660

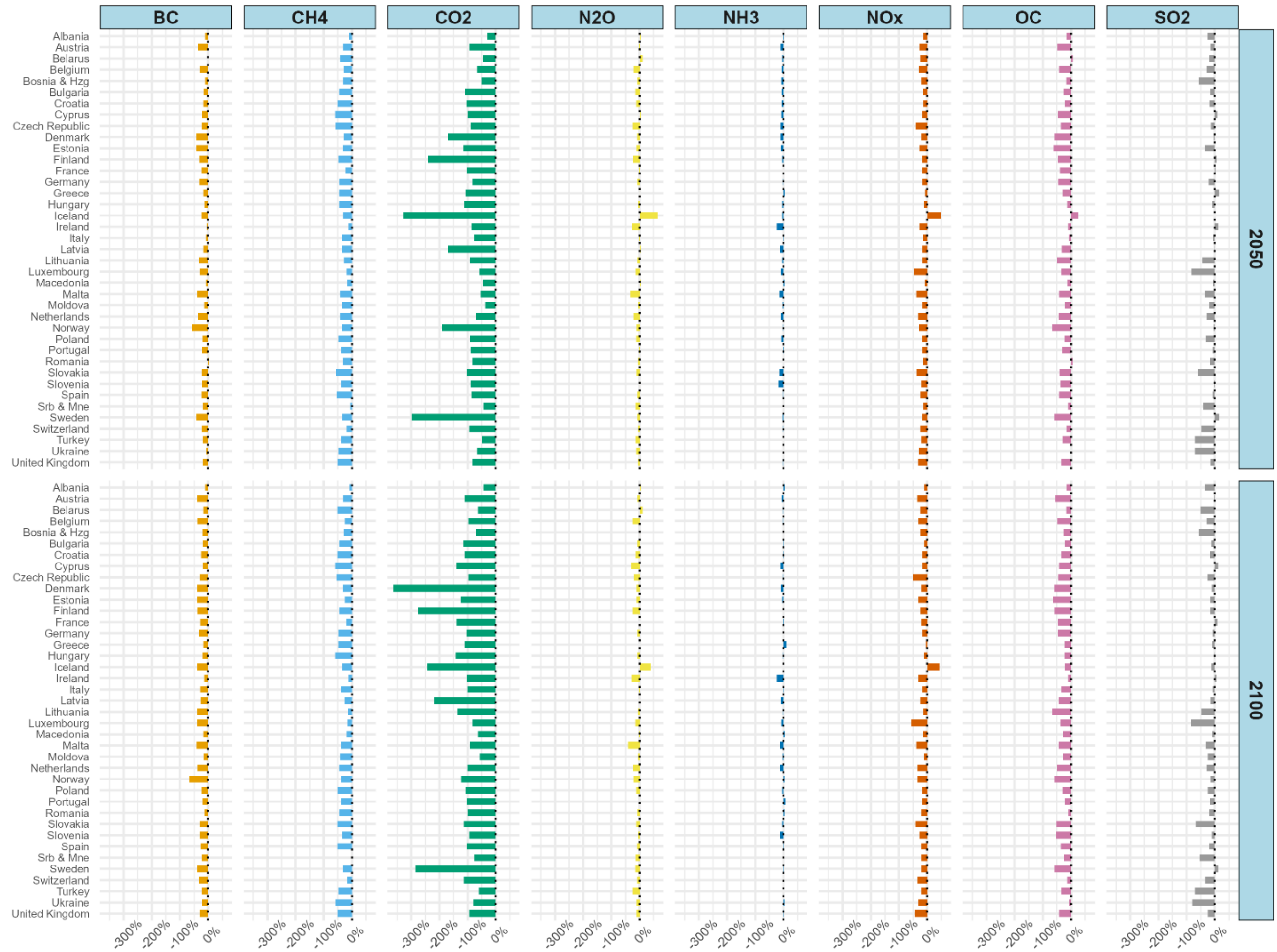


Figure 16: Percentage differences in GHG and air pollutant emissions between the policy and the baseline scenarios by period, country, and specie (%).

~~**Figure 16: Percentage differences in GHG and air pollutant emissions between the policy and the baseline scenarios by period, country, and specie (%).**~~

5. Discussion and conclusion

GCAM-Europe represents a significant advancement for both academic and policy-focused communities. With its improved geographical and sectoral detail, alongside an integrated representation of energy, water, ~~and~~ emissions, and socioeconomic systems, GCAM-Europe offers a robust platform for comprehensive climate and environmental analysis. The model supports detailed assessments of climate policy impacts both between European countries and within them, reflecting regional differences and sector-specific complexities. Moreover, the model operates within the global version, allowing users to explore how European policies may influence, and be influenced by, developments in the rest of the world. GCAM-Europe's level of disaggregation, combined with its open-source framework, makes it especially valuable to a broad range of stakeholders, ranging from academic institutions to government agencies, ~~NGO~~non-profit organizations, and private-sector experts. Particularly, the model is well-suited to support policymakers in the design and evaluation of alternative environmental and climate policies in a transparent and evidence-based manner.

This higher level of disaggregation aims to better address Europe-specific research questions, but it does not aim to substitute the current representation of the European continent in the GCAM-Core version. The extra level~~s~~ of complexity~~also~~ introduce~~s~~ ~~certain~~additional technical~~ological~~ challenges that are unnecessary for a model designed to maintain a global perspective~~ to have a broad global perspective~~. ~~compared to the core version.~~In particular, ~~T~~the expanded number of markets and the new electricity grid structure make the model significantly more memory-intensive, ~~increases~~resulting in longer ~~-~~overall run times. As in other models, the inclusion of policy scenarios further constrains the system, increasing computational demands. In the case of GCAM-Europe, these demands can reach technical thresholds that make it more suitable to run in a cluster computer. Beyond computational challenges, the development of a regional version of the model also entails important data-related difficulties that are likely to be relevant for other modelling efforts. In particular, the absence of country-level information in key databases (e.g., Eurostat) often necessitates filling data gaps with alternative sources, such as global balances or national statistics. This process requires extensive harmonization to ensure consistency across datasets and represents a substantial component of the overall modelling effort. ~~particularly for those scenarios that incorporate climate policies, such carbon prices or exogenous emission caps. Likewise, the greater complexity introduced by the expanded set of regions, sectors and markets makes the model more sensitive and less robust to the implementation of new features, potentially leading to a higher likelihood of solution challenges compared to the core version.~~

Several improvements and new developments are planned for future versions of GCAM-Europe. The model is planned to remain under continuous development, progressively integrating features from successive releases of the core GCAM model. In the near term, the most immediate update will be the incorporation of features from GCAM v8.2 (JGCRI, 2025), which includes the shift of the final calibration year to 2021. Since the current version of GCAM-Europe is calibrated to 2015, adopting the updated calibration year is expected to enhance the reliability of future projections.

Regarding consumer heterogeneity, the core GCAM model includes multiple consumers in the form of income deciles only in the residential sector, and allocates different residential energy services across consumers using exogenous assumptions based on the form of the demand function within each of the sectors. GCAM-Europe is planned to incorporate multiple consumers in all end-use sectors, namely food, transportation and municipal water. The within-region allocation of energy services across consumers will be improved by using country-level empirical data from the country-level Household Budget Surveys (HBS), which are available for all member states. In addition, we plan to explore new dimensions of consumer heterogeneity beyond income groups, including urban–rural distinctions, gender, and subregional classifications (e.g., NUTS levels). Finally, additional model expansion plans are under consideration, contingent on data availability. These include endogenizing industrial material use and building efficiency improvements, enhancing the representation of technology adoption, and refining consumer-specific elasticities to better capture behavioural responses. Further planned developments also involve sectoral and technological refinements, such as disaggregating diesel and gasoline vehicles, improving the representation of district heating, or incorporating hydrogen trade.

Data and code availability: The analysis has been developed using GCAM-Europe, which can be downloaded from the following open-access online repository: https://github.com/bc3LC-GCAMEurope/gcam-core. The repository includes all the equations, assumptions, and parameters that are read in by the model. The GCAM-Europe v7.2.0 release is available on Zenodo: https://zenodo.org/records/15655568

A detailed documentation for all the input assumptions used in the core GCAM model can be found in the following open-access repository: https://github.com/JGCRI/gcam-doc.

The code for reproducing the results and generating the figures has been stored in an open-access repository: https://github.com/bc3LC-GCAMEurope/sampedro_etal_gcameurope

Author contribution: All the authors contributed to the development of the model. JS wrote the original draft and RH, CR and DV contributed to Writing (review and editing). DV contributed to Funding acquisition.

Competing interests: The authors declare that they have no conflict of interest.

Disclaimer. The views and opinions expressed in this paper are those of the authors alone.

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